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Assessing the Efficiency of Local Rabies Vaccination Strategies for Raccoons (*Procyon lotor*) in an Urban Setting

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ABSTRACT: Raccoon rabies virus (RRV) has been managed using multiple vaccination strategies, including oral rabies vaccination and trap-vaccinate-release (TVR). Identifying a rabies vaccination strategy for an area is a nontrivial task. Vaccination strategies differ in the amount of effort and monetary costs required to achieve a particular level of vaccine seroprevalence (efficiency). Simulating host movement relative to different vaccination strategies in silico can provide a useful tool for exploring the efficiency of different vaccination strategies. We refined a previously developed individual-based model of raccoon movement to evaluate vaccination strategies for urban Hamilton, Ontario, Canada. We combined different oral rabies vaccination baiting (hand baiting, helicopter, and bait stations) with TVR strategies and used GPS data to parameterize and simulate raccoon movement in Hamilton. We developed a total of 560 vaccination strategies, in consultation with the Ontario Ministry of Natural Resources and Forestry, for RRV control in Hamilton. We documented the monetary costs of each vaccination strategy and estimated the population seroprevalence. Intervention costs and seroprevalence estimates were used to calculate the efficiency of each strategy to meet targets set for the purpose of RRV control. Estimated seroprevalence across different strategies varied widely, ranging from less than 5% to more than 70%. Increasing bait densities (distributed using by hand or helicopter) led to negligible increase in seroprevalence. Helicopter baiting was the most efficient and TVR was the least efficient, but helicopter-based strategies led to lower levels of seroprevalence (6–12%) than did TVR-based strategies (17–70%). Our simulations indicated that a mixed strategy including at least some TVR may be the most efficient strategy for a local urban RRV control program when seroprevalence levels >30% may be required. Our simulations provide information regarding the efficiency of different vaccination strategies for raccoon populations, to guide local RRV control in urban settings.

Key words: Animal movement, antibody prevalence, individual (agent)-based modeling, oral rabies vaccination, rabies virus, raccoons, trap-vaccinate-release, wildlife rabies control.

INTRODUCTION

Rabies is a globally distributed zoonosis transmitted between mammals by direct contact. Rabies virus infection can lead to a central nervous system infection that is almost always fatal (Rupprecht et al. 2002). In North America, several distinct rabies variants are present in mesocarnivore populations (Gilbert 2018; Ma et al. 2022). Raccoon (*Procyon lotor*) rabies virus variant (RRV) accounts for most rabies virus exposures to humans and spillover infections among animals in the United States (Wallace et al. 2014; Pieracci et al. 2019). An epizootic of RRV spread from the US into three Canadian provinces, Ontario in 1999, New Brunswick in 2000, and Quebec in 2006 (Trewby et al. 2017), which was successfully eliminated in each of these jurisdictions in 2005, 2002, and 2009, respectively, using vaccination (Gregory and Tinline 2020). However, RRV has reemerged in those same three Canadian provinces more recently (New Brunswick 2014, Quebec 2015, Ontario 2015) and remains enzootic in New Brunswick and Ontario to date (Stevenson et al. 2016; Gregory and Tinline 2020), with the greatest reported incidence in southern Ontario.

Re-eliminating RRV in urban southern Ontario using wildlife vaccination has been a challenging multiyear effort (Acheson et al. 2023).

Vaccination of wildlife species is recognized globally as a major strategy to control animal rabies at its source and has been successful at eliminating rabies variants or reducing the virus significantly in parts of Europe and North America (World Health Organization 2018; Gilbert and Chipman 2020). Rabies control efforts range from local-scale urban programs (Rosatte et al. 2007) to landscape-level elimination programs (Davis et al. 2021). In southern Ontario, RRV has been managed largely using oral rabies vaccination (ORV) distributed by hand, fixed-wing planes, helicopters, or bait stations, while also including trap-vaccinate-release (TVR) activities in strategic locations (Rosatte et al. 1992, 2009; Sterner et al. 2009; Slate et al. 2020). Rabies vaccination delivery methods can vary widely in the monetary costs associated with vaccination of adequate proportions of the population (efficiency) and constraints with the maximum proportion of a population that can be vaccinated at a particular spatial scale (scalability). For example, oral baiting by aerial delivery can occur over a larger spatial extent at a lower cost relative to TVR, but TVR is a more effective route of rabies vaccination for individual animals, with potential to reach higher seroprevalence along with higher costs. Also, landscape structure, raccoon (or other host) behavior, raccoon density, the presence of bait competitors, and the presence of RRV in other species (e.g., striped skunk *Mephitis mephitis*) can all influence the efficiency of a given strategy or combination of strategies (McClure et al. 2022), making it challenging to predict the most efficient and scalable strategies for a particular setting.

