HHS Public Access
Author manuscript
J Med Entomol. Author manuscript; available in PMC 2024 February 29.

Published in final edited form as:
J Med Entomol. 2022 May 11; 59(3): 911–921. doi:10.1093/jme/tjac027.

Designing an Intervention Trial of Human-Tick Encounters and Tick-Borne Diseases in Residential Settings Using 4-Poster Devices to Control *Ixodes scapularis* (Acari: Ixodidae): Challenges for Site Selection and Device Placement

Neeta P. Connally[1,6], **Adam Rowe**[2], **Alison Kaufman**[2], **James I. Meek**[3], **Sara A. Niesobecki**[3], **Amberjean P. Hansen**[3], **Jennifer White**[4], **Courtney Nawrocki**[5], **Erik Foster**[5], **Alison F. Hinckley**[5], **Lars Eisen**[5]

[1]Department of Biological & Environmental Sciences, Western Connecticut State University, Danbury, CT, USA

[2]Bureau of Communicable Disease Control, New York State Department of Health, Albany, NY, USA

[3]Connecticut Emerging Infections Program, Yale School of Public Health, New Haven, CT, USA

[4]Bureau of Communicable Disease Control, New York State Department of Health, Albany, NY, USA

[5]Division of Vector-Borne Diseases, Centers for Disease Control and Prevention, Fort Collins, CO, USA

Abstract

Blacklegged ticks, *Ixodes scapularis* Say, transmit Lyme disease spirochetes and other human pathogens in the eastern United States. White-tailed deer (*Odocoileus virginianus*) are key reproductive hosts for *I. scapularis* adults, and therefore control methods targeting deer have the potential for landscape-wide tick suppression. A topical acaricide product, containing 10% permethrin, is self-applied by deer to kill parasitizing ticks when they visit 4-Poster Tick Control Deer Feeders (hereafter, 4-Posters) Previous 4-Poster intervention studies, including in residential settings, demonstrated suppression of *I. scapularis* populations but did not include human-based outcomes. To prepare for a proposed 4-Poster intervention trial in residential areas of Connecticut and New York that would include human-tick encounters and tick-borne diseases as outcomes, we sought to identify areas (study clusters) in the 80–100 ha size range and specific locations within these areas where 4-Poster devices could be deployed at adequate density (1 device per 20–25 ha) and in accordance with regulatory requirements. Geographic Information System-based data were used to identify prospective study clusters, based on minimum thresholds for Lyme disease incidence, population density, and forest cover. Ground truthing of potential 4-Poster placement locations was done to confirm the suitability of selected clusters. Based on these efforts, we failed

[6] Corresponding author, connallyn@wcsu.edu.

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to identify more than a few residential areas fulfilling all criteria for a treatment cluster. We, therefore, reconsidered pursuing the intervention trial, which required inclusion of >30 treatment clusters to achieve adequate statistical power. The 4-Poster methodology may be more readily evaluated in natural or public areas than in residential settings in NY or CT.

Keywords

Ixodes scapularis ; 4-Poster device; Lyme disease; topical acaricide; white-tailed deer

Tick-borne diseases are increasing in the United States (US) and environmentally-based tick suppression methods, as currently used, have not proven sufficient to reverse this trend (Rosenberg et al. 2018, Eisen and Stafford 2021). The blacklegged tick, *Ixodes scapularis* Say (Acari: Ixodidae), is the primary vector in the eastern US for seven human pathogens, including causative agents of Lyme disease (*Borrelia burgdorferi* sensu stricto and *Borrelia mayonii*), anaplasmosis (*Anaplasma phagocytophilum*), babesiosis (*Babesia microti*), *Borrelia miyamotoi* disease, Powassan virus disease, and ehrlichiosis associated with *Ehrlichia muris eauclairensis* (Eisen and Eisen 2018, Rosenberg et al. 2018). Lyme disease alone is estimated to account for >450,000 annual infections in the US, with most cases occurring in the Upper Midwest, Northeast, and Mid-Atlantic regions (Kugeler et al. 2015, 2021). Human exposure to *I. scapularis*, including the small and easily overlooked nymphal life stage that likely accounts for most human tick-borne infections, is thought to occur commonly on residential properties, especially in the Northeast, but can also occur in neighborhood green spaces and on public lands (Stafford et al. 2017, Mead et al. 2018, Fischhoff et al. 2019, Jordan and Egizi 2019). Due in part to lack of public health infrastructure for tick control, community-based approaches aiming to suppress human-biting ticks across the landscape are rare in Lyme disease endemic areas (Eisen 2020, Eisen and Stafford 2021).

Approaches that target white-tailed deer (*Odocoileus virginianus* Zimmerman [Artiodactyla:Cervidae]), have the potential for landscape-wide suppression (including on residential properties) of both *I. scapularis* and the lone star tick (*Amblyomma americanum* L. [Acari: Ixodidae]), as deer serve as key reproductive hosts for these human-biting tick species (reviewed by Stafford 2007, Pound et al. 2009a, Eisen and Dolan 2016, Kugeler et al. 2016, Stafford and Williams 2017, Telford 2017, Eisen and Stafford 2021, Wong et al. 2021). One such approach includes the self-application of topical acaricide by deer to kill parasitizing ticks using the 4-Poster Tick Control Deer Feeder (hereafter, 4-Poster), which was originally developed by the US Department of Agriculture (Pound et al. 2000) and is available commercially from C.R. Daniels, Inc. (Ellicott City, MD). The 4-Poster device includes a food bait (whole kernel corn) to attract deer, and while feeding the deer self-apply acaricide from treated rollers to their head, ears, and neck. 4-Posters are not harmful to deer (Curtis et al. 2011) and the acaricide in 4-Posters is contained to the devices rather than distributed widely in the environment like other commonly used acaricidal products.

