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Estimating trappability of the common brushtail possum in an urban environment

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Estimating trappability of the common brushtail possum in an urban environment

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Summary

Project and Client

- Manaaki Whenua – Landcare Research was commissioned by Predator Free Dunedin to estimate spatial detection parameters for common brushtail possums interacting with two types of kill traps (AT220 and Trapinator) in urban Dunedin. The project was undertaken between 01 July 2021 and 15 October 2022.

Objectives

- Use home range and behaviour-at-trap data to estimate three parameters (σ , ε_0 and θ) that are used to describe the process of an animal (in this study, possums) encountering then interacting with a control device. By multiplying ε_0 and θ , we derive a fourth parameter, g_0 which is the nightly probability of capture or detection by a device that is located at the home range centre.
- Assess whether detection parameters ε_0 , θ and g_0 differ between two device types: the AT220 and the Trapinator™.
- Determine the relationship between the mean distance each possum moves per night, and ε_0 , θ and g_0 .

Methods

- We captured and GPS-collared possums in six Dunedin suburbs. We determined approximate home range boundaries of each possum and set 1–3 pairs of kill traps (i.e. one AT220 and one Trapinator) within each individual home range. AT220 traps were baited with mayonnaise, whereas Trapinator traps were baited with an aniseed flavoured dough developed especially for possums. At each kill trap, we set up a camera trap (comprising two trail cameras) to monitor possum activity, i.e. whether they encountered a trap (to estimate ε_0) and if they did, whether they subsequently interacted with it (to estimate θ).
- We combined the possum location data with the device encounter and interaction data, and developed a hierarchical Bayesian model to infer factors influencing the key parameters σ , ε_0 and θ , and ultimately the detection parameter g_0 .
- We used GPS data from each collared possum to estimate the mean (“average”) distance each possum moved per night. We correlated this variable with g_0 to determine the relationship between individual trappability and individual movement rates.

Results

- We GPS-collared 32 possums – 14 males and 18 females and obtained enough relocations from 30 collared possums to include in analyses.
- We monitored possums for a mean of 82 days (range = 17–141) and obtained a mean of 586 (range = 63–1733) relocations per possum.
- Twenty home ranges approximated a bivariate normal shape (i.e. circular), whereas 10 were elliptical and incorporated patches of forested habitat that bordered roads.

- There was no difference in home range size between males and females. The mean σ was 59.0 m, which equates to a circular home range of 6.6 ha (range, based on σ values = 2.9–17.2 ha). There was considerable variability in σ values between individuals (range = 39.1 m–95.5 m). Individual possums moved a mean distance of 528 m per night, and this was not difference between sexes.
- Of 2210 device-nights, we recorded 1182 nightly encounters by uncollared possums, of which 41% resulted in interactions with devices. For the individually identifiable collared possums, we recorded a total of 771 nightly device encounters. Of these, 40% resulted in an interaction with the encountered device.
- The mean nightly probability of an individual encountering a device that was placed at the home range centre (ε_0) was 0.24, although there was large variability between individuals (range = 0.11–0.44).
- The mean nightly probability of an individual interacting with a device given that it was encountered (θ) was 0.36 (range = 0.17–0.69), irrespective of its location in the home range.
- The nightly probability of a possum encountering a Trapinator was higher than for AT220 traps, but the nightly probability of an interaction, given an encounter with a trap, was lower for a Trapinator than for an AT220 trap.
- The mean nightly probability of encountering and subsequently interacting with a device placed at the home range centre (g_0) was estimated at 0.08 (range = 0.02–0.22). There was no difference in g_0 between the two kill trap types that we assessed.
- There was no relationship between mean distances moved per night and individual estimates of ε_0 , θ or g_0 .

Recommendations

- Based on our results, a trap layout design (i.e. trap spacing, potentially stratified by habitat; see below) could be developed for Predator Free Dunedin, especially if the chosen management strategy for possums in the city moved to eradication. To do so, we recommend using the parameters and relationships we describe here in TrapSim, <https://landcare.shinyapps.io/TrapSim/>.
- Further spatial modelling of the current dataset could assess the relationship between ε_0 , θ or g_0 and fine-scale habitat selection by possums in urban Dunedin. Results may show no clear relationship, as was found for nightly movements here. Nevertheless, such an assessment would further increase our knowledge of what habitats and resources are important for possums and thus could inform targeted control strategies in urban areas. This analysis would require access to fine-scale habitat map layers.
- Manufacturers of the kill traps that we assessed should be informed of the probability of encounter and probability of interaction given an encounter reported here. Future design iterations of these traps may seek to increase possum encounters (AT220) and the probability of interaction given an encounter (Trapinator).

1 Introduction

Manaaki Whenua – Landcare Research was commissioned by Predator Free Dunedin to estimate spatial detection parameters for common brushtail possums (*Trichosurus vulpecula*) interacting with two types of kill traps (AT220 and Trapinator) in urban Dunedin. The project was undertaken between 01 July 2021 and 15 October 2022.

2 Background

Common brushtail possums (hereafter possums) were introduced into New Zealand from Australia in the mid-1800s to establish a fur trade (Cowan 2005). They subsequently expanded their geographic range to include most of New Zealand, including many offshore islands, and rapidly became abundant in many areas (Clout & Ericksen 2000). Their introduction and subsequent establishment and geographic spread have been referred to as “a disastrous success” (Clout & Ericksen 2000). Possums are folivores, and they have caused widespread dieback of native forests (Payton 2000) and damage to plantation forests and pasture (Butcher 2000; Latham et al. 2020). They are also increasingly recognised as capable predators, killing and eating invertebrates (Cowan & Moeed 1987) and vertebrates, primarily birds (eggs, nestlings and adults; Brown et al. 1993, 1996; Innes et al. 2004, 2015). As predatory omnivores, there is strong evidence that they have caused or contributed to the decline of some of New Zealand’s native animal species (James & Clout 1996; Sadleir 2000; Innes et al. 2010). In addition, the possum is considered the primary wildlife reservoir of bovine tuberculosis (Tb) for farmed cattle and deer in New Zealand (Coleman & Caley 2000). Collectively, this suite of unwanted impacts has resulted in the possum being listed as one of New Zealand’s worst invasive mammals and highlighted the need for increased sustained control efforts or eradication of this pest (Clout and Ericksen 2000; Russell et al. 2015; Byrom et al. 2016).

Given the large geographic extent of possums in New Zealand, much of which is rugged and comparatively inaccessible, most possum control has been done using helicopters to aerially sow toxic baits (Morgan 1994; Nugent et al. 2012; Elliott & Kemp 2016). However, in some locations the aerial distribution of toxic baits can have high environmental or social risks, especially in urban areas and other areas of high human use, and therefore, ground-based poisoning or trapping are used (Morgan & Hickling 2000; Murphy et al. 2019; Warburton et al. 2022). Nevertheless, in comparison with modern aerial poisoning methodology, ground-based poisoning and trapping rarely deliver comparable results for a similar cost (Warburton et al. 2022), but, importantly, they are the only tools currently available for managing vertebrate pests in urban areas (Murphy et al. 2019).