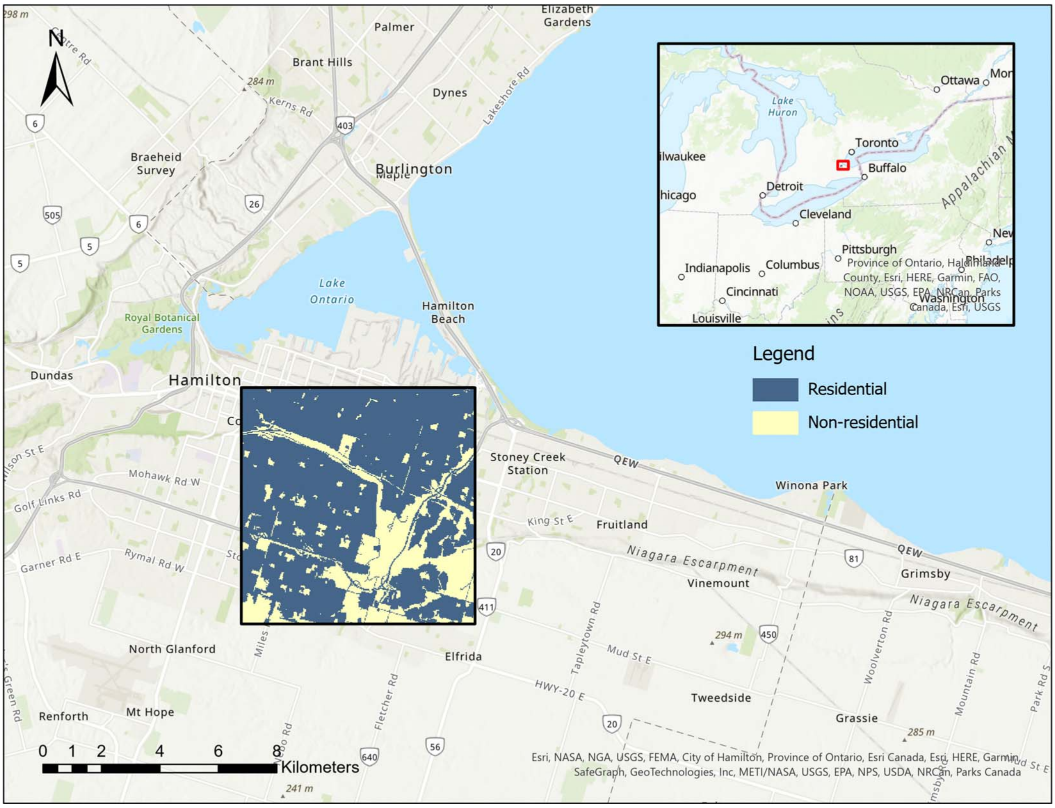
It is impractical for managers to evaluate every possible combination of wildlife disease intervention strategies in the field. In silico simulation can provide an alternative tool for exploring the efficiency of different vaccination strategies at a particular scale, including combinations of strategies. Here, we reparameterized a previously developed spatially explicit model of raccoon movement on real landscapes along with targeted vaccination strategies (McClure et al. 2022) to evaluate the efficiency of various rabies control strategies for raccoon populations at a local scale in urban Hamilton, Ontario, Canada. Our aim was, for each vaccination strategy, to evaluate the predicted vaccine-induced seroprevalence in the raccoon population relative to the monetary costs of implementation as a measure of efficiency and to report the efficiency of each strategy relative to the levels of seroprevalence that may be targeted as the level of seroprevalence needed to achieve control (i.e., effectiveness). Overall, our work aimed to provide a framework enabling managers to identify the most efficient vaccination strategy for their application scale and desired level of seroprevalence.

MATERIALS AND METHODS

Study area and data collection

We developed simulations within a 64-km^2 ORV management zone in urban Hamilton, Ontario, Canada (Fig. 1). The city of Hamilton is located in southern Ontario at the western end of Lake Ontario and has a population of 536,917. Hamilton is part of a contiguous urban area surrounding the city of Toronto, which has a population of over 7.8 million people (Statistics Canada 2016). The study area was located just east of downtown Hamilton and included roughly 25% nonresidential and 75% residential (Fig. 1). Reincursion of raccoon rabies virus into Ontario was first detected in December 2015 in Hamilton, possibly caused by a long-distance translocation from southeastern New York State (Nadin-Davis et al. 2020).

In response to the detection of RRV, the Ontario Ministry of Natural Resources and Forestry (MNRF) started an ORV program using ONRAB® baits in December 2015 to control and eliminate RRV in Hamilton (Lobo et al. 2018). Since 2015, ORV baits have been distributed by hand, bait stations, helicopter, and fixed-wing aircraft using various target densities and combinations of strategies (see Vaccination Strategy Design in Supplementary Material Appendix 1). Additionally, TVR was implemented starting in 2017 in targeted



Esri, NASA, NGA, USGS, FEMA, City of Hamilton, Province of Ontario, Esri Canada, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, USDA, NRCan, Parks Canada

Province of Ontario, Haldimand County, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada, Esri, USGS

FIGURE 1. Study area in Hamilton, Ontario, Canada, for which simulations were run to assess the efficiency of local rabies vaccination strategies for raccoons (*Procyon lotor*) in an urban setting. Residential and nonresidential areas are indicated in dark blue and light yellow, respectively. The inset 8×8-km (64-km^2) zone is where the simulations were conducted and where shading indicates residential and nonresidential areas.

areas. Fixed-wing aerial baiting is limited to rural areas located outside of our study area. In the study area, helicopter baiting and bait stations were used to target nonresidential urban areas (e.g., large public parks, buffered areas along highways and ravines) whereas hand baiting and TVR were generally limited to residential urban areas. Raccoon density in the area was assumed to be at 18/km^2.