The 4-Poster device has been used to suppress populations of *I. scapularis* in natural areas (Solberg et al. 2003, Schulze et al. 2009), mixed woodlands/residential settings (Carroll et al. 2009a, b; Miller et al. 2009; Curtis et al. 2011), and residential settings (Daniels et al. 2009, Stafford et al. 2009). When deployed at the density of one 4-Poster device per 20–25 ha, the overall reduction in the abundance of host-seeking *I. scapularis* nymphs has been shown to approach 50% by the third year of use and reach 60 and 70% in the fourth and sixth years, respectively (Brei et al. 2009, Pound et al. 2009b). The density of host-seeking *I. scapularis*, however, may not accurately predict the frequency of human-tick encounters (including ticks crawling on or biting a person) or the incidence of human tick-borne disease (Ginsberg 1993, Poland 2001, Eisen et al. 2012, Eisen and Eisen 2016, Hinckley et al. 2016, Eisen 2021, Hook et al. 2021), underscoring the need for a large-scale, residential intervention study to evaluate the public health impacts of using 4-Posters in areas where humans are at high risk for exposure to *I. scapularis* ticks.

Efforts to conduct a large-scale 4-Poster intervention study may be impacted by multiple logistical and operational factors. First, a single permethrin-based acaricide (4-Poster Tickicide with 10% permethrin, Y-Tex Corporation, Cody, WY) is approved by the Environmental Protection Agency (EPA) for use with the 4-Poster device. The 4-Poster Tickicide (hereafter, Tickicide) has replaced the pesticide (2% amitraz) used in previous 4-Poster studies targeting *I. scapularis* in residential settings that is no longer on the market. EPA label restrictions specifically for using Tickicide require the acaricide to be applied only by certified pesticide applicators and is not recommended for use within 91 m (100 yards) of any home, apartment, playground, or other places where children may be present without adult supervision. Any device needing to be placed closer than 91 m from the aforementioned locations must be surrounded by a protective fence, 71–76 cm (28–30 in) high and with a minimum diameter of 8.8 m (29 ft), and equipped with precautionary placards or warning signs (Environmental Protection Agency 2021) to limit public contact with these devices. The height of protective fences should not hinder deer movement, as deer can easily enter areas with fences shorter 2.4 m (Vercauteren et al. 2010).

Moreover, state-specific restrictions may also impact the use of 4-Posters. For example, New York State has placed additional restrictions on their use to further limit the potential for human interaction with the devices, prevent bears from accessing the corn bait, and ensure community acceptance for their placement. The use of 4-Poster devices in New York State requires that a deer feeding permit (including a requirement for a deer population management plan) must be obtained, devices must be placed more than 91 m (100 yd) from a public road or highway, and all owners of properties falling wholly or partly within 227 m (248 yd) of a proposed 4-Poster device location must agree to the placement via a signed consent form (New York State Department of Environmental Conservation 2021). Moreover, in areas of the state where bears may be present, the requirement for a fence around the 4-Poster device is upgraded to require an electric fence.

Yet another logistical consideration is that suppression of host-seeking *I. scapularis* by use of 4-Poster devices appears to depend on the adequate density of deployed devices: the strong tick suppression observed in five linked studies in Rhode Island, Connecticut, New York, New Jersey, and Maryland that deployed 4-Posters at a density of 1 device per 20–25 ha (~50–60 acres) (Carroll et al. 2009a, Daniels et al. 2009, Miller et al. 2009, Schulze et al.

2009, Stafford et al. 2009) could not be replicated in another study with a 3-fold lower density of 1 device per approximately 60 ha (~150 acres) (Grear et al. 2014).

The above-mentioned logistical challenges were taken into consideration to design an intervention trial to evaluate the impact of 4-Poster devices on host-seeking *I. scapularis* and human encounters with this tick species, as well as human tick-borne diseases, in settings dominated by residential properties. In contrast to previous small-scale 4-Poster intervention trials conducted in residential settings that focused on acarological outcomes (Daniels et al. 2009, Stafford et al. 2009), we sought to design an intervention trial to be conducted in geographical areas extensive enough to capture a human population sufficiently large to evaluate the human-based outcome measures (e.g., reports of human encounters with *I. scapularis,* or incidence of Lyme disease). Here, we describe the feasibility and challenges in identifying study areas (treatment clusters) for conducting a controlled trial in areas of high Lyme disease incidence in western Connecticut and southern New York. Specifically, we aimed to identify study sites and specific locations within residential settings where 4-Poster devices could be placed at a density adequate to not only suppress *I. scapularis* ticks, but also to evaluate their potential efficacy in reducing human-vector tick encounters and tick-borne diseases.

Materials and Methods

Experimental Design of Proposed 4-Poster Intervention Study

We set out to design a cluster randomized 4-Poster trial with primary outcome measures being human encounters with *I. scapularis* ticks (heretofore, ‘human-tick encounters’) and incidence of tickborne diseases associated with *I. scapularis* tick bites. Each treatment cluster would cover an area large enough (≥80–100 ha) for strategic placement of at least four 4-Poster devices based on the same deployment density (1 device per 20–25 ha) that resulted in strong suppression of *I. scapularis* populations in previous studies (Brei et al. 2009, Pound et al. 2009b). Control clusters would be of similar size but without the placement of 4-Poster devices. The decision to not include placebo 4-Poster devices (baited with corn but without acaricide on the rollers) and thus blind the intervention to the human study population and the field crews was based in part on general restrictions on deer feeding and in part on the potential for baited 4-Poster devices to impact deer movement patterns within the control clusters and thus also impact the primary study outcome measures.

Based on spatial movement patterns of deer in mixed natural/residential settings and following previous studies with 4-Poster devices (Pound et al. 2009a, Stewart et al. 2011, Stafford and Williams 2017), the outer edges of treatment and control clusters were to be separated either by a distance of at least 3.2 km (2 miles) in landscapes conducive to deer dispersal or by a barrier perceived to severely restrict deer movement, such as a river or a major highway. Additional required characteristics for all study clusters (treatment or control) included (1) location within a city/town with high incidence of Lyme disease (3-yr average of ≥50 reported cases per 100,000 population per year); (2) forest cover of ≥50%; and (3) presence of at least 100 residential properties. These three characteristics ensure that the intervention was evaluated in settings with high risk for human encounters with *I.*

scapularis ticks infected with *B. burgdorferi*, presence of suitable habitat for *I. scapularis* and deer, and with a human population that would provide a sufficient sample size and power to statistically evaluate any impact on human encounters with *I. scapularis* nymphs and adults.