We deployed GPS-collars on possums in Dunedin city, South Island, New Zealand, to obtain ecological data that could be used to optimise sustained control or eradication programmes of possums in urban areas (also see Patterson et al. 2021). Specifically, we used location data to describe home range sizes and shapes and camera traps to estimate the trappability of individually marked possums at two types of kill traps (see field sampling methodology, below). We estimate three parameters (σ , ε_a and θ) that are used to describe the process of encountering then interacting with a removal device (i.e. a lethal

or non-lethal trap or bait station) or surveillance device (Efford 2004). The first parameter, σ , is a spatial decay parameter that scales detection to the home range size of possums. The second parameter, ε_0 , is the nightly probability of an encounter with a device that is located at the centre of a possum's home range (i.e. it is the maximum probability of encounter). The final parameter, θ , is the conditional nightly probability of interacting with a device given that a possum encounters it (see Methods for further details on σ , ε_0 , and θ).

By multiplying ε_0 and θ we derived a fourth parameter, g_0 , which is the nightly probability of capture or detection by a device that is located at the home range centre (Ramsey et al. 2005). That is, g_0 is the probability of encountering and subsequently interacting with a device at the home range centre. The difference between θ and g_0 is that θ is an aspatial parameter that describes the probability of an animal interacting with a device regardless of where it is located, whereas g_0 describes the process of encountering and interacting with a device located at home range centre. Robust estimates of σ and g_0 are critical for: (1) optimising the spatio-temporal deployment of traps, bait stations, and monitoring devices, such as camera traps; (2) simulating the effectiveness of these spatial lethal control and monitoring designs, and; (3) quantifying the probability that eradication has been achieved given no target animals are detected during surveillance (e.g. Anderson et al. 2013; Samaniego-Herrera et al. 2013; Nathan 2016; Latham 2019).

Finally, we used GPS data from each GPS-collared possum to estimate the mean ("average") distance each possum moved per night. We correlated this variable with g_0 to determine the relationship between individual trappability and individual movement rates. We predicted that individuals that moved greater distances per night would be bolder individuals, and therefore more likely to interact with traps that they had encountered.

3 Objectives

- Use home range and behaviour-at-trap data to estimate three parameters (σ , ε_0 and θ) that are used to describe the process of an animal (in this study, possums) encountering then interacting with a control device. By multiplying ε_0 and θ , we derive a fourth parameter, g_0 which is the nightly probability of capture or detection by a device that is located at the home range centre.
- Assess whether detection parameters ε_0 , θ and g_0 differ between two device types: the AT220 and the Trapinator™.
- Determine the relationship between the mean distance each possum moves per night, and ε_0 , θ and g_0 .

4 Methods

Study areas

We conducted our study in six suburbs (Saint Clair, Andersons Bay, Corstorphine, Kenmure, Kew, and Helensburgh) in Dunedin (Fig. 1). We selected these suburbs because they had suitable habitat with confirmed populations of possums, there was no recent or impending intensive lethal control of possums in these suburbs, and we could establish a 'cluster' of residential properties and adjacent green belt (e.g. council reserves and wooded gullies) of approximately 10 ha in area.

Within potential clusters (two in Saint Clair; one in each of the other five suburbs) we canvassed residents using a leaflet drop and door-knocking, explaining the objectives of the study and inviting them to participate. Where possible, we selected larger residential properties with stands of mature trees that would provide attractive habitat for possums. We excluded properties with dogs and/or children under 10 years of age to minimise equipment disturbance and risk to children from traps (despite kill traps being wired open to prevent them from triggering). Based on these criteria, we signed up 4–16 residents per cluster.

Possum capture and GPS collaring

To determine where to set live-capture traps for capturing possums, we conducted surveys to identify recent possum activity using chewcards baited with peanut butter (Sweetapple & Nugent 2011). Depending on the size of the property, we deployed 1–6 chewcards per property and left them in situ for seven nights. We trapped at properties with confirmed possum activity using Grieve live-capture cage traps (1–6 per property). We live-trapped at each property for approximately five nights, which resulted in 3–7 adult possums collared per suburb.

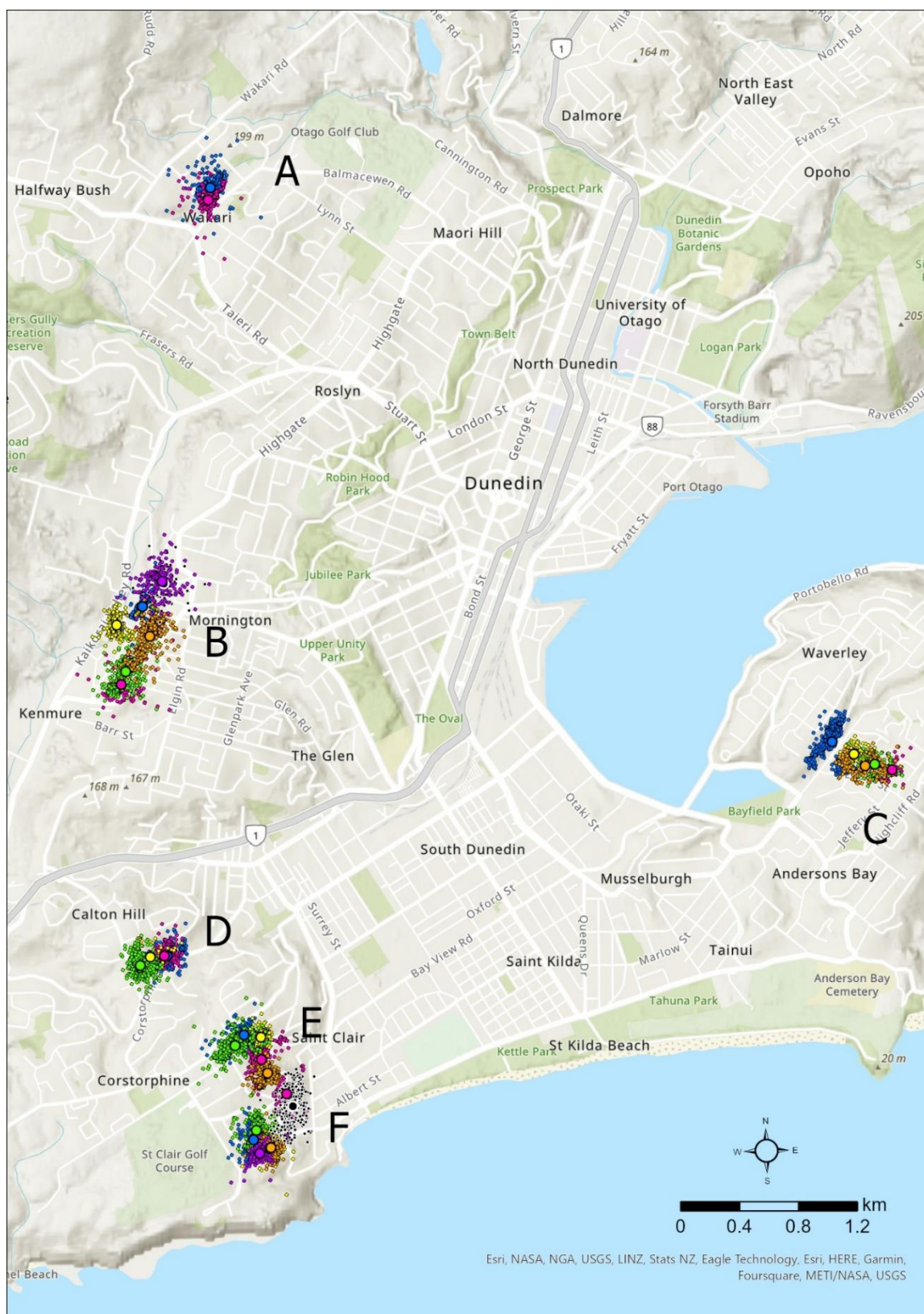


Figure 1. A map of Dunedin City, New Zealand, showing six suburbs where we conducted research assessing trappability parameters for common brushtail possums (*Trichosurus vulpecula*) in an urban environment. The smaller dots represent all the GPS locations collected for each collared possum, whereas the larger dots represent the estimated home range centres. A = Helensburgh, B = Kenmure, C = Andersons Bay, D = Corstorphine, E = Kew, F = St Clair.

