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Modelling alternative dispersal barrier and trap layout designs to protect the Orokonui Halo area from possum reinvasion

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Modelling alternative dispersal barrier and trap layout designs to protect the Orokonui Halo project area from possum reinvasion

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Summary

Project and client

- The Halo Project is delivering landscape-scale predator control north of Dunedin City as a delivery partner for Predator Free Dunedin. The Project aims to achieve a predator-free status in the urban and rural landscape around OrokonuiEcosanctuary.
- OSPRI's TBfree operations in the area began in 2018 and involved reducing the brushtail possum (*Trichosurus vulpecula*) population to 2% residual trap catch index (RTCI) by 2021 across a 12,541 ha landscape. The Halo Project will build on this OSPRI work as the basis for establishing a succession programme to maintain these gains and to develop a strategic plan to assess the feasibility of reducing the population further – if possible to eradication.
- Manaaki Whenua – Landcare Research was first contracted in 2019 to model possum control operations within the Flagstaff area of the project using TrapSim. The resulting report highlighted the potential to use a low-density control network (one leg-hold trap every 18 ha, checked monthly) to suppress the possum population in the Flagstaff area.
- Although the TrapSim report for the Flagstaff area provides guidance on likely suppression outcomes, there are limitations to applying this information to the entire Halo Project, because TrapSim treats a system as 'closed' to immigration and assumes a homogeneous possum-carrying capacity across the trapped area. Instead, understanding the likelihood of achieving alternative outcomes under several re-invasion scenarios and for differing possum densities in areas surrounding the Halo project may provide the Halo Project working group and funders with additional confidence prior to large scale investment. In addition, new and emerging tools such as automatic multi-capture traps potentially offer the ability to increase the number of effective trap nights per year and further reduce the required density of the control network.

Objectives

- To assess the effectiveness of three low-density control networks (one multi-capture trap per 18 ha, one per 25 ha and one per 36 ha; active all year) to maintain or further reduce the possum population across the Halo area.
- To assess reinvasion patterns from areas surrounding the Halo project *with* and *without* the use of a semi-permeable dispersal barrier (and different levels of effectiveness of the barrier) to limit reinvasion along SH1, and for differing possum densities in areas surrounding the Halo project.
- To assess how variable possum trappability affects predicted control or eradication outcomes.

Methods

- We combined an agent-based mathematical modelling framework with spatial information on possum habitat distribution, population dynamics and levels of control to investigate the effectiveness of different temporal distributions of control effort.

- We included variable trappability (random sampling from a PERT distribution) in the model to estimate how it affects predicted control outcomes.

Results

- A low-density control network of one multi-capture trap per 25 ha or one multi-capture trap per 18 ha, active all year, could maintain and further reduce possum population density to a low level (<2% residual RTCI) within the Halo control area.
- Reinvasion is likely to occur a year after OSPRI's departure from the Halo area, but the level of immigration could be mitigated by a control network of one device per 25 ha or one device per 18 ha within the Halo area.
- The simulated use of a semi-permeable dispersal barrier along SH1 had minimal effect on limiting the recovery of possum population size within the Halo control area.
- Possum density outside the Halo area has a small effect on the final density within the Halo area. This effect was more apparent when starting from a simulated density of zero.
- Small, but consistent, variations in trappability between possums had a very low impact on eradication outcome. However, when the population exhibited larger variations in trappability, the simulations suggested that none of these low-density control networks could maintain the Halo possum population at an RTCI target of 2% or below.

Conclusions and recommendations

- Automatic multi-capture traps requiring only one to two services per year potentially offer the ability to reduce the required trap network density to one multi-capture trap per 25 ha compared with the trapping network originally modelled with TrapSim. However, it is not recommended to use a control network of one multi-capture trap per 36 ha for maintaining the Halo possum population at an RTCI target of 2% or below.
- Reinvasion is likely to become significant a year after OSPRI's departure from the Halo area, but the level of immigration is likey to be mitigated by a control network of one device per 25 ha or one device per 18 ha.
- A transition from sustained possum control at low density to achieving elimination of possums from the Halo area would benefit from prioritising control in areas surrounding the Halo project over the use of a semi-permeable dispersal barrier along SH1.
- The trappability parameters g0 and σ appear to be particularly important to determine the level of trapping effort (trap density) needed to maintain the Halo possum population at an RTCI target of 2% or below. Small inter-individual variation in detection/capture probability can quickly hinder the efficacy of the management scenarios tested. Passive control methods that rely on possum investigation and contact with the control device may fail to sample individuals that are less active or too wary to approach the control device (low g_0). Priority should be given to validating these parameters.