We used previously collected information on the household study household enrollment rates and reported human encounters with ticks in nonintervention areas in western Connecticut (A.F. Hinckley, unpublished data) to conduct a power analysis to determine the target numbers of treatment and control clusters to include in the intervention study. Using conservative estimates of a 10% household recruitment rate and 3 residents per household, data for human encounters with ticks would require ≥10 households and ≥30 individuals per study cluster. Assuming that 80% of 0.117 tick encounters per person per year represent *I. scapularis*, the intervention study would need to include 34 clusters for each of the study's treatment and control groups (68 clusters total) to detect a drop of 35% (with 81% power) in the number of human-tick encounters per resident per year in treatment versus control clusters.

GIS-Based Characterization and Ground Truthing of Potential Study Areas in New York

In New York, we focused on five counties (Orange, Putnam, Rockland, Sullivan, and Westchester) located in the southeastern part of the state and with average incidence of reported Lyme disease cases ≥50 per 100,000 population per year during 2015–2017 (New York State Communicable Disease Statistics 2021). Relevant GIS data for these counties, as outlined below, were imported and processed in ArcGIS 10.8.1 and ArcGIS Pro 2.7.2 (Esri, Redlands, CA). The first step was to use GIS data from 2019 for civil boundaries (New York State GIS Clearing House 2021a) and tax parcels (New York State GIS Clearing House 2021b) to identify all land parcels that were located completely within the target counties and met residential property status, including parcels with various types of residences present as well as vacant residential parcels. The next steps were to overlay the entire five-county area with (1) 80 or 100 ha square grid layers, representing potential study clusters of a size suitable to hold four to five strategically placed 4-Poster devices; and (2) 30 × 30 m resolution land cover data from 2016 (United States Geological Survey 2021) reclassified to only include forested land cover classes (deciduous, evergreen, and mixed forests). We thereafter used spatial joins to identify all 80 or 100 ha square grids that both contained ≥100 residential parcels and had ≥50% forest cover (Fig. 1). The New York State specific requirement that 4-Poster devices cannot be placed within 91 m (100 yd) of a public road or highway (New York State Department of Environmental Conservation 2021) necessitated the creation of a data layer with a 91 m buffer around public roads and highways, using a transportation data set from 2019 (New York State GIS Clearing House 2021c), to rule out these buffer areas as potential device placement locations. This public roads and highways buffer data layer was then used, together with an ideal scheme for placement of 4-Poster devices to maximize the combined theoretical impact area for a group of four devices within 80 or 100 ha grid cells (see schematic in Fig. 2), to exclude those ideal 4-Poster device locations that fell within public roads and highways buffer areas.

A follow-up ground truthing exercise was conducted on 3 April 2019. Seven 100 ha grid cells and three 80 ha grid cells selected using the above-mentioned GIS criteria were chosen for ground truthing: two were located in southeast Sullivan County, seven in east Orange County, and one in the southwest Putnam County. Precise coordinates for the eight canonical cardinal bearings plus the center point of each 100 ha grid cell were calculated using GIS software. These coordinates were used with Google Maps to optimize a best-fit driving route that would transect through each grid. The ground truthing effort included visual assessment of the suitability of projected 4-Poster device placement locations with regards to their accessibility, presence of level, dry ground for the devices, and other features not evident from the GIS data that prevented convenient device placement such as the presence of schools, playgrounds, or other places where children may be unsupervised. Moreover, based on the Environmental Hazard language on the EPA Tickicide label relating to the toxicity of this product for aquatic organisms, we sought to avoid placing 4-Poster devices within wetlands or directly adjacent to gutters, storm drains, or drainage ditches.

GIS-Based Characterization and Ground Truthing of Potential Study Areas in Connecticut

In Connecticut, we focused on one county (Fairfield) located in the southwestern part of the state. Spatial data sets imported into ArcGIS 10.7.1 were used to identify towns in Fairfield County, characterized by (1) average incidence of reported Lyme disease cases ≥50 per 100,000 population per year during 2015–2017 (Connecticut Department of Public Health 2021); (2) human population density ≥50 households per km^2 in 2010 (United States Census Bureau 2012); (3) ≥50% of the land area represented by forested habitat (classified as deciduous, mixed deciduous, or coniferous forests, or forested wetlands) based on 30 × 30 m resolution 2010 Connecticut land cover data (UCONN CLEAR 2021); and (4) ≥20% of the private or public land parcels ≥0.8 ha (2.0 acres) in size to ensure flexibility of placement of the 4-Poster devices within the parcels including to minimize their visibility and potential for vandalism (Connecticut Department of Energy and Environmental Protection 2021, Town of Ridgefield 2012).

Two towns, Ridgefield and Newtown, fulfilling these requirements (Table 1) were selected to pilot the further use of GIS data for selecting specific potential land parcels for device placement. We first overlaid a 100 ha (1 km^2) square grid layer, where each grid cell represented a potential study cluster of a size suitable to hold four to five strategically placed 4-Poster devices. In Ridgefield, we then selected 100 ha grid cells that were located completely within the town boundary, contained ≥50% forested area, and included ≥100 residential parcels (Town of Newtown 2012, Town of Ridgefield 2012). Grid cells containing schools or partially falling outside of the town boundary were excluded as potential study clusters. To further locate land parcels within the 100 ha grid cells large enough to allow for convenient placement of 4-Poster devices without the need to construct protective fences based on the EPA Tickicide label (i.e., with device location >91 m from any home, apartment, playground or other places where children may be present without adult supervision), we identified parcels ≥0.8 ha (2 acres) in size. We then used visual observation of parcel polygons overlaid with orthoimagery (Esri 2021) to further identify 100 ha grid cells that could accommodate four to five strategically placed 4-Poster devices on parcels that met the selection criteria outlined above in each of the two pilot study towns.

Our initial ground truthing step involved visiting 16 parcels within five Ridgefield grid cells on 21 April 2019. None of these 16 parcels were deemed suitable following the ground truthing due to limited accessibility by roads or walking trails or due to steep elevation changes (presenting logistical challenges for device placement and weekly visits to replenish the corn bait), lack of level, dry ground for placing 4-Poster devices, or device placement being too close to homes or other buildings.