The Southern Ontario Land Resource Information System (SOLRIS) was used for land-cover classification. Land-cover categories "Transportation", "Built-up Area Pervious," and "Built-up Area Impervious" were reclassified as residential whereas other categories were reclassified as nonresidential (mostly forested areas). Pixels were therefore either residential or nonresidential. Individual raccoon movement data were not available for Hamilton, so auxiliary raccoon movement data were obtained from five raccoons (three female, two male) fitted with GPS collars in Toronto, Ontario, Canada. Collars were active during July–September 2010 and locations were subsampled every 30 minutes. Raccoons tracked in Toronto experienced a similar range of urban conditions to the Hamilton study area, representing residential areas and nonresidential areas. The raccoon project was approved by the York University Animal Care Committee (approval number 2010-25W).

Simulation structure

Our framework followed the approaches developed in McClure et al. (2022). Code for this framework is available as supporting information in McClure et al. (2022). Briefly, we analyzed raccoon GPS data to extract raccoon movement speed (step length) by fitting a gamma distribution and estimated resource selection coefficients to parameterize the movement simulations. These coefficients were estimated using a third-order resource selection function (RSF; Johnson 1980; Boyce et al. 2002) in

TABLE 1. Summary of vaccination strategies and equivalencies among units (percentage, actual number, actual density) used in simulations run to assess the efficiency of local rabies vaccination strategies for raccoons (*Procyon lotor*) in Hamilton, Ontario, Canada. For each strategy, the reference level is presented first and indicates the intensity generally used. The actual number of baits used in the simulation is specified as well as the resulting actual density (baits/km^2). This density is reflective of where the specific strategy is being deployed. Spatial vaccination data specific to the study area were used to estimate actual number and actual density and any mismatch between actual and target density. The area column indicates whether the strategy is applied to a residential area (R) or nonresidential area (NR).

Variable[a]	Level	Percentage	Actual number	Actual density	Area
Hand baiting	Reference	100	11,008	172	R
Hand baiting	Half	50	5,504	86	R
Hand baiting	Double	200	20,224	316	R
Helicopter	Reference	100	1,523	95	NR
Helicopter	Half	50	762	48	NR
Helicopter	Double	200	3,046	190	NR
Bait station number	Reference	100	30	2	NR
Bait station number	Half	50	15	1	NR
Bait station number	Double	200	60	4	NR
No. baits per station	Reference	100	300		NR
No. baits per station	Half	50	150		NR
No. baits per station	Double	200	600		NR
No. raccoon TVR (50% of area)	Reference	100	434	18	R
No. raccoon TVR (50% of area)	Half	50	217	9	R
No. raccoon TVR (100% of area)	Reference	100	868	18	R
No. raccoon TVR (100% of area)	Half	50	434	9	R

[a] TVR = trap-vaccinate-release.

which GPS locations were compared with 10,000 generated locations within each individual home range (estimated using a kernel density estimate). We assumed that the five tracked raccoons were representing a random sample of the overall population and used the mean and standard deviation in the observed parameters (coefficients from RSF and shape and scale parameters of the gamma distribution) to generate realistic movement parameters for 1,000 individuals. We then developed a spatially explicit model of raccoon movement informed by the SOLRIS land cover and our estimates of movement and habitat selection. We simulated raccoon movement for a 1-mo period (August) within our 64-km^2 study area and evaluated how different vaccination strategies might lead to different vaccine-based seroprevalences. We validated simulated raccoon movement by comparing home-range size of simulated raccoons with that of the five GPS-collared raccoons. Compared with McClure et al. (2022), we simulated only one type of raccoon movement, based on observed movement patterns based on the GPS-tracked individuals and observed density in the study areas (18/km^2 or 1,152 raccoons).

We simulated 560 vaccination strategy designs that combined the different ORV baiting and TVR vaccination strategies used by MNRF since 2015 (Table 1). Hand baiting and TVR were simulated only in residential areas, whereas bait stations and helicopter baiting were limited to nonresidential areas. No hand baiting was applied if TVR coverage was 100%.

We then overlaid simulated vaccination strategies on raccoon movement and estimated the proportion of raccoons that encountered and consumed a vaccine bait or that were trapped and vaccinated when in the same grid cell, resulting in seroconversion (rabies antibody response; Sobey et al. 2010; Brown et al. 2012; Gilbert et al. 2018). Oral bait consumption and seroconversion involved three processes: 1) colocation of a raccoon and bait within the same grid cell (30 × 30 m), 2) bait encounter and consumption given colocation that accounted for nontarget and conspecific bait competition and reduced bait availability over time, and 3) seroconversion given bait consumption. In the simulation, TVR was applied in a subsequent step in which a specific number of raccoons were randomly selected as trapped, vaccinated, and released back into the study area. As there was no disease in our simulated raccoon populations, we estimated the vaccine-induced population seroprevalence as the number of seroconverted individuals divided by the raccoon population across the study area. For each management strategy, we estimated the population seroprevalence achieved through vaccination and the associated monetary cost of the strategy. More details regarding each step of the simulations are provided in Supplementary Material Appendix 1.