1 Introduction

The Orokonui Halo Project is a landscape-scale predator control project within Predator Free Dunedin, which includes collaboration between the Halo Project and Landscape Connections Trust (LCT), OSPRI, Dunedin City Council (DCC), Otago Regional Council (ORC) and Orokonui Ecosanctuary. The project's goal is to reduce the brushtail possum (*Trichosurus vulpecula*) population to 2% residual trap catch index (RTCI) by 2021 across a 12,541 ha landscape. OSPRI's TBfree operations in the area began in 2018 and involved large-scale possum control, protecting not only agricultural livelihoods in the area but also the highly significant fenced Orokonui Ecosanctuary, which sits at the core of this project area (Figure 1). OSPRI's expected departure in mid-2021 will leave a low residual possum population, but one that will rebound in the absence of management.

In early 2020, a working group was formed from key stakeholders (ORC, DCC, Predator Free Dunedin, and the Halo Project) to develop and drive the creation of a site-led possum control programme to ensure a timely transition as OSPRI departs. This programme will maximise gains resulting from the anticipated residual possum population of 2% RTCI. The group will invest in surveillance and detection equipment across the 12,541 ha landscape, maintaining low-level suppression through a model that promotes technology and community participation over traditional pest control labour.

Manaaki Whenua – Landcare Research (MWLR) completed a report on modelling possum control operations within the Flagstaff area of the project (Figure 1; Howard 2019), using TrapSim (Gormley & Warburton 2017). This report highlighted the potential to use low-density control networks to achieve management objectives, including a single-kill trap network with 600 m × 300 m spacing (one trap every 18 ha), checked monthly.

New and emerging tools such as the NZ Autotraps AT220 multi-kill trap[1] potentially offer the ability to increase the number of effective trap nights per year and further reduce the required network density and labour inputs (but with increased trap costs). The use of multi-capture traps is untested at scale in New Zealand, and its effectiveness is therefore unknown. If effective, the potential cost savings through reduced labour could further the goals of a predator-free New Zealand by 2050.

Although the TrapSim report for the Flagstaff area provides guidance on likely eradication outcomes, there are limitations to applying this information to the proposed trap network because TrapSim treats a system as 'closed' to immigration and assumes a homogeneous possum-carrying capacity across the trapped area. Instead, understanding the likelihood of achieving alternative outcomes under several re-invasion scenarios, with several low-density trap layout scenarios and differing probabilities of detection/capture, may provide the working group and funders with additional confidence prior to large-scale investment.

In addition, the Halo area takes advantage of local geographical features, with the Leith Stream potentially creating a semi-permeable barrier to re-invasion from the south (Figure 1). A 1 km-wide semi-permeable dispersal barrier will also be considered along State Highway 1 (500 m either side) to impede reinvasion to the project area from the west.

[1] https://nzautotraps.com

OSPRI's TBfree possum operations in areas surrounding the Halo are expected to reduce possums in those areas to 2 or 5% RTCI, and the semi-permeable barriers to reinvasion may reduce invasion from these source populations by some unknown amount.

We currently lack understanding of:

- the feasibility of a low-density control network (e.g. one multi-capture trap per 18 ha, one per 25 ha or one per 36 ha, active all year) to maintain or further reduce possum populations in the Halo area
- the level of immigration that can be mitigated by such a control network (e.g. an open system versus a semi-permeable dispersal barrier along SH1, where the dispersal barrier is 80%, 90% or 99% effective at preventing dispersing animals from invading the Halo)
- the impacts of reducing possum density in areas surrounding the Halo project (to 2 or 5% RTCI) on population recovery within the Halo area.

Understanding the combined effects of these factors will provide additional insight into the likely outcomes of any future possum control programme in the Halo area, and a better understanding of the utility of barriers and buffers.

2 Objectives

We used a stochastic, spatially explicit, spread simulation model (Lustig et al. 2019) to gauge the effects of different spatial distributions of control effort to maintain or further reduce the possum population in the Halo area and investigate the risk of reinvasion by dispersing possums, based on their known dispersal behaviour and habitat patches as sources of reinvaders.

The results of the simulations were then used to:

1. assess the effectiveness of three low-density control networks (one multi-capture trap per 18 ha, one per 25 ha and one per 36 ha, active all year) to maintain or further reduce the possum population across the Halo area (i.e. by removing survivors, new animals born *in situ* and invading animals)
2. assess reinvasion patterns from areas surrounding the Halo project to the Halo area, *with* and *without* the use of a semi-permeable dispersal barrier (and with different levels of effectiveness of the barrier) to limit reinvasion along SH1, and for differing possum densities in areas surrounding the Halo project
3. assess how variable possum trappability affects predicted control or eradication outcomes.