We sedated all captured possums using an intramuscular injection of 5 mg per kg of Zoletil® 100 (tiletamine–zolazepam; Morgan et al. 2012). We fitted Lotek LiteTrack 60 GPS collars (Lotek, Havelock North, New Zealand) to adult possums. We programmed the GPS fix-rate schedule to alternate between high-intensity monitoring (one attempted fix every 15 min) and low-intensity monitoring (four attempted fixes per night) for periods of seven and 21 nights, respectively. We alternated between high- and low-intensity fix-rates as a compromise between obtaining fine-scale movement data while ensuring animals were monitored over 1–2 seasons. The schedule gave an estimated collar battery life of six months. The collars contained an internal loop VHF aerial inside the collar strap to prevent aerial damage. However, we also fitted a 5-cm external marker ‘aerial’ (initially made of steel and subsequently plastic) to the collars, which had a unique combination of reflective strips to allow identification of individual GPS-collared possums at camera traps. As a final method for identifying collared possums, we placed two reflective ear-tags in the right ear of females and two in the left ear of males.

We determined if GPS-collared possums were alive one week after collaring using the VHF signal of each collar. If an animal had died or lost a collar, the VHF mortality signal was activated after a 24-h period and emitted a pulse rate double that of the live signal. We retrieved GPS-collars transmitting a VHF mortality signal and attempted to trap new adult possums and redeploy the collars. We tracked all GPS-collared possums that remained alive and remotely downloaded the onboard GPS data using a Lotek hand-held commander unit (Lotek, Havelock North, New Zealand) once every 2 weeks.

Captured possums that weighed less than 2.4 kg and those that were deemed to have immature pouches or testes, were classified as juveniles. We did not GPS-collar juveniles because they can suffer welfare impacts as they grow over the course of the study, especially the potential for strangulation as their necks outgrow the collars. Instead, we fitted juveniles with a uniquely numbered ear-tag (right ear for females and left ear for males) and a second yellow reflective ear-tag in the same ear as the numbered tag. All ear-tags were stainless steel and measured 2 mm × 10 mm when fitted.

All capture, handling, and collaring protocols used in our study were approved by the Manaaki Whenua – Landcare Research Animal Ethics Committee (approval no. 20/12/01).

Quantifying possum encounters and interactions with traps

We estimated ε_0 and θ , and ultimately g_0 , for two types of kill traps, the AT220 (NZ AutoTraps, Whakatane, New Zealand) and the Trapinator™ (CMI Ltd, Auckland, New Zealand), that are commonly and increasingly used for possum control (Warburton et al. 2022). We determined approximate home range boundaries (based on initial downloads of GPS locations) for all GPS-collared possums in a suburb and subsequently superimposed these on a map of property boundaries within the suburb. We set between one and three pairs of traps (i.e. one AT220 and one Trapinator) in wooded areas in the parts of the properties that possums included in their home ranges. We ensured that each trap within a pair was at least 20 m from its partner trap and that traps were not in line-of-sight of one another as this could influence ε_0 . We set traps following the manufacturer’s instructions, which in short, included placing them on a tree at approximately 1.2 m above the ground with a 1-m wooden ramp set at an angle up to the trap entrance. We wired the traps open to prevent them from firing. Following manufacturer’s instructions, we

lured AT220 traps with a high-tech mayonnaise, while Trapinator traps were lured with the lure used by Predator Free Dunedin (an aniseed flavoured dough developed especially for possums). Both types of traps were re-baited weekly with their respective lures.

We set up a camera trap at each kill trap to determine whether a possum encountered a trap (to estimate ε_0) and if so, whether the possum subsequently interacted with that trap (to estimate θ). Camera traps comprised two trail cameras, each 3–5 m from the kill trap and set at right-angles to one another. We set one trail camera to take 20-second videos aimed at the kill trap at the top of the ramp, i.e. this camera focused on θ . We defined a possum interaction with a kill trap if a possum inserted its head (at least as far as its ears) into the trap entrance. We set the second trail camera to take still images of possum activity on the ground at the base of the ramp within a 2-m area marked by two pegs in the ground. Any possum activity within this area was defined as an encounter with the kill trap (ε_0). Cameras remained active at each location for 3–5 weeks.

Video and photo processing

We extracted the following information from the images and videos: date and time of possum sightings; individual possum ID (according to the aerial code and ear-tag combination or designated as 'P' for unmarked possums); whether or not an encounter occurred (as defined above); and, whether or not an interaction occurred (as defined above).

Data analysis

We combined the possum location data with the device encounter and interaction data, and developed a hierarchical Bayesian model to infer factors influencing the key parameters σ , ε_0 , and θ . This analytical approach builds on that described in Anderson et al. (*in press*) and Mackenzie et al. (2022) and is described in detail in Appendix 1.

We report the mean and 90% credible interval for each parameter presented in Appendix 2, and we used those means to derive individual-level values for ε_0 and θ using equations 8 and 10 (Appendix 1), respectively. For these calculations, we used the posterior mean estimates for δ and ρ from each individual, where δ is the individual deviation from the population-level ε_0 and ρ is the individual deviation from the population-level θ . We derived the nightly probability of encounter and subsequent interaction with a device at the home range centre, g_0 , from the product of the population-level estimates for ε_0 and θ :

$$g_0 = \varepsilon_0 \times \theta$$

This was calculated separately for each device type and for each individual possum. Population-level means are summarised from the individual-level estimates.

Finally, we used the high-intensity GPS data from each collared possum to estimate the mean distance each possum moved per night. We correlated this variable with g_0 to determine the relationship between individual trappability and individual movement rates.

5 Results

Possum home ranges

We GPS-collared 32 possums – 14 males and 18 females. We obtained enough relocations from 30 collared possums to include them in analyses (seven possums in Saint Clair, five in Andersons Bay, four in Corstorphine, seven in Kenmure, five in Kew, and two in Helensburgh). Two additional collars deployed on possums in Helensburgh failed to collect any data and were excluded from subsequent analyses. We monitored possums for a mean of 82 days (range = 17–141) and obtained a mean of 586 (range = 63–1733) relocations.