Statistical analysis

We used a linear mixed-effects model with a logit link to analyze the relative impacts of baiting strategy features on vaccine-based seroprevalence (McClure et al. 2022). All covariates were considered as categorical (i.e., "dummy" variables). Strategy was added as a random intercept because each strategy was repeated 250 times. Parameters (hand baiting, TVR, helicopter baiting, and bait-station baiting) were included as main effects. Observed vaccine-based seroprevalence was also summarized graphically to highlight the potential interactive effects of hand baiting and TVR in residential areas and helicopter baiting and bait stations in nonresidential areas. We evaluated the magnitude of the correlation between predicted vaccine-based seroprevalence and cost of the strategy (cost calculations for each strategy are presented in Supplementary Material Appendix 2). Using a separate linear mixed-effects model, we examined the effects of vaccination strategies on efficiency, where the efficiency of a strategy s was defined as

$$\mathrm{eff}_s = \mathrm{cost}_s/\mathrm{seroprevalence}_s$$

and relative efficiency was calculated as

$$\mathrm{rel.eff}_s = 1 - \left(\mathrm{eff}_s - \min(\mathrm{eff})\right)/\left(\max(\mathrm{eff}) - \min(\mathrm{eff})\right).$$

where min(eff) and max(eff) represent the minimum or maximum values across all strategies. Independent variables included each vaccination strategy (hand baiting, TVR, helicopter baiting, and bait station baiting) as categorical variables and with strategy as a random intercept. We identified the three most efficient strategies across a range of target levels of vaccine-based seroprevalence, including 20%, 30%, 40%, 50%, and 60% seroprevalence. All simulations and statistical analyses were run on a workstation using R 4.0.3 (R Core Team 2022).

RESULTS

Raccoon movement and model parameterization

Raccoons varied in their responses to nonresidential areas, with three individuals showing strong avoidance of nonresidential areas (relative to residential areas) and two individuals weakly selecting for nonresidential areas (Supplementary Material Table S1 and Appendix 1). GPS-tracked raccoon home-range sizes ranged from 0.11 to 0.31 km^2. Simulated raccoon movement had similar properties regarding home-range size but with slightly larger variance, ranging from 0.05 to 1 km^2 (Supplementary Material Fig. S1 and Appendix 1).

Seroprevalence achieved by vaccination strategies

Across the 560 vaccination strategies, the predicted vaccine-based seroprevalence in raccoons averaged 33% (range 0–75%). Increasing the number of baits for hand baiting from a target density of 50% to 200% (Table 1) increased predicted seroprevalence from around 10% to 13% (Fig. 2). Trends were highly similar for helicopter baiting, with predicted increases in seroprevalence ranging from 10% to 12% for strategies with 50% and 200% of target bait densities. The number of bait stations used in the simulations had a smaller impact on seroprevalence than hand and helicopter baiting, and the number of baits per station very minimally impacted seroprevalence (Fig. 2). Combining TVR with other vaccination strategies led to an increase in seroprevalence across all strategies. The highest seroprevalence was observed when TVR was used to cover 100% of residential areas (Fig. 3). In nonresidential areas, combining helicopter baiting and bait stations led to higher seroprevalence,