3 Methods

Simulation modelling was carried out using a spread model that describes the behaviour of individual mammals located in a map of their habitat. Key events in an individual's lifetime are birth, death and dispersal, and these are simulated as stochastic events (i.e. there is uncertainty in the timing of each event). Dispersal of juveniles is biased toward habitat of higher quality. A simulation module provides the probability of an animal being caught at a particular location with a given local trap density. The user specifies the current density of the target species, as well as parameters related to home range size and trappability, and investigates various trapping regimes by altering trap spacing and trapping intervals.

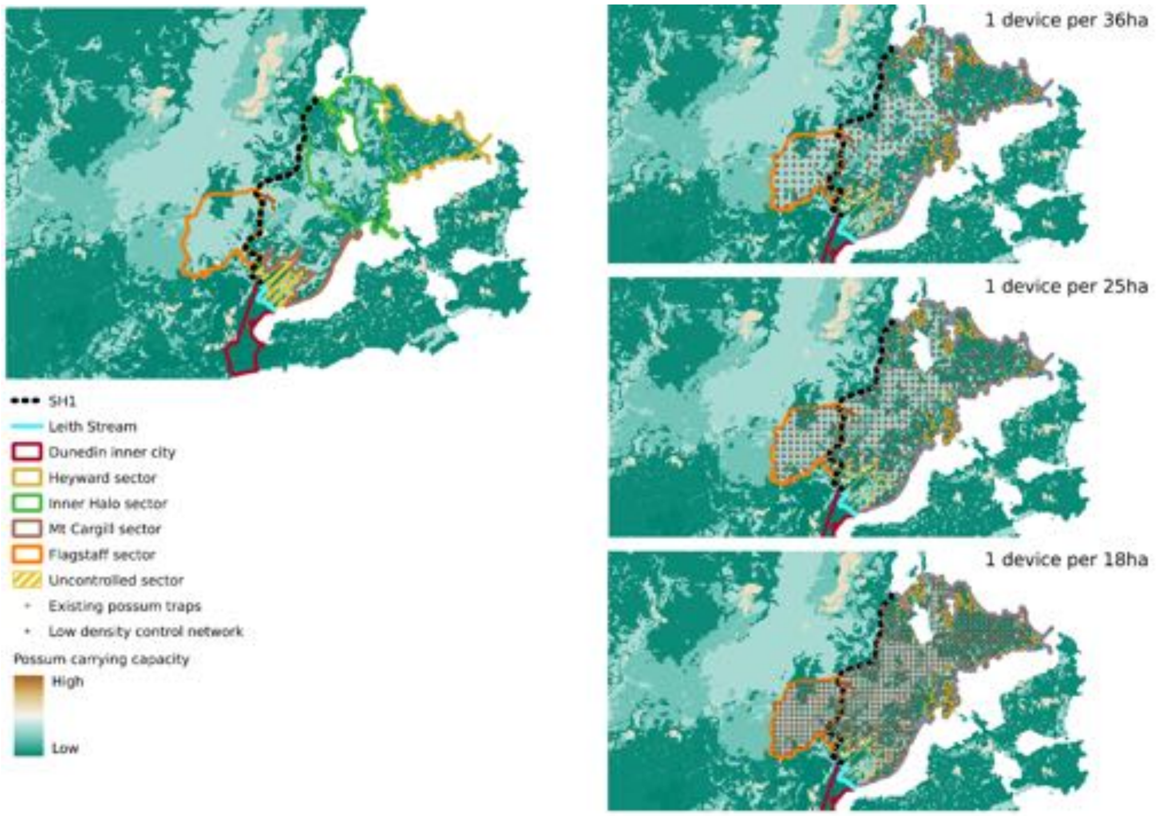

Figure 1. Halo possum-controlled area (left) and different simulated control device layouts (right). The controlled area on the right-hand maps are delimited by the yellow, green, brown and orange boundaries. The boundaries of Dunedin inner city are indicated in red. The Dunedin inner city and the Leith Stream (in blue) potentially create a semi-permeable barrier to reinvasion from the south. State highway 1 (dotted black) can potentially impede reinvasion from the west.

Based on discussions with the Halo Project and Predator Free Dunedin, we agreed on a number of parameter values and trapping scenarios to assess the feasibility of maintaining or further reducing the possum population across the Halo area. We allocated a carrying capacity (K) to available georeferenced New Zealand land-cover classes (Figure 1) that was based on possum-carrying capacities in various classes of habitat (Warburton et al. 2009). We used the LRIS-LCDB-v41 Land Cover Database, along with the EcoSat indigenous forest layer, to provide finer differentiation of forest classes.[2]

The polygon data set had 31 categories of land cover. Land surfaces were partitioned into three types: habitats in which possums could settle and establish home ranges (most of

[2] lris.scinfo.org.nz

the land cover); habitats through which animals could disperse but not settle (e.g. rivers); and those that possums were assumed not to enter (e.g. estuarine open water). The spatial layer was rasterised so that each grid cell was characterised in isolation by the local carrying capacity. Using the Dunedin Habitat Map (Freeman & Buck 2003), we differentiated urban residential habitat into two categories (Residential II and Residential I) and assigned carrying capacities calculated by Patterson (2020). The Residential II and Residential I polygons replaced the LRIS-LCDB-v41's single classification for all urban habitat as 'Built-Up settlement'.