Based on these lessons learned, we improved the GIS-based parcel selection for grid cells in Newtown by modifying our selection criteria to increase the minimum parcel size to 1.0 ha (2.5 acres) and to exclude parcels with more than 61 m (200 ft) elevation change (Connecticut Environmental Conditions Online 2021). In addition, we used visual inspection of orthoimagery to pinpoint possible 4-Poster device locations and then confirmed the suitability of placement locations by calculating the distance from these points to nearby buildings. Point locations within 91 m (100 yd) of any building were excluded as 4-Poster devices placed in such locations would require a protective fence. The next steps were to apply a circular buffer of 21 ha around each suitable point location to approximate the theoretical impact area for a single 4-Poster device and then to identify 100 ha grid cells that could potentially allow for the strategic placement of four to five such devices. The goal was to distribute 4-Poster devices spatially across each 100 ha grid cell so that the combined theoretical impact areas of the devices would include or surround the majority of residential properties in the grid cell. The final step was to conduct ground truthing for 18 parcels located in five Newtown grid cells on 31 May 2019, to assess their suitability for 4-Poster device placement in the field. A parcel was deemed suitable if the projected device placement location was confirmed to (1) be accessible by road or walking trail; (2) provide sufficient level, dry ground for the device; and (3) was not situated close to homes or other places where children could be assumed to play unsupervised. Similar to New York, we also sought to avoid placing 4-Poster devices within wetlands or directly adjacent to gutters, storm drains, or drainage ditches in Connecticut.

Results

Feasibility of 4-Poster Device Deployment Across Residential Neighborhoods in New York

The process of first selecting suitable study clusters (80 or 100 ha grid cells) based on GIS-data and then ground truthing to determine if they met all New York State requirements for 4-Poster device placement is summarized in Fig. 3 and described below. The five-county target area included 488,594 land parcels that met residential property status and the total area covered by these counties could be divided into 9,284 grid cells of 80 ha size or 7,467 grid cells of 100 ha size. For the 80 ha grid cell size, the five-county area included 292 grid cells that met the criteria of both containing ≥100 residential parcels and having ≥50% forest cover; and for the 100 ha grid cell size, 352 grid cells contained ≥100 residential parcels and had ≥50% forest cover. Based on the use of four ideally placed 4-Poster devices per 80 or 100 ha grid cell, this represented suitable placement locations for 1,168 devices for the 80 ha grid cell option and 1,408 devices for the 100 ha grid cell option. However, the regulatory requirement for New York to not place 4-Poster devices within 91 m of a public road or highway led to the majority of these otherwise suitable device placement locations being excluded from consideration: only 431 (37%) of the possible device placement locations remained eligible for the 80 ha grid cell size and 563 (40%) for the 100 ha grid cell size. Overall, only six (2%) of the 292 grid cells of 80 ha size and 10 (3%) of the 352 grid cells of 100 ha size were judged to be suitable for inclusion in the intervention study based on adequate parcel density and forest cover as well as allowing for optimal placement of all four 4-Poster devices after the public roads and highways buffer exclusion criterion was applied. This represented totals of 1,097 and 1,558 residential parcels included for the 80 and 100 ha grid cell sizes, respectively.

After conducting the ground truthing exercise, none of the seven potential 100 ha grid cells or three potential 80ha grid cells visited were found to satisfy the complete optimal placement of four to five devices. Reasons for deeming a grid cell nonviable for optimal device placement (including multiple reasons in some cases) after ground truthing were as follows: projected device location too close to homes, outbuildings, playsets, or other places where children may be unsupervised ($n = 7$ grid cells, 70%); lack of level, dry land allowing for device placement or other obstacles hindering device placement or maintenance, such as dense vegetation ($n = 5$ grid cells, 50%). Overall, we deemed few individual locations across the visited grid cells viable for 4-Poster placement and there was no grid cell that supported optimal placement of a sufficient number of 4-Poster devices to reach the target density of 1 device per 20 ha.

Feasibility of 4-Poster Device Deployment Across Residential Neighborhoods in Connecticut

The process of first selecting suitable study clusters (100 ha grid cells) based on GIS-data and then ground truthing to determine if they met all requirements for 4-Poster device placement is summarized in Fig. 4 and described below. Using our initial GIS selection scheme in Ridgefield, we fit a total of 66, 100 ha grid cells containing 7,967 parcels within the town's spatial extent. Of these, 53 grid cells (80%) contained ≥50% forested area, and 42 grid cells (64%) were characterized by having both ≥50% forested area and containing ≥100 residential parcels. We further refined our selection to remove four grid cells with schools present, resulting in a total of 38 grid cells meeting our suitability criteria for *I. scapularis* and deer as well as household enrollment. A total of 3,768 parcels with an area ≥0.8 ha completely occupied or mostly occupied (i.e., had their centroids within) the 38 selected grid cells. We then visually inspected parcels together with orthoimagery for a sample of 18 selected grid cells and identified 10 grid cells (56%) that could potentially serve as study clusters that would allow the placement of four or five devices in each. However, as noted in the Materials and Methods section, none of the 16 parcels in Ridgefield visited in the subsequent ground truthing effort was found to be suitable for placement of a 4-Poster device. The breakdown of reasons for finding a parcel unsuitable for 4-Poster device placement (including multiple reasons for some individual parcels) after the field visit were as follows: steep elevation changes limiting access or lack of level, dry ground prohibiting device placement ($n = 12$ parcels, 75%); projected device location too close to homes or other buildings ($n = 10$ parcels, 63%); and access limited by dense vegetation ($n = 5$ parcels, 31%).

Using our improved GIS characterization scheme in Newtown, we fit a total of 115, 100 ha grid cells containing 8,396 parcels within the town's spatial extent. Of these, 102 grid cells (89%) contained ≥50% forested area, and 38 grid cells (33%) were characterized by having both ≥50% forested area and containing ≥100 residential parcels. We further refined our selection to remove one grid cell with a school present, resulting in a total of 37, 100 ha grid cells meeting our suitability criteria for *I. scapularis* and deer as well as household enrollment. After excluding parcels with >61 m (200 ft) elevation change, we identified 414 parcels with an area ≥1.0 ha that completely occupied or mostly occupied (i.e., had their centroids within) the 37 selected grid cells. We then visually inspected parcels together with orthoimagery and building distance data for a sample of 18 selected grid cells and identified 14 grid cells (78%) that could potentially serve as study clusters. After calculating distances from theoretical location points to nearest buildings, however, we further reduced our grid cell selection to identify eight grid cells (44%) that could potentially allow the placement of four to five 4-Poster devices.