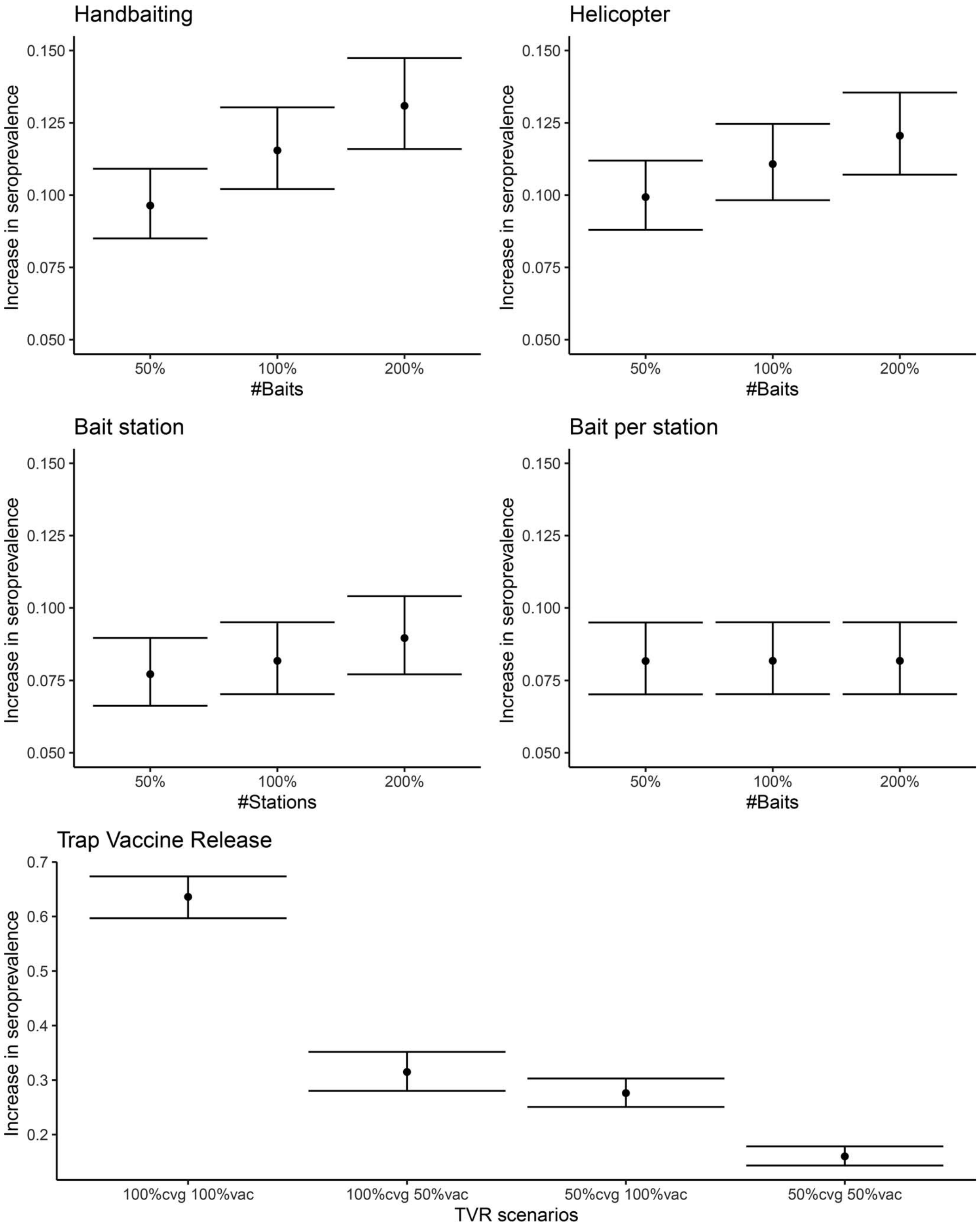


FIGURE 2. Effects of vaccination strategy on predicted seroprevalence for raccoons (*Procyon lotor*) in the urban setting of Hamilton, Ontario, Canada. Plots show predicted seroprevalence for different baiting designs relative to the absence of vaccination. For bait stations, one panel shows the effect of the number of stations while holding the number of baits per stations at 300 (100%) and the other panel is showing the effect of the number of baits per station while holding the number of bait stations at 30 (100%; the standard rates used by Ministry of Natural Resources and Forests in urban settings). For trap-vaccinate-release (TVR), the fraction of the study area covered (cvg) and the percentage of target animals vaccinated (vac) are provided. Density and number of baits associated with each strategy is presented in Table 1. Note the different y-axis scale for TVR.

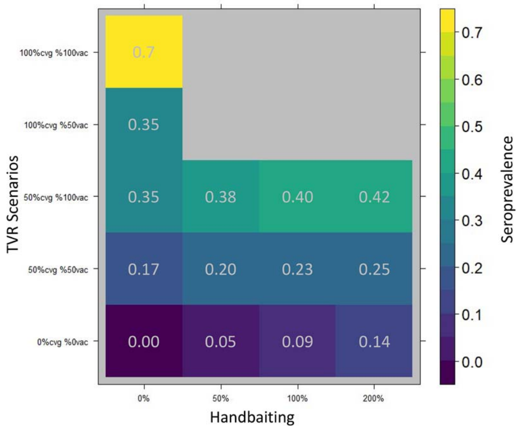


FIGURE 3. Interactive effects of vaccination strategies in residential areas on simulated seroprevalence for raccoons (*Procyon lotor*) in the urban setting of Hamilton, Ontario, Canada. Hand baiting was done at four different densities, whereas trap-vaccinate-release (TVR) was done at two different spatial coverages (cvg) and two different percentages of raccoons vaccinated (vac). No hand baiting was performed when TVR was done over the whole study area (100% coverage).

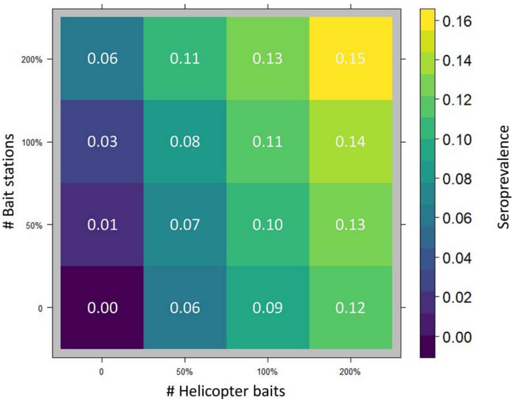


FIGURE 4. Interactive effects of vaccination strategies in nonresidential areas on simulated seroprevalence for raccoons (*Procyon lotor*) in the urban setting of Hamilton, Ontario, Canada. Helicopter baiting was done at three different efforts, and the number of bait stations varied from 15 (50%) to 30 (100%) to 60 (200%). Given the very weak effect of the number of baits per station (Figure 2), the number of baits was set at 300 (100%) per station for the figure. Table 1 presents the equivalencies between percentage and actual numbers.

with an increased intensity of both strategies (Fig. 4). However, using these two techniques in nonresidential areas led to a predicted seroprevalence of only 16% in raccoons (Fig. 4).