The shape of 20 home ranges approximated a bivariate normal (i.e. circular shape), whereas 10 were elliptical and incorporated patches of forested habitat that bordered roads. Most of the possums with elliptical home ranges were from Kenmure. There was no difference in home range size between males and females (Appendix 2). The mean σ was 59.0 m; however, there was considerable variability in σ values between individuals (range = 39.1 m–95.5 m; Appendix 3) but not between suburbs (Appendix 4). The two largest estimated σ values (over 90 m) were for a female in Kenmure and a male in Andersons Bay that had elliptical home ranges measuring 540 m and 480 m in length, respectively. The mean σ equates to a circular home range (95% activity contour) of 6.6 ha (range = 2.9–17.2 ha; based on σ values).

Encounters and interactions

Of the 30 GPS-collared possums for which we had sufficient location data, 28 were recorded in the video footage from trail cameras placed at devices. The remaining two collared possums were not recorded in any video footage, and therefore they were not used in subsequent analyses for estimating ε_0 , θ , and g_0 .

Of 2210 device-nights, we recorded a total of 1,182 nightly encounters by uncollared possums, of which 40% (486) resulted in interactions with devices. For the individually identifiable collared possums, we recorded a total of 771 nightly device encounters. Of these, 40% resulted in an interaction. The mean number of device-nights when collared possums encountered a device was 26, although this estimate was right skewed by nine possums that encountered devices on more than 37 nights. Thus, a less biased descriptor of possum-device-nights encounters is the median, which was 22 (range = 1–58).

The mean nightly probability of an individual encountering a device that was placed at the home range centre (ε_0) was 0.24, although there was large variability between individuals (range = 0.11–0.44). There was a strong negative relationship between the home range parameter, σ , and the predicted ε_0 (Appendix 2, Fig. 2A), i.e. the predicted ε_0 decreased from c. 0.35 for possums with the smallest estimated σ (c. 40 m) to 0.15 for possums with larger estimated σ (over 90 m). The nightly probability of a possum encountering a Trapinator trap was high relative to AT220 traps (Appendix 2). The estimate for τ (device encounter 'shyness' or 'happiness' parameter – see Appendix 1 for explanation) was below 1.0 (mean: 0.261; 90% CI = 0.177–0.354), indicating that the probability of encounter increased after a previous encounter with a trap.

The mean nightly probability of an individual interacting with a device, given that it was encountered (θ), was 0.36 (range = 0.17–0.69). The nightly probability of an interaction with a device, given that it was encountered, was lower for a Trapinator trap relative to an AT220 trap (Appendix 2). The mean for λ_2 (device interaction shyness or happiness parameter) was positive (mean: 0.709; 90% CI = 0.317–1.113), indicating that possums were more likely to interact with a new device after previous interactions.

The mean nightly probability of encountering and subsequently interacting with a device placed at the home range centre (g_0) was estimated at 0.08 (range = 0.02–0.22), and this parameter did not differ between the two types of kill traps that we assessed. The inverse relationship between g_0 and σ is shown in Figure 2B.

Individual possums moved a mean distance of 528 m per night, with the longest recorded movement per night covering a distance of 1523 m and the shortest one covering only 70 m. Male and female possums covered similar mean distances per night (males = 555, females = 510 m). There was no relationship between mean distances moved per night and individual estimates of ε_0 , θ or g_0 (Fig. 3).

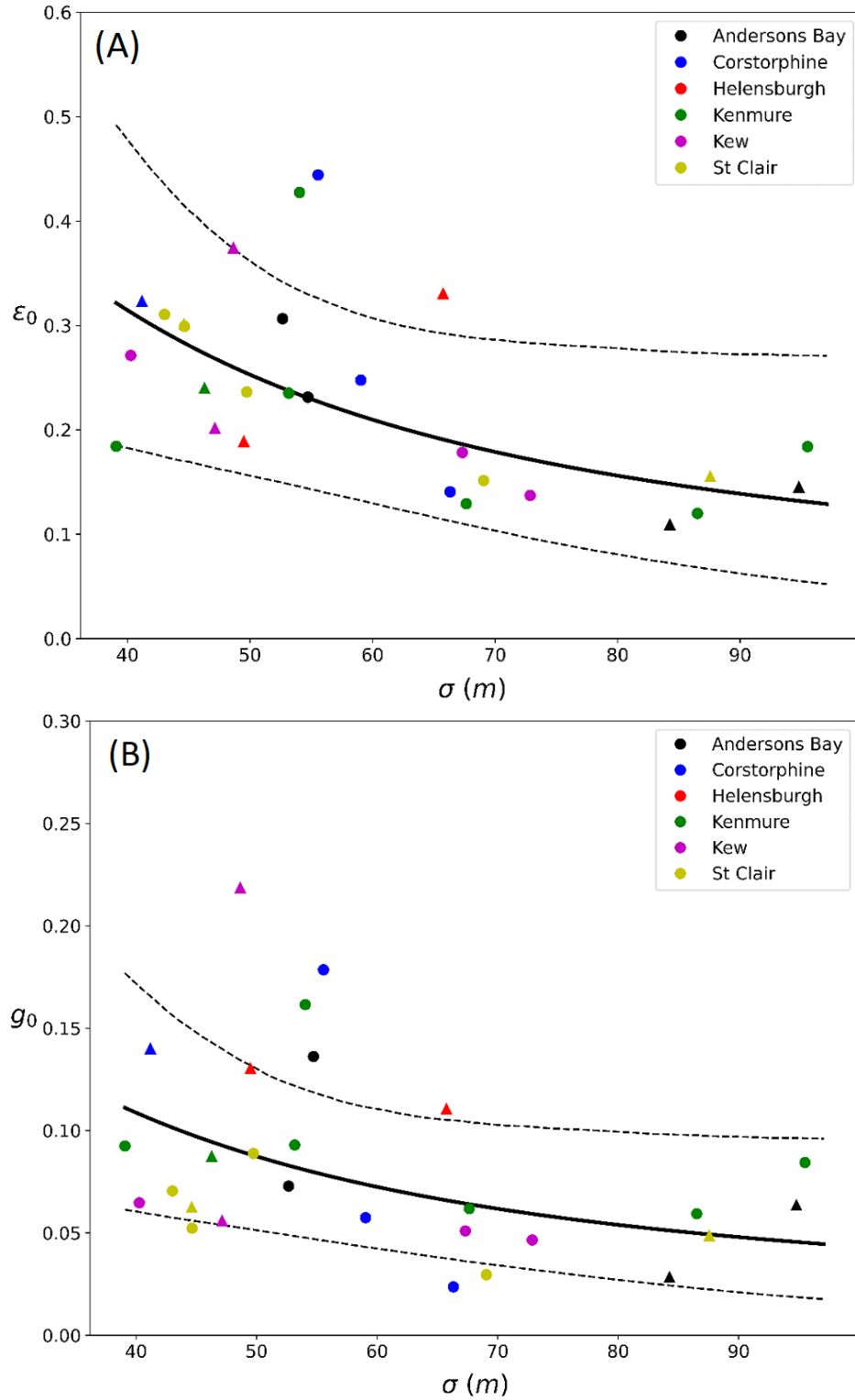


Figure 2. (A) The predicted ϵ_0 (the nightly probability of an animal encountering a device located at its home range centre) for 28 individual common brushtail possums (*Trichosurus vulpecula*) in six different suburbs in Dunedin city, New Zealand. The probability of encounter ϵ_0 was modelled as a function of the estimated σ (a spatial decay parameter that scales probability of detection to home range size). (B) The predicted g_0 (the nightly probability of an animal interacting with an encountered device located at its home range centre) for 28 individual brushtail possums. The solid line indicates the modelled mean, averaged across individuals and the two kill trap types. The dashed lines indicate 90% credible intervals. Circles indicate females, triangles indicate males.