3.1 Assessing the expected abundance of possums under different control layout scenarios

We first simulated the model assuming a closed system, meaning no immigration from outside the south and west of the eradication area (i.e. we assumed a perfect barrier to immigration along SH1 and the Leith Stream). Simulations began with a starting density of 0.4 possums per hectare across the Halo area, which we assumed is equivalent to an RTCI of 2% (Ramsey et al. 2005). This density reflects the control target in the area for the TB control operations presently conducted by OSPRI. Individual possums were randomly located within the Halo area.

The model was simulated using the mean life history and dispersal parameters for possums used in Lustig et al. 2019 (see Table A1, Appendix 1). To investigate the effect of varying the spatial distribution of traps, we explored three trapping scenarios: one device per 18 ha, one per 25 ha and one per 36 ha. The two key animal parameters for this control sub-model are g_0 (the nightly probability of capture for a control device set at the centre of the animal's home range) and σ (the spatial decay parameter for a half normal home-range kernel that describes the decline in detection probability with increasing distance between the home-range centre and a control device) (Efford 2011).

We carried out simulations at two main levels of g_0 and σ to reflect several combinations of low probability of capture and large home range (g_0 = 0.08 and σ = 140 m), and high probability and small home range (g_0 = 0.13 and σ = 100 m) (Table 1). These values correspond to the potential range of values from several field studies (Glen & Byrom 2014) and have been previously used to model possum control operations within the Flagstaff area of the project (Figure 1; Howard 2019). A worst-case combination of animal parameters (i.e. low capture probability and small home range; g_0 = 0.08 and σ = 100) was also modelled.

The home-range parameter (σ) is specific to animals and independent of trap types. However, values of g_0 may differ between trap types, and assigning g_0 values for differing trap types is an active area of research at MWLR. Because g_0 for AT220 multi-kill traps is unknown, we used three different values of g_0 (low, mode and high) for each scenario (see Table 1). The mode values (i.e. the value that is most often used in other research) for g_0 were estimated for leg-hold traps (Glen & Byrom 2014), and the high and low values were chosen arbitrarily.

The duration of control was set to 360 effective control nights per year. We simulated the population for 3 years post-OSPRI control operations and recorded the total number of individuals present each month. Results were averaged over 150 simulations to account for model stochasticity.

Table 1. Combinations of animal parameter values used in simulations to assess the expected abundance of possums under different control layout scenarios

Scenario	Home range parameter (σ)	Trappability (g_0)	Initial possum density inside the Halo area
High trappability, small home range (c. 18 ha)	σ =100 m	g_0 (low) = 0.08 g_0 (mode) = 0.13 g_0 (high) = 0.18	0.4 possums / ha (2% RTCI)
Low trappability, large home range (c. 36 ha)	σ =140 m	g_0 (low) = 0.06 g_0 (mode) = 0.08 g_0 (high) = 0.10	0.4 possums / ha (2% RTCI)
Low trappability, small home range (c. 18 ha)	σ =100 m	g_0 (low) = 0.06 g_0 (mode) = 0.08 g_0 (high) = 0.10	0.4 possums / ha (2% RTCI)

3.2 Effect of immigrants on suppression of possum numbers in the Halo area

Simulations in Section 3.1 assumed a 'closed population' and therefore did not include immigration from outside the Halo area, which, if present, would compromise the effectiveness of any control/eradication programme. To account for immigration, we delineated a buffer area of 12 km (maximum juvenile dispersal distance reported in field studies, Table A1, Appendix 1) around the Halo area (Figure 1), in which the modelled possum population was left undisturbed. This undisturbed population provided immigrants from outside the eradication area (i.e. the population was open rather than closed). We simulated the effect of a semi-permeable barrier to reinvasion along SH1 and Leith Stream, where this barrier was 80%, 95% and 99% effective at preventing dispersing animals from entering the SH1 protected Halo area (Mt Cargill, Inner Halo and Heyward sector). These numbers were chosen based on discussions with the Halo Project and Predator Free Dunedin.

We then investigated how different possum densities outside the perimeter of the Halo area (at carrying capacity and equivalent to 2% and 5% RTCI) might affect suppression of the possum population in the Halo area, with and without a semi-permeable barrier to reinvasion along SH1 and the Leith stream.