Efficiency of vaccination strategies

There was a strong correlation (R^2=0.94) between predicted seroprevalence and the associated cost of management strategies (Fig. 5). Strategies in which 100% of the residential areas were treated with TVR had distinctly higher seroprevalence (>0.6) in raccoons, but TVR strategies also had a markedly higher associated cost. When standardizing the predicted seroprevalence in raccoons by strategy cost (relative efficiency), strategies in which lower seroprevalence was achieved were often more efficient (Fig. 6), especially for target population thresholds under 40%. Helicopter-only strategies tended to be the most efficient (Fig. 6 and Table 2), although the highest seroconversion in raccoons achieved by this strategy alone was <0.2 (Fig. 6). The TVR strategies were overall the least efficient, although high-density hand baiting had similar efficiency to TVR with 50% coverage (Fig. 6, Supplementary Material Appendix 3 and Table S1). A smaller number of bait stations was more efficient than strategies using more stations (Fig. 6, Supplementary Material Appendix 3 and Table S1). Even though TVR was inefficient when considering strategy costs, incorporating some level of TVR was necessary to achieve population seroprevalence higher than 30% (Table 2). Treating the entire residential area solely with TVR was the only method that led to seroprevalence higher than 60%. Combining an intermediate level of TVR with other vaccination methods was able to achieve seroprevalence between 30% and 60%.

DISCUSSION

Our simulations indicated that for a study area that is predominantly urban residential, heavy use of TVR would be required to achieve seroconversion >60%, but that a combination of partial TVR and other vaccination strategies could be efficient to achieve seroconversion rates between 30% and 60% in raccoons. Our results provide a framework that may be used to

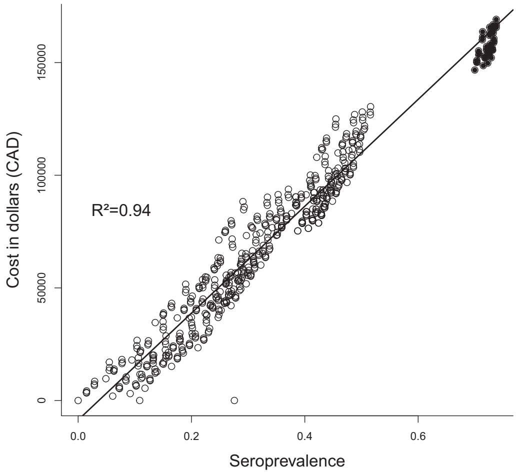


FIGURE 5. Relationship between averaged predicted rabies seroprevalence in raccoons and cost of the vaccination strategy (in Canadian dollars) based on simulations run to assess the efficiency of local rabies vaccination strategies for raccoons (*Procyon lotor*) in Hamilton, Ontario, Canada. The cluster of filled-in points represents strategies in which the entire residential area was treated with trap-vaccinate-release (TVR; 100% coverage) with regular effort (100% vaccination).

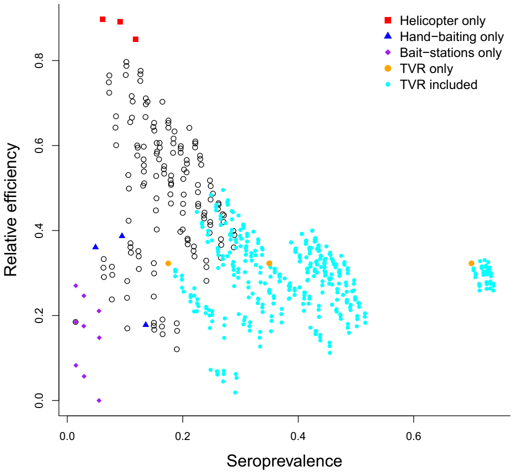


FIGURE 6. Relationship between averaged predicted seroprevalence and relative efficiency for each vaccination strategy based on simulations run to assess the efficiency of local rabies vaccination strategies for raccoons (*Procyon lotor*) in Hamilton, Ontario, Canada. Strategies in which only one method was used are coded by symbol to highlight their overall efficiency. Each point on the graph represents one of the 560 vaccination strategies. The open circles represent mixtures of strategies that do not include trap-vaccinate-release (TVR).

estimate the efficiency of wildlife vaccination strategies to achieve a desired level of seroprevalence for user-defined data on animal movement and landscape spatial scale and complexity.

Increasing hand-baiting density led to a slight increase in seroprevalence in the raccoon population, but the rate of increase per effort was not linear. For example, decreasing bait density by half led to a seroprevalence decrease from 11.5% to 9.6% (18% decrease). Similarly, doubling the bait density led only to an increase from 11.5% to 13.1% seroprevalence (14% increase). One factor that might explain this is that our simulation assumes that baits disappeared from the landscape after 60 h (to reflect observed patterns of bait disappearance observed using trail camera studies in Hamilton). Similar patterns have been reported from other urban areas where RRV is managed (McClure et al. 2022), which indicates that increasing hand-baiting densities alone may have negligible added benefits to RRV control efficiency if baits remain available to raccoons for a short duration of time. Very similar patterns were observed for helicopter-baiting strategies. Despite similar predicted seroprevalence, helicopter baiting was limited to less than 25% of the study area because of Canadian regulations restricting use over urban areas. The fact that ORV by helicopter baiting resulted in a similar increase in seroconversion to hand baiting, despite being applied to a significantly smaller part of the study area, indicates the importance of not neglecting the nonresidential areas if higher seroprevalence is to be achieved.