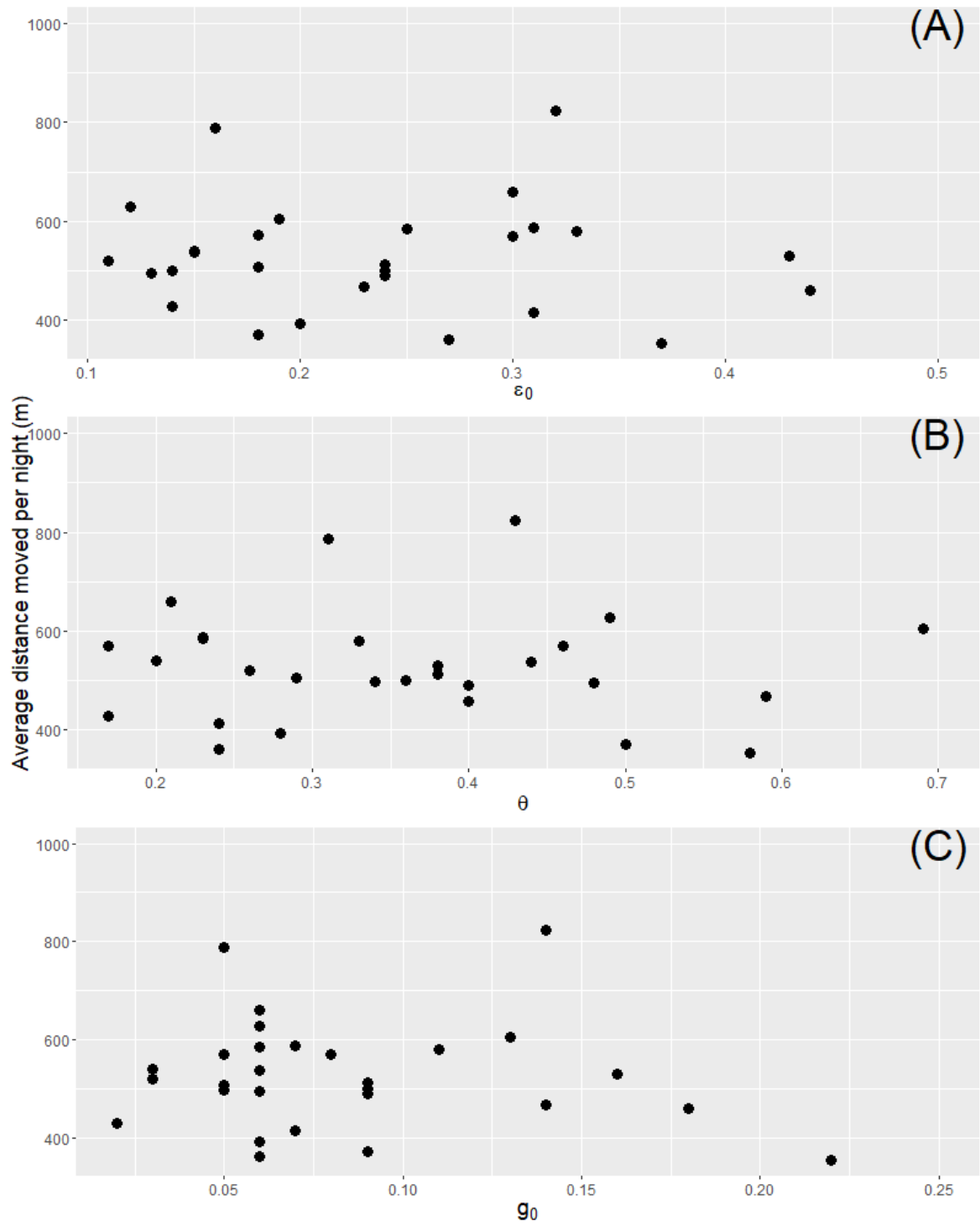


Figure 3. Mean distance moved per night as a function of increasing values of (A) ϵ_0 , (B) θ and (C) g_0 for each of 28 common brushtail possums (*Trichosurus vulpecula*) collared in six different suburbs in Dunedin city, New Zealand.

6 Conclusions

To date, most studies assessing detection and trappability parameters for possums have concentrated on non-urban areas, e.g. grassland, scrub, and forest (Warburton et al. 2009; Yockney et al. 2013; Rouco et al. 2017; Sweetapple & Nugent 2018; O'Malley et al. 2022; Anderson et al. in press). While studies have assessed various aspects of urban possum ecology (e.g. Statham & Statham 1997; Adams et al. 2013, 2014; Chen et al. 2020; Patterson et al. 2021), to our knowledge none have focussed on the detection and trappability parameters we report here, although σ could be derived from estimates of home range sizes reported in some of those studies.

We provide estimates of home range sizes (mean = 6.6 ha, range = 2.9–17.2 ha) based on σ values. Comparing home range size estimates must be done cautiously, as they can be affected by the analytical method used, the number of relocations, and the duration of monitoring (Girard et al. 2002; Boyle et al. 2009). For possums, home range size is also strongly influenced by habitat type (Cowan 2005). We found that mean possum home range sizes in the Dunedin suburbs studied here were generally larger than previous estimates from Dunedin (mean = 3.5 ha; Adams et al. 2014). Possums in contiguous native forest typically have smaller home ranges (1–2 ha) than those in other habitats (Cowan 2005). Therefore, the difference between our estimates and those of Adams et al. (2014) may be related to the relative proportions of houses versus native forest in the green belt, with possums from our study having more residential areas and less native forest available to them, on average, and therefore they may have had to travel further per night to find high-quality food. Interestingly, we found that one third of possums had elliptical home ranges, a result which potentially has implications for simulation models that predict the removal and surveillance efforts needed to achieve and confidently declare eradication of pests, and which in many cases assume circular home ranges.

Our mean estimate of σ (59.0 m) is at the lower end of the range for possums in various non-urban habitats in New Zealand (range of means = 53–235 m; Table 1, Anderson et al. in press). The lowest σ values reported in Anderson et al. (in press) tended to be for uncontrolled populations from forest and were more similar to the patches of urban forest in our study (notwithstanding inclusion of some residential areas) compared with the other habitats reviewed. Our estimate of g_0 for kill traps was 0.08 (range = 0.02–0.22). This estimate falls within the mean g_0 values estimated for cage and leghold traps (i.e. non-lethal traps) for possums in various habitats in New Zealand (range of g_0 means = 0.03–0.29; Table 1, Anderson et al. in press). In contrast, O'Malley et al. (2022) reported far lower g_0 values for cage traps (0.0036), leghold traps (0.0069), and AT220 (0.0012) for possums at low density (0.079 per ha) after control operations in Taranaki, North Island. O'Malley et al. (2020) suggest that low encounter and capture probabilities may be a common feature of individuals with large home ranges, which is supported by the strong inverse relationship between σ and g_0 (Monks & Tompkins 2012; Sweetapple & Nugent 2018; Anderson et al. in press; this study), presumably because the likelihood of encountering a particular device on a particular night (ϵ_0) is lower for possums that roam over large areas (O'Malley et al. 2022). Also, past exposure to management tools may lead to aversion to those devices in survivors (Garvey et al. 2020; O'Malley et al. 2022).