Simulations were run with a starting density of 0 and 0.4 possums per hectare in the Halo area (Table 2). We carried out simulations at two levels of g_0 and σ to reflect low probability of capture and large home-range (g_0 = 0.08 and σ = 140 m), and high probability of capture and small home-range (g_0 = 0.13 and σ = 100 m). The duration of control was set to 360 effective control nights per year. We simulated the population and control for 3 years and recorded the total number of individuals present each month. Results were averaged over 100 simulations to account for model stochasticity.

Table 2. Combinations of animal parameter values used in simulations to assess the effect of immigrants on suppression of possum numbers in the Halo area

Scenario	Home range parameter (σ)	Trappability (g_0)	Initial possum density inside the Halo area*	Semi-permeable dispersal barrier along SH1	Possum density surrounding the Halo area
High trappability, small home range (c. 18 ha)	σ =100 m	g_0 = 0.13	0.4 possums / ha (2% RTCI) versus 0 possums / ha (0% RTCI)	Yes (80%, 90%, 99% effective)	At carrying capacity
				Yes (80%, 90%, 99% effective)	Equivalent 2% and 5% RTCI
				No	Equivalent 2% and 5% RTCI
Low trappability, large home range (c. 36 ha)	σ = 140 m	g_0 = 0.08	0.4 possums / ha (2% RTCI) versus 0 possums / ha (0% RTCI)	Yes (80%, 90%, 99% effective)	At carrying capacity
				Yes (80%, 90%, 99% effective)	Equivalent 2% and 5% RTCI
				No	Equivalent 2% and 5% RTCI

* For each combination of semi-permeable fence and possum density surrounding the Halo area, we investigated two initial densities inside the Halo area.

3.3 Assessing both the effects of immigrants and variable trappability on suppression of possum numbers in the Halo area

In the simulations described above, the model assumed that all possums have the same trappability. However, there may be sub-sets of the population that are much harder to capture, thereby making the goal of eradication more difficult. This variable trappability could result in a significant difference between the simulation predictions and reality.

In order to test the influence of this variability on our model predictions we randomly sampled values for σ from Program Evaluation and Review Technique (PERT) distributions (Malcolm et al. 1959). The PERT distribution is a continuous distribution defined by the minimum, most likely and maximum values the variable can take. We fixed the most likely value, σ = 140 m, to enable a comparison with previous analyses. The minimum σ = 90 m and maximum σ = 160 m were determined through a preview of the literature on home ranges and capture probabilities (Glen & Byrom 2014; Glen et al. 2017).

Values of g_0 were randomly sampled from a beta distribution, a continuous probability distribution defined on the interval [0, 1] and parameterised by two positive parameters that regulate the expected values (mode) and variance of the distribution. We fixed the expected value to g_0 = 0.08 to enable a comparison with previous analyses. We investigated four values of variance v = {0.001, 0.01, 0.02 and 0.05} (Table 3), where 0.001

indicates a situation in which each possum has a relatively similar probability of being captured by a control device located at the centre of its home range and 0.05 indicates a situation in which each possum might exhibit a different probability of capture (Figure 2).

Each possum retained the same g_0 and σ values across all trapping sessions. In other words, we assumed these are traits that characterise the behaviour of an animal from birth to death. Both parameters were sampled independently, which meant assuming no covariance between the probability of detection (g_0) and the decline in detection probability with distance between the home-range centre and the control device (σ). By drawing the g_0 and σ parameters from distributions with sufficient variance, we ensured that selected values provided a representative sample of variation across individuals, sexes, and population densities. Capture probabilities of both adults and juveniles were assumed to be independent of habitat categories.

Simulations were run with a starting density of 0 and 0.4 possums per hectare in the Halo area (Table 3). The duration of control was set to 360 effective control nights. We simulated the population for 3 years and recorded the total number of individuals present each month. Results were averaged over 150 simulations to account for model stochasticity.

Table 3. Combination of animal parameter values used in simulations to assess the effect of variable trappability on predicted eradication outcomes

Scenario	Home range parameter (σ)	Trappability (g0)	Initial possum density inside the Halo area*	Semi-permeable fence along SH1	Possum density surrounding the Halo area
Low trappability, large home range (c. 36 ha)	σ_{min} = 90 m σ_{mode} = 140 m σ_{max} = 160 m	g_0 = 0.08 and variance {0.001, 0.01, 0.02 and 0.05}	0.4 possums / ha (2% RTCI) versus 0 possums / ha (0% RTCI)	No	At carrying capacity
				No	Equivalent 2% and 5% RTCI

***** For each combination of semi-permeable dispersal barrier and possum density surrounding the Halo area, we investigated two initial densities inside the Halo area.