Bait stations appeared to have the least influence on vaccine-based seroprevalence in raccoon populations, especially changes to the number of ORV baits per station. The pattern may be explained by the smaller spatial extent (number of pixels with baits in them) of bait stations relative to other baiting strategies. With only 15–60 stations placed over the same area as used for helicopter baiting, it is likely that a smaller number of raccoon home ranges may overlap with the stations. It is also possible that

TABLE 2. Top three lowest-cost rabies vaccination strategies to achieve seroprevalences of 20, 30, 40, 50, and 60% in a 64 km^2 study area of urban Hamilton, Ontario, Canada, based on simulations run to assess the efficiency of local rabies vaccination strategies for raccoons (*Procyon lotor*).

Seroprevalence Threshold (%)	Observed seroprevalence (%)	Cost/km^2 (Can$)	TVR coverage (%)	TVR effort (%)	Hand-baiting density (%)	Bait stations (no. stations/ no. bait per stations) (%)	Helicopter baiting (%)
20	21.1	366.42	0	0	100	0/0	200
20	22.2	418.84	0	0	100	50/50	200
20	22.2	423.53	0	0	100	50/100	200
30	30.4	862.11	50	50	50	50/50	200
30	30.5	866.80	50	50	50	50/100	200
30	30.5	876.19	50	50	50	50/200	200
40	40.6	1,194.22	100	50	0	0/0	100
40	40.7	1,194.22	50	100	0	0/0	100
40	42.4	1,232.50	100	50	0	0/0	200
50	50.4	1,876.80	50	100	200	100/50	200
50	50.5	1,886.19	50	100	200	100/100	200
50	50.5	1,904.97	50	100	200	100/200	200
60	70.0	2,292.06	100	100	0	0/0	0
60	71.5	2,322.52	100	100	0	0/0	50
60	72.3	2,340.30	100	100	0	0/0	100

our simulations might not fully capture raccoon behavior in areas where they might be more likely to overlap in greater numbers and where a carefully placed bait station could prove valuable for reducing impacts of nontarget bait uptake. Likewise, it is possible that the parameters for bait disappearance might have been biased low in the context of bait stations relative to other strategies. These reasons might explain why predicted seroprevalence in raccoons based on bait station strategies appeared lower than observed in southern Ontario.

Vaccination strategies including some level of TVR led to the highest predicted seroprevalence for urban raccoon populations. Even the least intensive TVR strategy, in which 50% of the study area was covered at 50% of target animals vaccinated, led to higher seroprevalence (16%) in raccoons compared with any other single vaccination strategy. Unsurprisingly, changing the spatial coverage but keeping the number of raccoons vaccinated constant led to relatively similar seroprevalence. This was the only strategy for which a simulated increase in effort led to a roughly linear predicted increase in raccoon population seroprevalence. This was partly because our model assumed that 93% of individuals captured for TVR seroconverted, whereas many oral baits were never consumed by a raccoon. Combining TVR with hand baiting highlighted the limited effect of hand baiting on seroprevalence relative to TVR when used in urban areas, although the combination of both still led to higher seroprevalence.

We found a strong correlation between predicted seroprevalence and the associated monetary cost, indicating that managers are facing a trade-off between the cost and the benefits (higher seroprevalence) when choosing a vaccination strategy. Despite this trade-off, considering the efficiency of each strategy provided a more nuanced assessment. Helicopter baiting appeared to be the most cost-efficient baiting strategy, although its contribution to overall seroprevalence remained limited, in part because, due to flight restrictions, it cannot be used in most residential areas. On the other hand, TVR was the least efficient strategy, but also the only strategy leading to robust vaccine-induced seroprevalence levels.

A target population threshold of 50% or greater rabies antibody seroprevalence is often considered necessary for RRV elimination (Robbins et al. 1998; Rees et al. 2011; Mainguy et al. 2012; McClure et al. 2020), but the relationship between seroprevalence and rabies control is also strongly context dependent based on local reservoir ecology and epizootiology and the type of baits, and has been understudied in urban habitats. Our simulations showed that in urban areas with similar raccoon densities to Hamilton, treating the totality of the residential areas using TVR (instead of hand baiting) would be the only way of achieving seroprevalence rates higher than a 60% threshold. Complementing TVR with helicopter baiting in nonresidential patches would be the most efficient way of preventing patches of susceptible raccoons from arising. However, operational efforts in Hamilton suggest it is possible to contain and even eliminate RRV with seroprevalence lower than 60%. Indeed, ongoing simulation analyses indicate that RRV elimination in Hamilton may be possible at a seroprevalence threshold closer to 30–40% (Acheson et al. 2023). If a threshold of 40% would be sufficient for RRV control and elimination, a combination of lower-effort TVR and helicopter baiting at a typical target density could achieve adequate seroprevalence in raccoons while representing nearly half the cost of a TVR-only strategy. Similar to concerns mentioned earlier, where a large area would not be treated with TVR it might be preferable to select a strategy in which the totality of the residential area is covered, but with a smaller number of animals being vaccinated, to avoid creating large patches of susceptible animals.