We found that there was a higher nightly probability of a possum encountering (ε_0) a Trapinator than an AT220. This result is difficult to explain because, although these two trap types are structurally different, they both look broadly similar, i.e. they both incorporate white plastic in the trap housing. Although AT220s also have a metal grille as part of the housing, and this tends to blend with the surrounding vegetation, it seems unlikely that this difference produced the difference in ε_0 between the two traps. Therefore, it could be that the odour from the possum dough made Trapinators more likely to be encountered by possums compared with the AT220. However, the reverse pattern was found when we assessed θ , i.e. possums were more likely to interact with the AT220 once they encountered one compared with a Trapinator. As stated, from the perspective of an encounter, both traps look broadly similar, but the open metal grille design for the entrance of the AT220 may appear less constrictive to a possum than the entrance of the Trapinator. Alternatively, once encountered, the mayonnaise lure used for the AT220 traps may be more attractive than possum dough, thereby increasing interaction rates with encountered AT220 traps. These results require further assessment, and if they are found to hold, it may be worth considering if the trap designs can be modified to increase ε_0 and θ for the AT220 and Trapinator, respectively.

We predicted that individuals that moved greater distances per night would be bolder (less shy) individuals, and therefore more likely to interact with traps that they had encountered. Our prediction assumed that movement and trappability are both proxies for personality. For example, significant positive correlations have been observed between trappability and activity levels in female American red squirrels (*Tamiasciurus hudsonicus*; Boon et al. 2008), although some studies observed the opposite trend for that species (Brehm & Mortelliti 2018). Likewise, a previous study on possums showed that the least trappable individuals tended to concentrate their movements in small activity centres between traplines (Morgan et al. 2007). However, we found no discernible relationship between mean distances moved per night and individual estimates of ε_0 , θ or g_0 . In addition to nightly movement distances, it would be valuable to assess fine-scale habitat selection to determine if, for example, individuals that are more likely to encounter or interact with traps were more likely to include areas with a greater proportion of houses and roads in their home ranges. Fine-scale delineation of habitats within each of the study areas would be needed to conduct this analysis.

There were a number of biological and analytical limitations in our study. From a biological perspective, there was a capture bias towards areas that were not highly urban, i.e. we set traps to capture and collar possums in areas only where there were reasonable-sized patches of tall vegetation near housing. If some individual possums have home ranges centred permanently on high density housing with little green space, this could conceivably affect the trappability parameters that we have reported. Similarly, the absence of collared juvenile possums in our study could affect estimates of trappability parameters. Alternative GPS-collar designs that have lower animal welfare concerns for juvenile possums may be available, and an assessment of trappability parameters for this cohort may be warranted in the future. Nevertheless, our results should be considered most applicable to individuals of at least 2.4 kg. Another limitation that applies to most, if not all, of these types of studies is a lack of understanding about very wary individuals (e.g. Garvey et al. 2020). The proportion of ultra-wary individuals in a population is poorly

understood (Garvey et al. 2020), but is important, especially for an eradication strategy. Our estimates of ε_0 , θ or g_0 may not be applicable to ultra-wary recalcitrant individuals.

7 Recommendations

- Based on our results, a trap layout design (i.e. spacing and potentially stratified by habitat, see below) could be developed for Predator Free Dunedin, especially if the chosen management strategy for possums in the city moved to eradication. To do so, we recommend using the parameters and relationships we describe here in the individual-based model developed by Warburton and Gormley (2015) and Gormley and Warburton (2020), which simulates the animal removal process using multiple-capture devices (TrapSim, <https://landcare.shinyapps.io/TrapSim/>).
- Further spatial modelling of the current dataset could assess the relationship between ε_0 , θ or g_0 and fine-scale habitat selection by possums in urban Dunedin. Results may show no clear relationship, as was found for nightly movements here. Nevertheless, such an assessment would further increase our knowledge of what habitats and resources are important for possums and thus could inform targeted control strategies in urban areas. This analysis would require access to fine-scale habitat map layers.
- Manufacturers of the kill traps that we assessed should be informed of the probability of encounter and probability of interaction given an encounter reported here. Although based on a single study (but note that O'Malley et al. (2022) also assessed AT220 traps), future design iterations of these traps may seek to increase possum encounters (AT220) and the probability of interaction given an encounter (Trapinator).

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Appendix 1 – Analytical approach

The GPS location data Z_{ij} were composed of x_{ij} (eastings) and y_{ij} (northings) locations for each individual possum i at site j . To simplify the notation, we drop the j subscript from all subsequent equations. We modelled the probability of observing Z_i as a symmetric bivariate normal variable

$$P(Z_i) = \prod_{i=1}^{L_i} \text{Normal}(\Delta x_i | 0, \sigma_i^2) \text{Normal}(\Delta y_i | 0, \sigma_i^2) \quad \text{eq. 1}$$

where σ_i is the standard deviation of a normal distribution with zero mean, L_i is the number of location fixes for individual i , and Δx_i and Δy_i are the straight-line distances from the home range centre of individual i to x_i and y_i respectively. The home range centre for each individual was calculated as the mean of all x_i and y_i i.e. the centroid of all locations that we recorded for that individual.

We modelled σ_i as a log-normal variable with mean $\ln(\mu_i)$, which was a function of the sex of the individual:

$$\ln(\sigma_i) \sim \text{Normal}(\ln(\mu_i), V) \quad \text{eq. 2}$$

$$\ln(\mu_i) = \beta_0 + \beta_1 \text{sex}_i \quad \text{eq. 3}$$

where V is the variance of $\ln(\sigma_i)$, and $\ln(\mu_i)$ is a linear function of a categorical variable indicating whether possum i is a male (0) or a female (1). The priors on the β coefficients and V were $\text{Normal}(0, 10)$ and $\text{InverseGamma}(0.01, 0.01)$, respectively.

The encounter data (E_{imt}) across all devices m and nights t was modelled as a Bernoulli process:

$$E_{imt} \sim \text{Bernoulli}(\gamma_{imt}) \quad \text{eq. 4}$$

$$\text{logit}(\gamma_{imt}) \sim \text{MultivariateNormal}(\text{logit}(P_{imt}), \Sigma) \quad \text{eq. 5}$$

where γ_{imt} is a latent variable representing the degree to which the nightly probability of possum i encountering a given device is not independent of the encounter outcomes of nearby devices, i.e. we assumed there is spatial autocorrelation in the probability of encountering a device. To account for the spatial autocorrelation not explained by the covariates explicitly modelled (i.e. σ and device type, see below), we included an exponential spatial covariance error structure (Σ) as follows:

$$\Sigma = v^2 e^{-\phi r} \quad \text{eq. 6}$$

where v^2 is the variance, ϕ is a correlation distance parameter, and r is the distance between pairs of devices (Cressie 1993; Clark 2007). We used moderately informative log-normal priors for the covariance parameters to obtain proper posteriors (Clarke 2007): $v^2 \sim \text{logN}(3, 1)$ and $\phi \sim \text{logN}(1, 1)$.