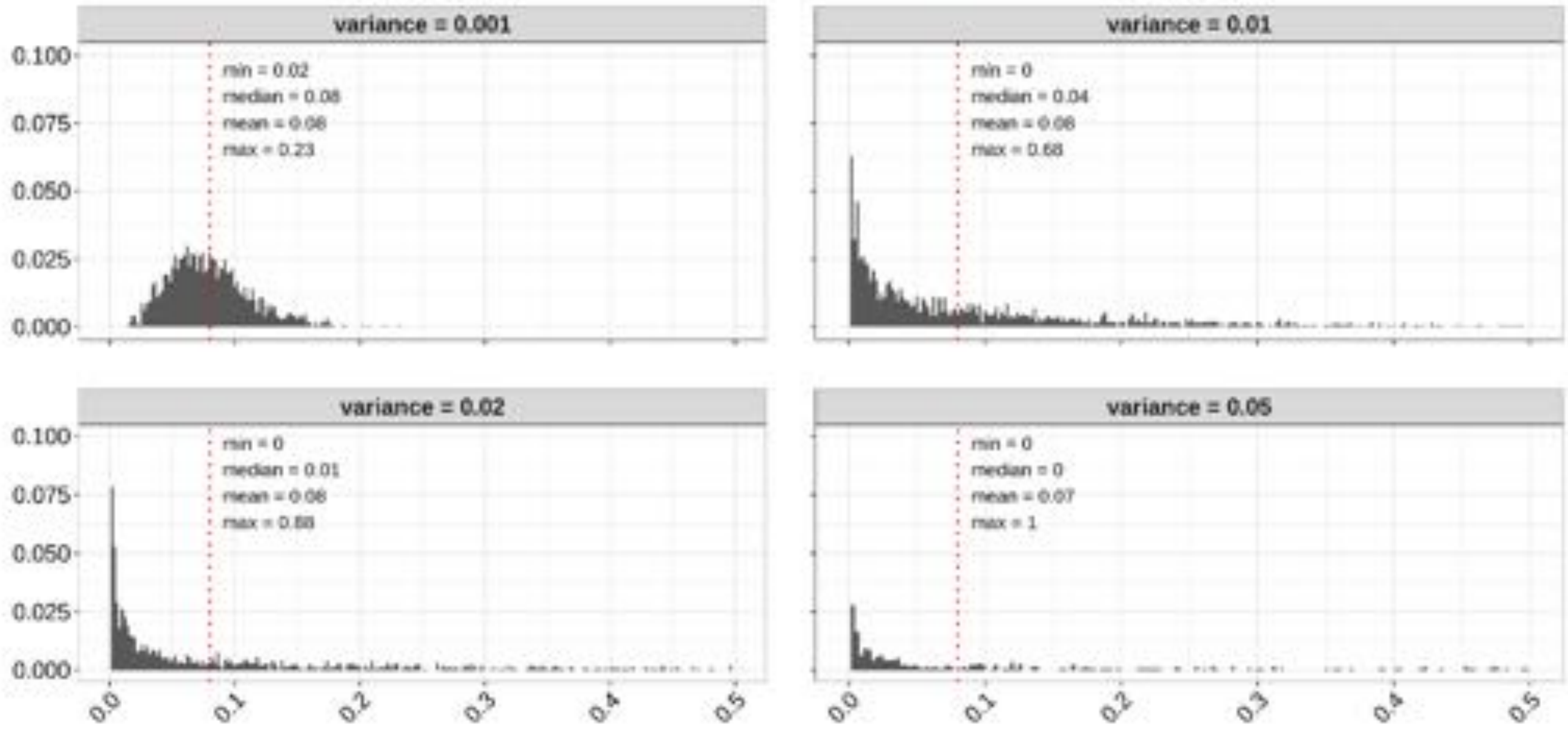

Figure 2. Initial distribution (frequency) of the probability of capture g_0 ('trappability') for different levels of variability. g_0 was sampled from a beta distribution for which we fixed the mean to 0.08 and investigated the effect of changing the variance of the distribution. The dotted red line indicates the mean of the distribution (fixed to g_0 = 0.08). The variance of the distribution varies between 0.001 (i.e. all animals have a relatively similar level of trappability) to 0.05 (i.e. there is large variation in trappability between animals).

4 Results

4.1 Predicted possum density under different control scenarios

In a closed system (meaning no immigration from outside the south and west of the eradication area), the model predicted markedly lower possum density across the Halo area (Flagstaff, Mt Cargill, Inner Halo and Heyward sectors) as a result of the three proposed spatial control strategies (Figure 3). Eradication was unlikely under any of the investigated control scenarios, but the number of remaining animals was nevertheless very low (Figure 3). It is important to note that no control devices were modelled to the south of the targeted area (Figure 1 – uncontrolled sector). In this area, the modelled possum population was left undisturbed, creating a possum population protected from control (Figure 4), and a source of immigrants to the Flagstaff, Mt Cargill, Inner Halo and Heyward sectors.