Follow-up ground truthing visits to 18 parcels located across five of the grid cells (with four to five parcels visited per grid cell) in Newtown revealed that none of these grid cells could accommodate more than two devices. Seven of the 18 parcels (39%) were deemed suitable for 4-Poster device placement after the field visit: these parcels had a median area of 3.9 ha (9.7 acres), ranging from 1.6 to 12.4 ha (3.9–30.7 acres), and four (57%) were publicly-owned or belonged to a land trust whereas the remaining three (43%) were privately-owned properties. The remaining 11 parcels observed (61%) were deemed unsuitable for 4-Poster device placement after the field visit: these parcels were smaller than the suitable parcels, with a median area of 1.4 ha (3.4 acres), ranging from 1.1 to 4.7 ha (2.7–11.5 acres), and 10 (91%) of the parcels were privately-owned. The breakdown of reasons for finding a parcel unsuitable for 4-Poster device placement (including multiple reasons for some individual parcels) after the field visit were as follows: steep elevation changes or lack of level, dry ground (n = 6 parcels, 55%); access limited by dense vegetation (n = 5 parcels, 45%); projected device location too close to homes or other buildings (n = 3, 27%); and access limited by deer fencing (n = 1, 9%).

In Newtown, we also identified seven additional parcels that met suitability criteria during the ground truthing effort, based on observations within three of the grid cell areas visited. Subsequent analysis of GPS waypoints taken from those additional observed locations showed that four of the parcels were forested public or land-trust properties larger than 2.2 ha (5.5 acres), whereas the three remaining parcels were privately owned farm-style properties with pasturelands adjacent to forested areas, larger than 1.6 ha (4.0 acres).

Discussion

We sought to identify specific study cluster locations for a proposed randomized cluster trial to evaluate the impact of 4-Poster devices on human-*I. scapularis* encounters and tick-borne diseases associated with *I. scapularis*. We were unable to identify a sufficient number of study clusters suitable for implementing such a study in the residential settings we examined in Connecticut and New York. Given this study required inclusion of >30 treatment clusters to achieve adequate statistical power (>80%) and that we identified only a few residential areas fulfilling our criteria for a treatment cluster, we suspended plans to proceed with the proposed intervention study.

The challenges faced in our study underscore the logistical difficulties of site selection and placement of 4-Poster tick control devices in landscapes dominated by residential properties. Although 4-Poster devices have successfully been used in studies conducted in some residential settings in the Northeast (Daniels et al. 2009, Stafford et al. 2009), the roadblocks to implementing a study intended to measure human outcomes (e.g., vector ticks encountered by people, disease occurrence) are more extensive than those encountered when deploying devices in residential neighborhoods and using acarologic outcomes (e.g., densities of host-seeking, infected vector ticks) as the primary measure of effect. Previous intervention studies with 4-Poster devices in residential settings (Daniels et al. 2009, Stafford et al. 2009) were restricted to evaluate suppression of *I. scapularis* populations and therefore could be conducted using single large areas representing treatment (total of 570–780 ha) and control (total of 330–780 ha), without needing to account for human population density. This creates an unfortunate paradox, as human encounters with *I. scapularis* in the Northeast frequently result from exposures on residential properties or in neighborhood green spaces (Stafford et al. 2017, Mead et al. 2018, Fischhoff et al. 2019, Jordan and Egizi 2019), and successful evaluation of 4-Posters for their impact on human-tick encounters and tick-borne disease in these regions requires enrollment of enough households to measure the intended outcomes. Unfortunately, areas that may provide sufficient human population density needed for study enrollment may be inappropriate for large-scale 4-Poster use due to landscape factors (e.g., availability of level ground), or the proximity of device placement locations to areas of human activity (e.g., backyards or parks where children may play) or development (e.g., roads).

The respective approaches in Connecticut and New York for GIS-based assessment of suitability for deployment of 4-Poster devices shared basic selection criteria (minimum thresholds for Lyme disease incidence, density of residential parcels/human population, and forest cover) but differed in other respects based on state-specific regulations. The New York State-specific regulation prohibiting the placement of 4-Poster devices within 91 m of public roads or highways greatly restricted our ability to identify areas where this tick control technology could be implemented in clusters across residential neighborhoods. No similar restriction was imposed by state agencies in Connecticut where the regulatory 4-Poster device deployment hurdles stemmed primarily from the EPA Tickicide product label.

The most common impediment to the placement of a 4-Poster device based on ground truthing of prospective sites in New York was proximity to homes or other buildings, followed by lack of level ground for the device and limited access to the site, whereas in Connecticut the main impediment was lack of level ground for the device, followed by limited access to the site and proximity to homes or other buildings. Our efforts in Connecticut did identify a selection of large, individual parcels suitable for 4-Poster device placement, each with an area ≥1.6 ha, and more than half of which were non-residential properties (e.g., owned by a municipality or land trust). Nevertheless, despite substantial efforts we were unable to readily identify a single 100 ha study cluster area in either Connecticut or New York that could accommodate the placement of 4–5 devices without the need for a protective fence around some or all of the devices, in or around a residential area large enough to support the participant enrollment required in our proposed intervention trial.

One lesson learned in this study was the value of complementing GIS-based characterization of suitability for 4-Poster device placement with ground truthing. An iterative approach in Connecticut led to successive improvement of the GIS characterization scheme as well as ultimately ruling out prospective parcels for 4-Poster device placement based on factors not readily observed before a field visit, such as the presence of a deer fence or dense vegetation preventing access to suitable device placement locations. The GIS component of the overall approach could be improved by using (1) higher resolution land use/landcover data to more effectively rule out impractical 4-Poster device placement locations based on the presence of impenetrable vegetation or standing water; and (2) finer scale topography data to locate level ground for device placement. Overall, we found that using a combined GIS-based and ground truthing approach is a useful, albeit very labor intensive, strategy to identify areas suitable for 4-Poster placement.