The nightly probability of encounter of device m by individual i on night t (P_{imt}) was calculated using a half-normal detection function (Efford 2004):

$$P_{imt} = \left(\varepsilon_{0,im} e^{\left(-\frac{d_{im}^2}{2\sigma_i^2} \right)} \right)^{\tau E_{it}^*} \times \left(\varepsilon_{0,im} e^{\left(-\frac{d_{im}^2}{2\sigma_i^2} \right)} \right)^{1-E_{it}^*} \quad \text{eq. 7}$$

where $\varepsilon_{0,im}$ is the maximum nightly probability of encounter for device m , or the probability if device m was placed at the centre of the home range of possum i . The variable d_{im} is the distance between the home range centre of possum i and device m ; only devices within a distance of $3.72\sigma_i$ were considered in the calculation in eq. 7 (Efford 2004). Finally, τ is a strictly positive parameter (i.e. $\tau > 0$), measuring the degree of device-shyness and is multiplied by E_{it}^* , an indicator variable which takes a value of 0 when individual i has not encountered a device (of any type) on nights before night t , or a value of 1 if it had previously encountered one, regardless of the type of device it encountered. If $\tau < 1$, possums are 'device-happy', meaning they are more attracted to devices on nights after an initial encounter, whereas if $\tau > 1$ then possums are 'device-shy' and thus more likely to avoid devices on nights following an initial encounter. E_{it}^* was reset to 0 after 20 days of no encounters with a device. The prior on τ was *Gamma*(0.933, 8.33).

Values of $\varepsilon_{0,im}$ were predicted as a function of σ_i , device type, and individual effects using the following equation:

$$\text{logit}(\varepsilon_{0,im}) = \alpha_0 + \alpha_1 \ln(\sigma_i) + \alpha_2 \text{trapinator}_m + \delta_i \quad \text{eq. 8}$$

where α_2 quantifies the increase or decrease in the maximal probability of encountering a Trapinator trap relative to a AT220 (which is the reference category). The δ_i parameters account for individual differences in ε_0 . Finally, we allowed ε_0 to be a function of $\ln(\sigma_i)$ because we assumed encounter probability at home range centre will decrease with increasing home range size. The priors on the α coefficients and δ were *Normal*(0, 10) and *Normal*(0, 1), respectively.

The interaction data (I_{imn}) across all devices m and nights n when encounters occurred were modelled as a Bernoulli process with probability θ , which was a function of device type and individual effects:

$$I_{imn} \sim \text{Bernoulli}(\theta_{imn}) \quad \text{eq. 9}$$

$$\text{logit}(\theta_{imn}) = \lambda_0 + \lambda_1 \text{trapinator}_m + \lambda_2 I_{in}^* + \rho_i \quad \text{eq. 10}$$

where θ_{imn} is the probability of possum i interacting with device m given that it has encountered it on night n , and λ_1 quantifies the increase or decrease in the conditional probability of interaction with a Trapinator trap relative to a AT220. The λ_2 parameter is analogous to τ in eq. 7 but for the process of interaction given encounter with a device. However, by incorporating λ_3 directly into a linear equation, this parameter can take negative values and thus should be interpreted differently from τ : if $\lambda_3 < 0$, possums are 'device-shy' after an initial interaction, whereas $\lambda_3 > 0$ indicates that individuals become 'device-happy' after an initial interaction. This parameter is multiplied by I_{in}^* , which is an indicator variable that takes a value of 0 when individual i has not interacted with a device

(of any type) on nights before night n , or a value of 1 when it has interacted with one previously, regardless of the type of device it interacted with. If a possum had not interacted with a device for 20 days, I_{in}^* was reset to 0. Finally, the ρ_i parameters account for individual differences in θ . The priors on the λ coefficients and ρ were $Normal(0, 10)$ and $Normal(0, 1)$, respectively.

We used Markov Chain Monte Carlo (MCMC) simulation to estimate model parameters using Python programming language. The variance parameter V was sampled from the full conditional posteriors, but all other parameters were estimated using the Metropolis algorithm (Clarke 2007). Posterior summaries were taken from four chains containing 3000 samples each (with a burn-in of 8000 and a thinning rate of 30). Convergence on posteriors was assessed by visual inspection and a scale reduction factor < 1.05 (Gelman & Rubin 1992; Gelman et al. 2004).

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Appendix 2 – Table of parameter estimates

Means and 90% credible intervals for parameter estimates derived from a Bayesian model of common brushtail possum (*Trichosurus vulpecula*) encounter and interaction probabilities with two types of kill traps (AT220 and Trapinator) in Dunedin city, New Zealand. AT220 is the default device modelled via parameter α_0 for the process of encountering a device, and in parameter λ_0 for the process of interacting with a device. See Appendix 1 for a detailed description of each parameter or refer to the equation number where each parameter is used.

Process	Parameter	Equation	Mean	90% credible interval
σ	β_0	3	4.224	2.929; 5.534
	$\beta_1 - \text{sex}$	3	-0.320	-2.044; 1.408
	$V - \text{variance of } \ln(\sigma)$	2	2.749	2.205; 3.437
Encounter	α_0	8	4.026	-0.597; 9.156
	$\alpha_1 - \ln(\sigma)$	8	-1.347	-2.605; -0.149
	$\alpha_2 - \text{Trapinator}$	8	0.279	0.123; 0.425
	$\tau - \text{previous encounter}$	7	0.261	0.177; 0.354
	$v^2 - \text{spatial variance}$	6	4.339	3.52; 5.497
	$\phi - \text{spatial correlation}$	6	6.055	5.218; 7.148
Interaction	λ_0	10	-0.783	-1.205; -0.357
	$\lambda_1 - \text{Trapinator}$	10	-0.428	-0.705; -0.147
	$\lambda_3 - \text{previous interaction}$	10	0.709	0.317; 1.113

Appendix 3 – Individual parameter estimates

Individual estimates (mean and standard error) of six spatial detection parameters obtained from a hierarchical Bayesian model of common brushtail possum (*Trichosurus vulpecula*) radio-collared in 6 neighbourhoods in Dunedin, New Zealand. A dash indicates animals that were not recorded on any video footage or that had home range centres located at a distance $> 3.72\sigma$ from any trail camera-device pair that yielded viable video recordings; these animals were not considered for the estimation of ε_0 or θ . σ is a spatial decay parameter that scales probability of detection to home range size; ε_0 is the nightly probability of an encounter with a device that is located at the animal's home range centre; δ is the individual deviation from the population-level ε_0 ; θ is the conditional nightly probability of interacting with a device, given that an animal encounters it; ρ is the individual deviation from the population-level θ ; and g_0 is the nightly probability of interaction, given an encounter with a device that is located at the home range centre. Mean and SE values for each individual possum were derived using posterior distributions for each parameter in eqs 3, 8, and 10.