As expected, the predicted effectiveness of possum control declined with increasing trap spacing. Trapping scenarios with the lowest trap density (i.e. one device per 36 ha) could maintain possum density under 0.25 possums per ha (1.25% RTCI equivalent) in 95% of the simulations (Figure 3 – blue lines). However the population did not reach a stable state, suggesting that density could keep increasing for a few years before stabilising under such control scenarios. Trapping scenarios with a higher trap density (i.e. one device per 18 ha (Figure 3 – red lines) or one device per 25 ha (Figure 3 – green lines), could maintain possum density under 0.04 possums per ha (c. 0.2% RTCI equivalent) and 0.06 possums per ha (c. 0.3% RTCI equivalent), respectively.

These conclusions hold for all animal parameter scenarios, in particular for the more realistic animal parameter combinations (high trappability, small home range g_0 = 0.13, σ = 100; and low trappability, large home range g_0 = 0.08, σ = 140) and expected densities within the Halo area were similar irrespective of g_0 and σ.

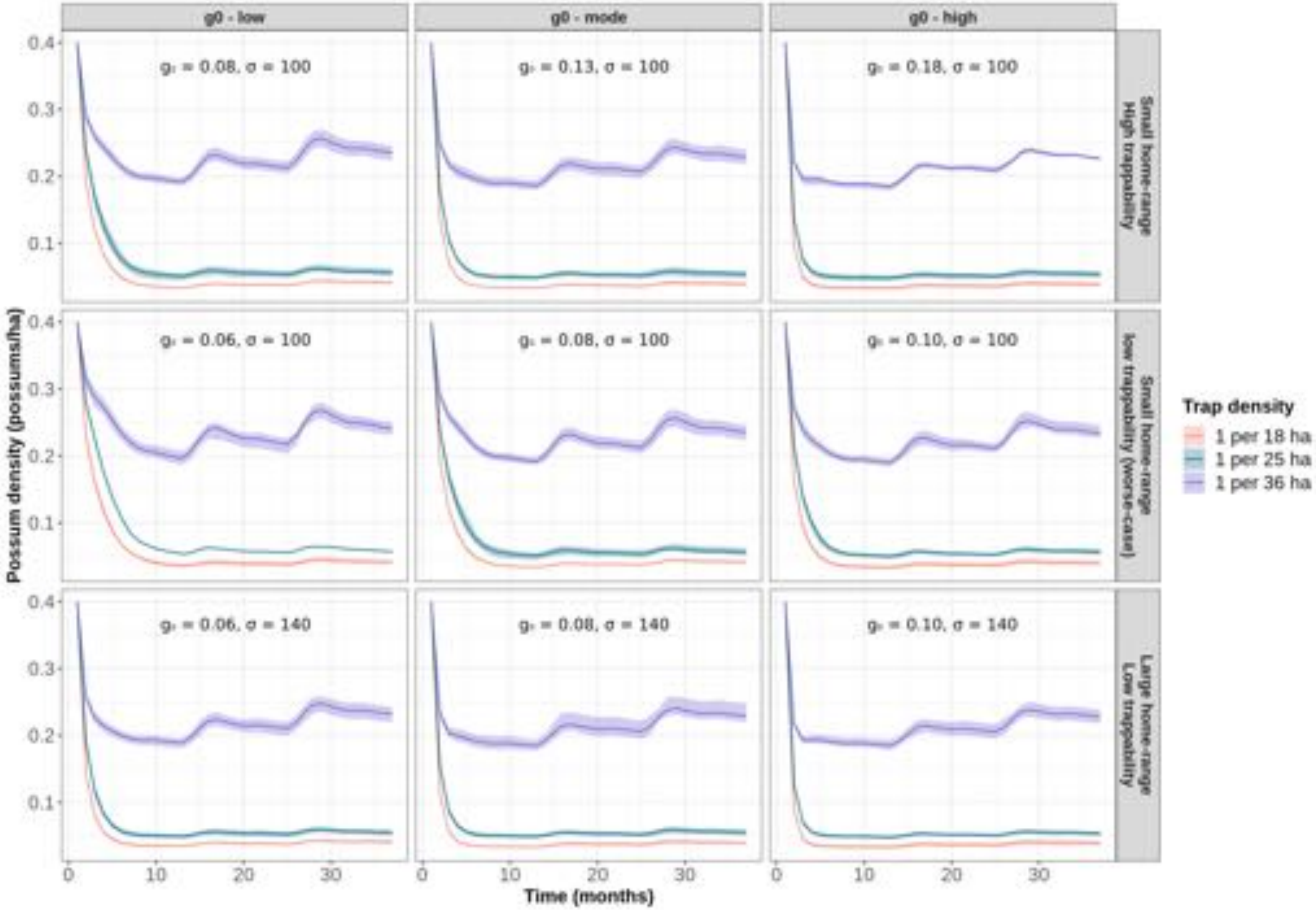

Figure 3. Modelled possum density over time in control area (Mt Cargill, Inner Halo and Heyward sectors). Outcomes of three control scenarios are displayed: one device per 18 ha (red), one device per 25 ha (green), and one device per 36 ha (blue). Panels are shown for each of three scenarios (combinations of g_0 and σ; rows) and variation in g_0 values within each scenario (columns). Corresponding values for g_0 and σ can be found in Table 1. Lines and confidence bands represent the mean and 95% quantiles across all simulations.