Based on our assessment, neither EPA label restrictions nor additional state-mandated regulations should prevent the deployment of 4-Poster devices with Tickicide-treated rollers in large natural areas on public lands, such as forested nature preserves. In this case, a potential reduction in human tick-encounters would be associated with recreational activities away from the home. It also should be feasible to deploy 4-Poster devices with Tickicide-treated rollers in sparsely populated landscapes dominated by private properties, for example on farms, but this would come at high cost per potentially prevented human tick-bite due to low human population density within the treatment areas. Another logistically feasible option would be to deploy 4-Poster devices with Tickicide-treated rollers in natural areas adjacent to residential neighborhoods with smaller property sizes and higher population density, based on the notion that there would be spillover tick suppression extending from the core 4-Poster treatment areas into the nearby residential neighborhoods. However, there are no published field data on tick suppression to support this strategy. A final possible strategy may be to target larger forested properties, owned by towns or land trusts, that are nestled into residential neighborhoods for 4-Poster device placement.

In addition to EPA or state-mandated regulatory restrictions, other obstacles may limit deploying devices specifically in residential settings. First, the general acceptability of homeowners to have devices placed on their properties is yet unclear. Moreover, several other previously noted concerns may influence specific 4-Poster device placement locations, including: competitive use by dominant deer; interference with devices by nontarget mammals such as tree squirrels, raccoons, and bears; spatial variability in access to alternative food sources such as hay and corn fields; acorn mast providing a competing food source in some years; and that use of devices that serve to aggregate deer (e.g., using food bait as in the 4-Poster device) may lead to increased potential for spread of disease agents that are transmitted by contact with saliva, respiratory droplets, or other body fluids from infected animals (Carroll et al. 2008, 2009a; Miller et al. 2009; Stafford et al. 2009; Stafford and Williams 2017). The logistical problems encountered in this study highlight the need to better define the specific landscapes in which 4-Poster devices can readily be deployed using the EPA-approved Tickicide acaricide product formulation and find new solutions to address the control of ticks on deer across residential neighborhoods to prevent human-tick encounters. Such new solutions to address the control of ticks on deer across residential neighborhoods could include the development of new acaricide formulations for use on the 4-Poster device rollers or alternative methodologies and products. A new acaricide product formulation with a more favorable human safety profile, compared with the currently used product containing 10% permethrin, could potentially have a less restrictive product label and thus facilitate the deployment of 4-Poster devices in residential neighborhoods. Another strategy that could result in a less restrictive product label, and thus being more feasible to implement across residential neighborhoods, is an oral acaricide delivered via a smaller device where the acaricide-laced deer bait is less accessible to children compared with Tickicide applied to the openly positioned rollers in the 4-Poster device. A final approach with promise for use in residential neighborhoods, but with a longer time horizon for commercial products to potentially emerge, is an anti-tick vaccine for deer to prevent ticks from feeding to completion or to molt to the next life stage or produce viable eggs (Carreón et al. 2012, Contreras et al. 2020).

The work presented here has several limitations. As the intent was to evaluate the feasibility of site selection and device placement in preparation for a cluster-based research study, there were strict criteria for the inclusion of residential neighborhoods in the treatment and control arms of the trial. We did not explicitly assess the potential for operational implementation of 4-Poster devices in single unique residential neighborhoods, and given personnel constraints we were only able to visit a sample of the 80 or 100 ha grid cells identified by our GIS characterization scheme as potential study clusters suitable for implementation of 4-Poster devices. Moreover, our approach focused on 80 or 100 ha square grid cells, whereas a more flexible approach to the shape of the cells may have produced a greater number of suitable cells.

We also limited the selection of clusters to those where a group of four 4-Poster device placement locations within a grid cell could be identified to maximize the combined theoretical impact area, and it is possible that by fitting a fishnet of grid cells in or around neighborhoods, we inadvertently excluded residential areas that could have been suitable for device placement had they not been artificially fragmented or poorly encompassed by the grid cells. Consequently, some residential neighborhood settings may be suitable for the implementation of 4-Poster devices regardless of the difficulty we encountered for a larger scale research-driven implementation. It also should be noted that a single 4-Poster device is sometimes described as having an operational range of 20 ha (~50 acres) envisioned as a circle with the device as the center point, but this theoretical representation might not accurately reflect the shape or effective area of a device given local deer movement patterns. We aimed to ensure adequate area coverage by strategic placement of multiple 4-Poster devices (based on a minimum density of 1 device per 20–25 ha) to attempt to maximize the potential for all deer frequenting the target area to come into contact with one of the devices.

Lastly, the 4-Poster device placement locations identified in our analysis were limited to those where a protective fence would not be required around the device to prevent access by children. Allowing for fenced-in 4-Posters likely would have improved our success rate for identifying suitable parcels for device placement as well as grid cells that could hold the required number of strategically placed 4-Poster devices. It is possible, however, that using fencing around 4-Posters may make the devices more conspicuous in residential areas, which may impact public acceptability for their use.

In conclusion, our findings suggest that although the 4-Poster device is a potentially effective technology for landscape-wide suppression of *I. scapularis* in natural settings, it is more challenging to deploy 4-Posters at a large-scale specifically across residential neighborhoods where human encounters with *I. scapularis* most often occur in the Northeast. In addition to following EPA and state-mandated regulations for using 4-Posters, any future efforts to implement a large-scale 4-Poster intervention to reduce human encounters with *I. scapularis* and blacklegged tick-associated diseases should consider several other factors. First, constructing protective fencing around devices may allow more flexibility with regards to device placement, but added costs and conspicuousness of a fenced device within the residential landscape may impact deployment. Moreover, any estimates of human-tick encounters as a primary outcome measure for a 4-Poster intervention should account for the contribution by human-biting tick species present in the study area but not impacted by this tick control methodology. In particular, the American dog tick, *Dermacentor variabilis* (Say) (Acari: Ixodidae), is a human-biting tick that is abundantly present in the areas of New York and Connecticut that we examined, but does not favor deer as blood meal hosts (Cooney and Burgdorfer 1974, Kollars et al. 2000) and therefore is not impacted by 4-Posters. In contrast, 4-Posters can suppress populations of *A. americanum,* in addition to *I. scapularis* (Pound et al. 2009b, Curtis et al. 2011, Williams et al. 2021). *Amblyomma americanum* is currently emerging in southern regions of the geographic area examined for this study, and is of increasing public health importance due to ongoing range expansion, its role as a vector of human pathogens, and its involvement in alpha gal syndrome/red meat allergy (Jordan and Egizi 2019, Molaei et al. 2019, Eisen and Paddock 2021, Mitchell et al. 2020, Young et al. 2021). Lastly, public acceptability of this methodology (treatment of deer with topical acaricide) and the product itself (4-Poster device with Tickicide-treated rollers), as well as the willingness of pest control firms to manage the 4-Poster devices, are yet unclear. Centers for Disease Control and Prevention TickNET surveys are underway in Connecticut and New York to fill some of these important knowledge gaps.