Broader applications and caveats

A critical question regarding our simulations is how well they could be transferred to other urban areas of RRV management outside the 64-km^2 focal area in Hamilton, Ontario, Canada. In terms of efficiency, we contend that our simulations should be directly applicable to other urban areas of southern Ontario and nearby areas in the US where raccoon density and behavior remain similar to those in southern Ontario. Indeed, raccoon movement was parameterized using radio-collar data from raccoons in Toronto, Ontario, Canada, and a simple land-cover classification system (residential and nonresidential). However, because different vaccination strategies were applied to residential areas (hand baiting and TVR) versus nonresidential areas (bait stations and helicopter baiting) and these strategies vary in their efficiency, it would be risky to directly extrapolate our results to areas with a markedly different ratio of residential to nonresidential areas (e.g., 75% to 25% in our case study). Our results may, however, inform what to expect if vaccinating an area with a larger fraction of nonresidential area. In such an instance, it is likely that the efficiency of the overall vaccination program would be increased, because a larger fraction of the area could be covered via helicopter baiting. This could mean that in an area where 50% of the area could be baited via helicopter, seroprevalence of up to 24% could be achieved via helicopter baiting alone. However, if higher seroprevalence is needed, TVR might also be required in the nonresidential areas.

Although the use of animal movement data and individual-based modeling is increasing in disease ecology (Dougherty et al. 2018; Holbrook et al. 2019), the analyses remain challenging, and caution is required when interpreting and generalizing the results. Our movement model integrates many aspects of raccoon behavior, such as confined home ranges, habitat-driven movement, avoidance of areas with high density of conspecifics, and individual variation in animal movement. However, this model remains a simplification of the raccoon movement and bait uptake process and is also based on some assumptions regarding the values of specific parameters (which were generally based on local agency knowledge). A prior study from an urban area of RRV management also reported generalist tendencies of raccoons across habitats (McClure et al. 2022). More complex habitat-based modeling of raccoon movement in urban areas is computationally unrealistic and would be unlikely to lead to major differences in the results. Likewise, given that some parameters were based on expert opinion, simulating bait and vaccine distributions may not perfectly reflect how baiting is generally done on the landscape, even if existing baiting data were used to parameterize the models. To reduce these potential differences, our baiting simulation not only replicated the same number of baits but also ensured that the same spatial coverage (number of pixels receiving baits) remained similar to what is achieved by MNRF. Previous work has shown that altering the spatial coverage could drastically change vaccine-based seroprevalence (McClure et al. 2022). Even if we use the best information available to parameterize bait uptake given bait discovery on the landscape and seroconversion given bait uptake, these parameters directly impact our estimated seroprevalence. In such cases, it may be safer to compare relative seroprevalence instead of absolute seroprevalence. Studies have also demonstrated a cumulative impact of baiting annually across years for reaching seroprevalence targets and case elimination (Davis et al. 2019; Acheson et al. 2023), whereas a single-season population simulation without disease may yield more limited predictions in the context of long-term RRV control programs.

Additional analyses may be warranted to further expand our understanding of how to optimize vaccination programs to control and eliminate RRV across a broader context. For example, replicating our analyses over different urban areas with varying configuration and composition (e.g., Tardy et al. 2018) of residential and nonresidential areas could expand our findings on efficiency to a broader range of spatial contexts. Relatedly, although the study focused on urban vaccination, eliminating rabies in rural areas may present its own set of challenges. Rural baiting is often done using a fixed-wing plane flying in a straight line, but it remains unclear if the baiting distribution in this type of landscape could be improved by better matching baiting flight lines with raccoon movement behavior and habitat selection at practical scales of implementation across broad landscapes. The current simulation framework could be easily adapted to different spatial scales and levels of urbanization. Additionally, the current simulation exercise focused only on the spatial aspect of vaccination, with little consideration to the temporal aspect. Combining the current approach with a temporal disease-transmission model might provide better information regarding where and at what intensity to vaccinate. More explicit consideration of interacting disease transmission and population demographic processes would allow us to assess the cumulative effect of vaccination over multiple seasons and overall efficacy. Lastly, expanding our framework for other mesocarnivores such as skunks and other species would benefit local efforts in Hamilton and could also expand the application to other areas of the world. Efforts to carry out ORV targeting free-roaming dogs has been a main priority to supplement parenteral mass-vaccination strategies in order to reach adequate fractions of the dog population for rabies control and elimination (Yale et al. 2022). Simulation-based frameworks could aid in the design of interventions targeting free-roaming dogs in regions with endemic canine rabies, along with other bioeconomic simulation tools (Anderson et al. 2019).

Although assessing efficiency (here defined as the cost associated per percentage increase in seroprevalence) of various vaccination approaches is the first step in informing on-the-ground interventions, ultimately the goal is to scale this information to cost-effectiveness (cost associated with a desired outcome of rabies management). Even if seroprevalence level and effectiveness are tightly linked, some factors can impact the scaling from one to the other. Considering disease transmission and the potential cumulative impact of repeating vaccination over several seasons might show that efficient approaches are less cost-effective in the long term (or vice versa) as well as inform on how to distribute the effort temporally (e.g., high vaccination rate in the first years vs. a lower rate over many years). Similarly, some approaches are more scalable spatially than others. For example, our results indicated TVR as being more efficient than hand baiting in residential areas, but it could be financially or logistically infeasible to perform TVR at a much larger extent than cities (e.g., at the state or provincial level). In mixed landscapes with large rural patches, incorporating other methods such as aerial baiting could be most efficient. However, for small urban areas as in our study, TVR combined with other approaches might be the most efficient strategy for contingency actions to contain local outbreaks.

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SUPPLEMENTARY MATERIAL

Supplementary material for this article is online at http://dx.doi.org/10.7589/JWD-D-23-00059.

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