Possum	Area	Sex	Mean σ (SE)	Mean ε_0 (SE)	Mean δ (SE)	Mean θ (SE)	Mean ρ (SE)	Mean g_0 (SE)
49a	Andersons Bay	M	94.79 (1.95)	0.15 (0.07)	0.08 (0.45)	0.44 (0.08)	0.39 (0.35)	0.06 (0.03)
65a	Andersons Bay	M	46.50 (2.94)	–	–	–	–	–
80a	Andersons Bay	F	52.65 (1.88)	0.31 (0.10)	0.31 (0.42)	0.24 (0.06)	-0.56 (0.35)	0.07 (0.03)
85a	Andersons Bay	F	54.72 (1.59)	0.23 (0.07)	-0.02 (0.36)	0.59 (0.08)	1.01 (0.35)	0.14 (0.05)
91a	Andersons Bay	M	84.26 (2.60)	0.11 (0.06)	-0.42 (0.46)	0.26 (0.06)	-0.43 (0.34)	0.03 (0.02)
79c	Corstorphine	F	59.04 (1.3)	0.25 (0.09)	0.15 (0.43)	0.23 (0.08)	-0.61 (0.46)	0.06 (0.03)
82c	Corstorphine	F	55.55 (1.29)	0.44 (0.09)	1.01 (0.38)	0.40 (0.13)	0.22 (0.53)	0.18 (0.07)
93c	Corstorphine	F	66.32 (2.90)	0.14 (0.06)	-0.42 (0.44)	0.17 (0.06)	-1.01 (0.40)	0.02 (0.01)
94c	Corstorphine	M	41.18 (0.59)	0.32 (0.10)	0.07 (0.43)	0.43 (0.07)	0.37 (0.30)	0.14 (0.05)
81h	Helensburgh	M	49.49 (0.85)	0.19 (0.06)	-0.42 (0.38)	0.69 (0.07)	1.47 (0.35)	0.13 (0.05)
96h	Helensburgh	M	65.75 (2.12)	0.33 (0.09)	0.73 (0.38)	0.33 (0.12)	-0.09 (0.53)	0.11 (0.05)
65n	Kenmure	F	54.03 (1.48)	0.43 (0.11)	0.90 (0.39)	0.38 (0.10)	0.12 (0.41)	0.16 (0.06)
70n	Kenmure	F	86.52 (1.46)	0.12 (0.06)	-0.26 (0.45)	0.49 (0.07)	0.62 (0.28)	0.06 (0.03)
83n	Kenmure	F	39.07 (0.64)	0.18 (0.07)	-0.78 (0.46)	0.50 (0.09)	0.65 (0.37)	0.09 (0.04)

Possum	Area	Sex	Mean σ (SE)	Mean ε_θ (SE)	Mean δ (SE)	Mean θ (SE)	Mean ρ (SE)	Mean g_θ (SE)
86n	Kenmure	F	67.64 (1.17)	0.13 (0.05)	-0.48 (0.43)	0.48 (0.08)	0.56 (0.33)	0.06 (0.03)
90n	Kenmure	F	95.51 (1.66)	0.18 (0.09)	0.38 (0.45)	0.46 (0.09)	0.47 (0.37)	0.08 (0.04)
97n	Kenmure	F	53.16 (1.66)	0.24 (0.08)	-0.04 (0.40)	0.40 (0.08)	0.20 (0.36)	0.09 (0.04)
98n	Kenmure	M	46.27 (0.81)	0.24 (0.07)	-0.19 (0.36)	0.36 (0.11)	0.05 (0.48)	0.09 (0.04)
55w	Kew	M	47.13 (1.32)	0.20 (0.07)	-0.41 (0.38)	0.28 (0.06)	-0.33 (0.30)	0.06 (0.02)
57w	Kew	F	72.86 (2.23)	0.14 (0.06)	-0.31 (0.41)	0.34 (0.07)	-0.04 (0.31)	0.05 (0.02)
87w	Kew	F	40.26 (1.57)	0.27 (0.07)	-0.20 (0.39)	0.24 (0.07)	-0.56 (0.40)	0.06 (0.03)
95w	Kew	M	48.63 (0.94)	0.37 (0.10)	0.53 (0.38)	0.58 (0.09)	0.99 (0.38)	0.22 (0.07)
99w	Kew	F	67.32 (1.12)	0.18 (0.07)	-0.10 (0.39)	0.29 (0.08)	-0.30 (0.39)	0.05 (0.02)
51s	St Clair	F	49.73 (1.05)	0.24 (0.08)	-0.12 (0.41)	0.38 (0.07)	0.13 (0.29)	0.09 (0.03)
57s	St Clair	M	59.05 (2.09)	–	–	–	–	–
66s	St Clair	M	44.61 (1.02)	0.30 (0.09)	0.07 (0.38)	0.21 (0.05)	-0.72 (0.30)	0.06 (0.02)
77s	St Clair	F	69.06 (2.16)	0.15 (0.06)	-0.26 (0.39)	0.20 (0.04)	-0.80 (0.29)	0.03 (0.01)
84s	St Clair	F	43.01 (0.89)	0.31 (0.08)	0.07 (0.43)	0.23 (0.05)	-0.61 (0.32)	0.07 (0.03)
88s	St Clair	M	87.56 (1.63)	0.16 (0.07)	0.08 (0.41)	0.31 (0.10)	-0.19 (0.48)	0.05 (0.03)
89s	St Clair	F	44.64 (1.44)	0.30 (0.09)	0.06 (0.38)	0.17 (0.04)	-0.94 (0.31)	0.05 (0.02)

Appendix 4 – Area-specific parameter estimates

Area-specific estimates (mean and standard error) of six spatial detection parameters obtained from a hierarchical Bayesian model of common brushtail possum (*Trichosurus vulpecula*) radio-collared in six neighbourhoods in Dunedin, New Zealand. σ is a spatial decay parameter that scales probability of detection to home range size; ε_0 is the nightly probability of an encounter with a device that is located at the animal's home range centre; δ is the individual deviation from the population-level ε_0 ; θ is the conditional nightly probability of interacting with a device that an animal encounters it; ρ is the individual deviation from the population-level θ ; and g_0 is the nightly probability of interaction, given an encounter with a device that is located at the home range centre.

Area	Number of animals	Mean σ (SE)	Mean ε_0 (SE)	Mean δ (SE)	Mean θ (SE)	Mean ρ (SE)	Mean g_0 (SE)
Andersons Bay	5	66.58 (19.22)	0.20 (0.08)	-0.01 (0.26)	0.38 (0.14)	0.10 (0.64)	0.07 (0.04)
Corstorphine	4	55.52 (9.15)	0.29 (0.11)	0.20 (0.51)	0.31 (0.11)	-0.26 (0.57)	0.10 (0.06)
Helensburgh	2	57.62 (8.13)	0.26 (0.07)	0.15 (0.58)	0.51 (0.18)	0.69 (0.78)	0.12 (0.01)
Kenmure	7	63.17 (19.50)	0.22 (0.10)	-0.07 (0.52)	0.44 (0.05)	0.38 (0.23)	0.09 (0.03)
Kew	5	55.24 (12.57)	0.23 (0.08)	-0.10 (0.33)	0.34 (0.12)	-0.05 (0.55)	0.09 (0.07)
St Clair	7	56.81 (15.30)	0.24 (0.07)	-0.02 (0.13)	0.25 (0.07)	-0.52 (0.37)	0.06 (0.02)