Acknowledgments

We thank Brad Biggerstaff of the Centers for Disease Control and Prevention for statistical assistance and Dr. Susan Booth-Binczik from the New York State Department of Environmental Conservation for regulatory consultation. We also thank Bryon Backenson, Kristen Howard, and Vanessa Vinci from the New York State Department of Health, Beau Payne of the town of Shelter Island, Mario Posillico of the Village of Saltaire, and Linda Niccolai of the Connecticut Emerging Infections Program at Yale School of Public Health, for their contributions to study design. This work was supported by the Centers for Disease Control and Prevention, Emerging Infections Program via Cooperative Agreements U50CK000486 and U50CK000488. The findings and conclusions of this study are by the authors and do not necessarily represent the views of the Centers for Disease Control and Prevention, New York State Department of Health, Yale University, or Western Connecticut State University. The mention of commercial products does not represent an endorsement by the authors, the Centers for Disease Control and Prevention, New York State Department of Health, Yale University, or Western Connecticut State University.

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Fig. 1.

Classification of the 5-county study area (Orange, Putnam, Rockland, Sullivan, and Westchester) in southeastern New York displaying a) continuous 100 ha grid cells overlaying the study area, b) 100 ha grid cells containing ≥100 residential land parcels, and c) 100 ha grid cells both containing ≥100 residential land parcels and having ≥50% forest cover.

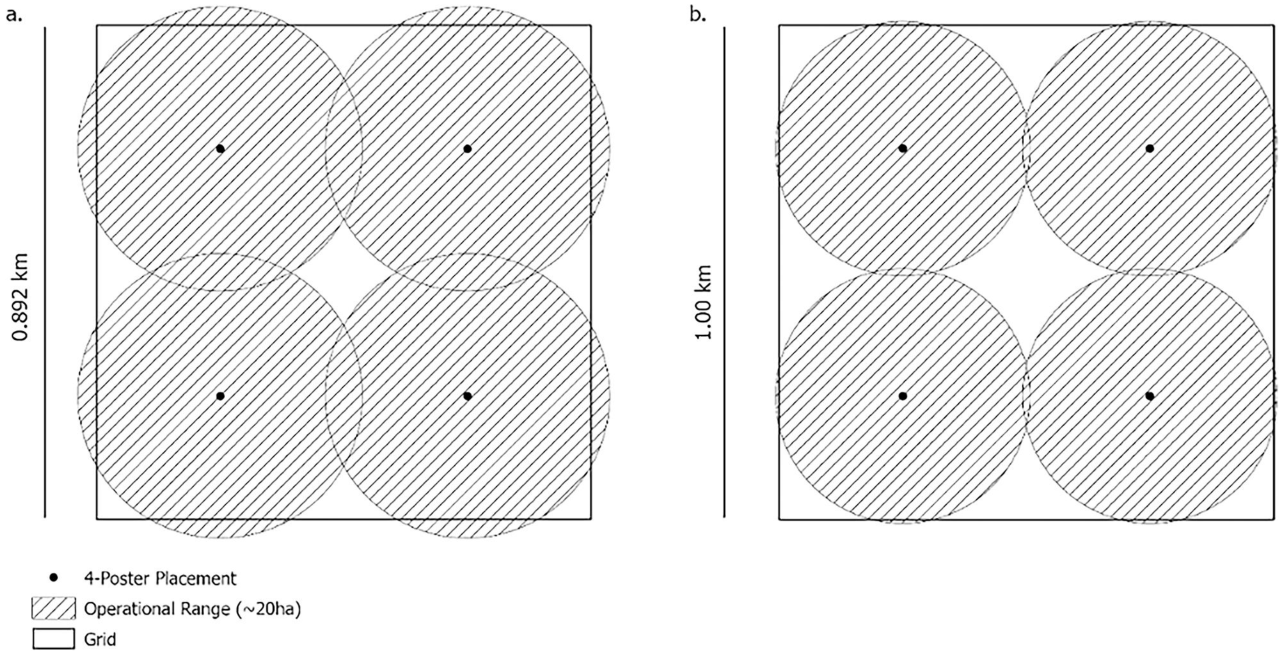

Fig. 2.
Ideal scheme for placement of 4-Poster devices to maximize the combined theoretical impact area for a group of 4 devices, each with a theoretical impact area of 20 ha, located within a) 80 ha or b) 100 ha grid cells.

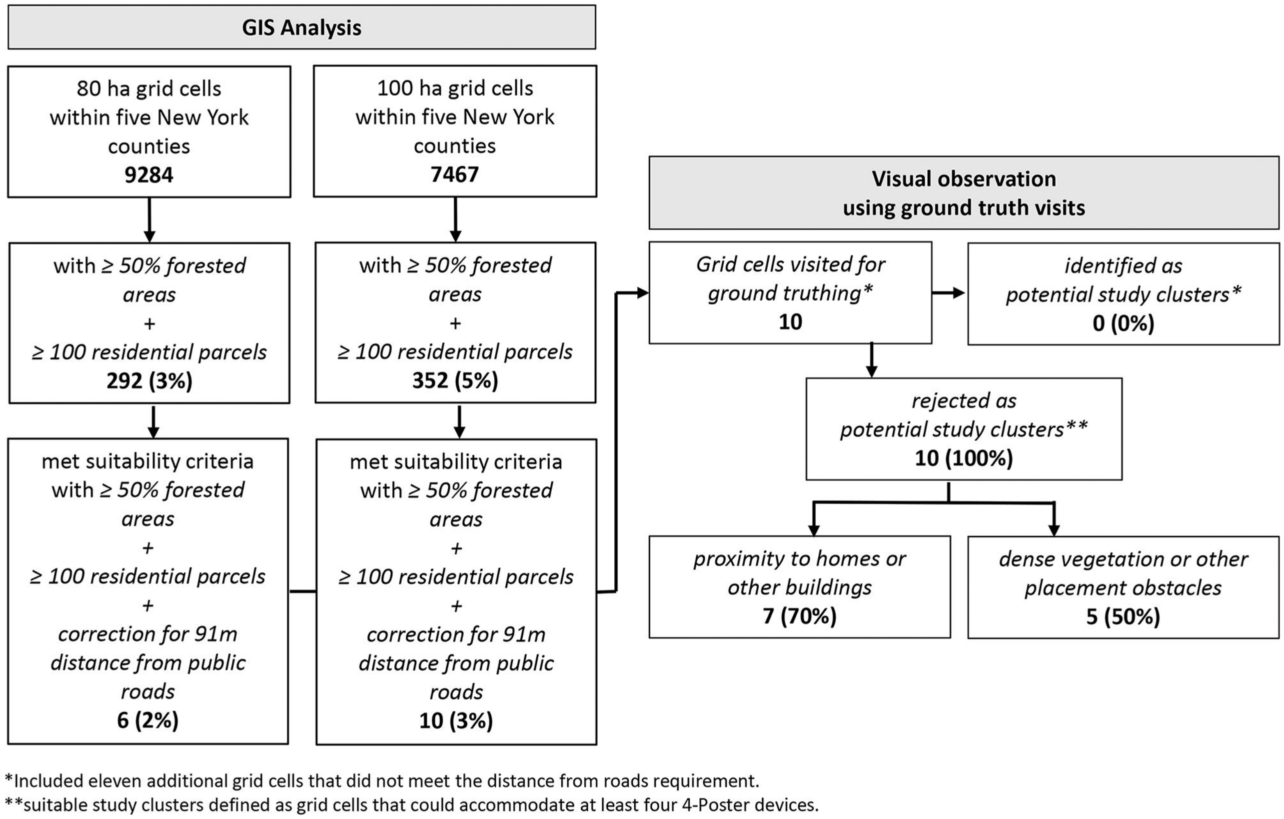

Fig. 3.

The process of selecting suitable study clusters (80 or 100 ha grid cells) in five New York State counties, based on GIS-analysis with ground truthing.

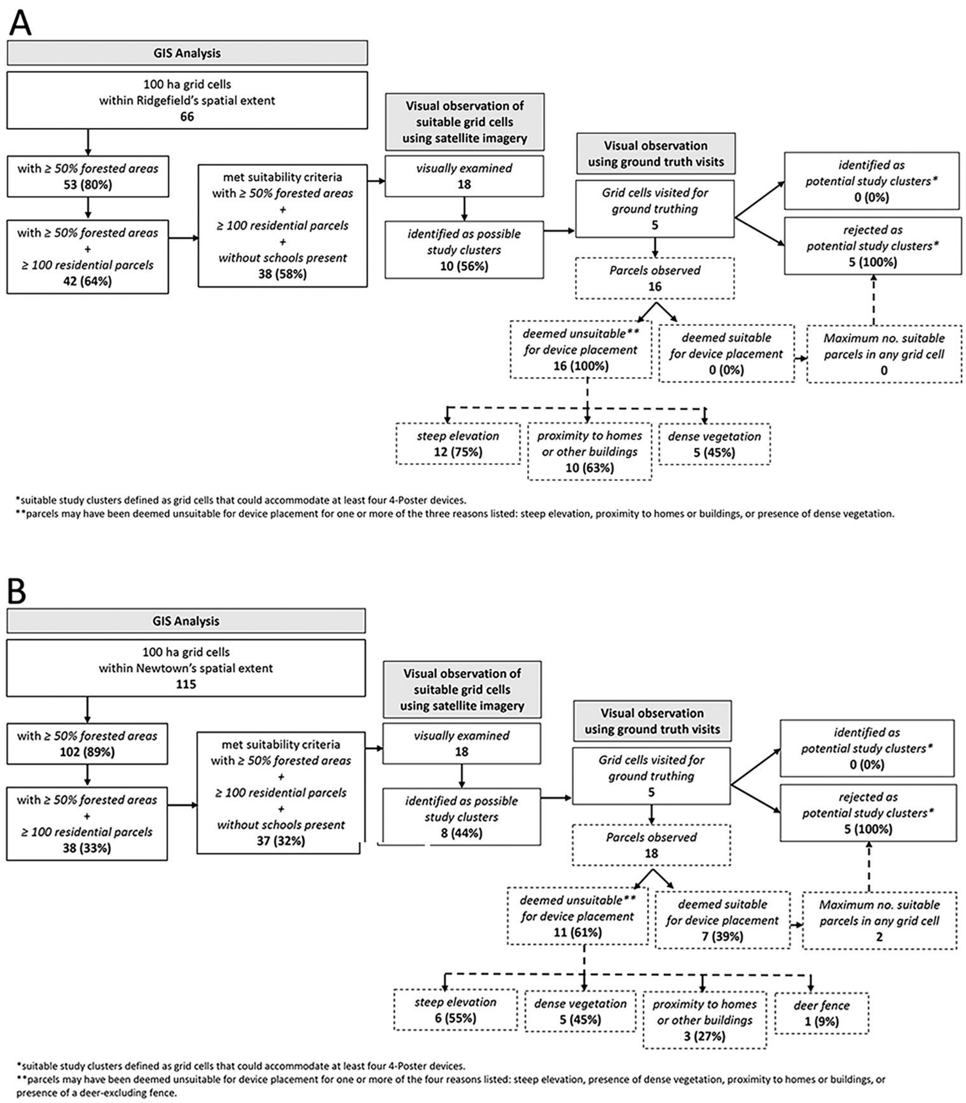

Fig. 4.

The process of selecting suitable study clusters (100 ha grid cells) in the Connecticut towns of A) Ridgefield, and B) Newtown, based on GIS-analysis with ground truthing.

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Table 1.

Characteristics of two towns, Ridgefield and Newtown, in Fairfield County, Connecticut

	Ridgefield	Newtown
Human population (2010) per km^2	273	184
Average number annual reported Lyme disease cases (2015–2017)	25	35
Average annual incidence of reported Lyme disease cases per 100,000 population (2015–2017)	101	128
Total land area (km^2)	90	149
Forested land area (%)	67	75
Households per km^2	103	67
Land parcels≥0.8 ha (%)	40	43