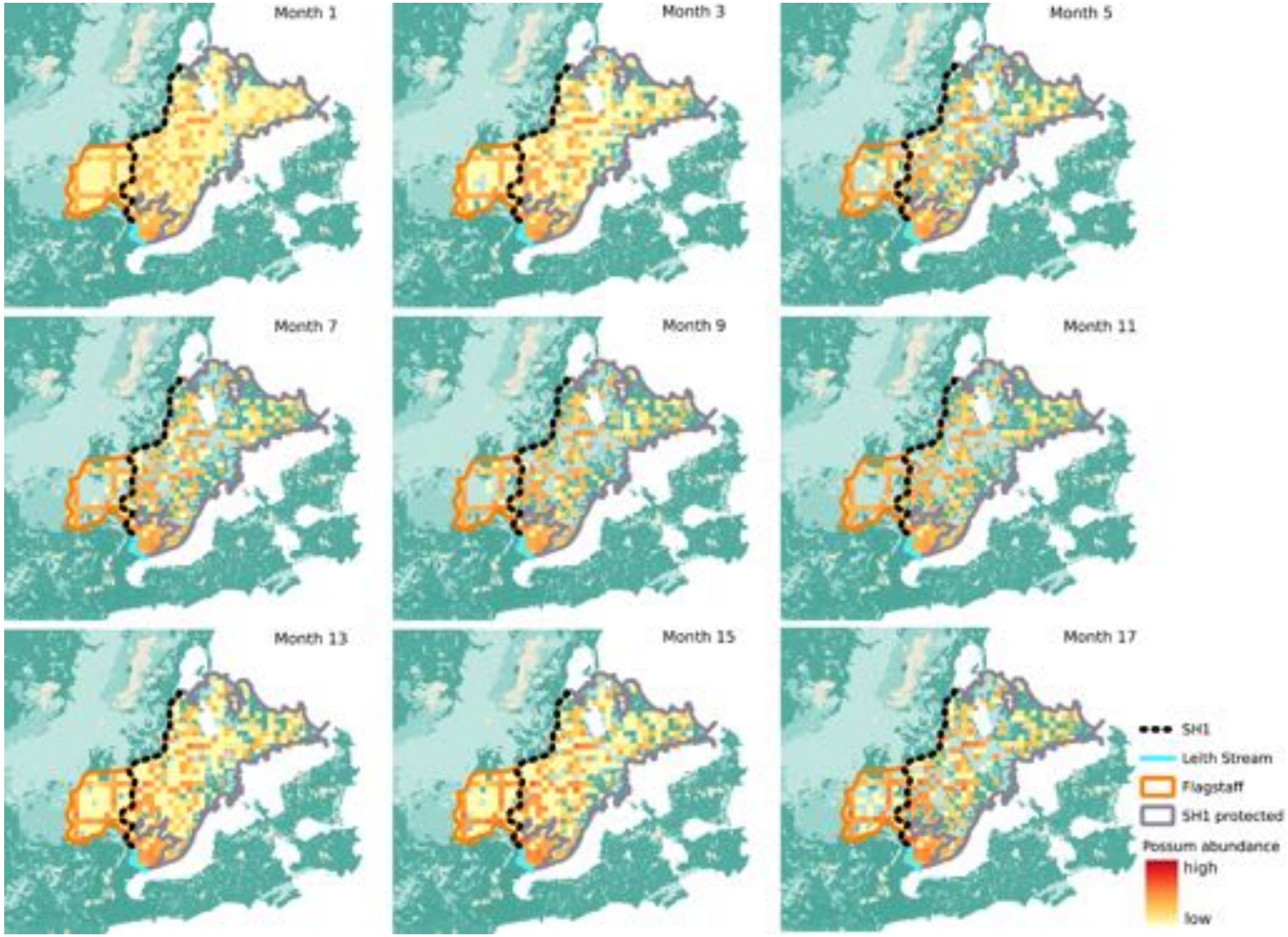

Figure 4. Modelled possum density in the Halo control area. Results are shown for simulations in which control devices were deployed at one device per 36 ha (the Halo Project's presently proposed layout) and are averaged over 150 simulations. The gradient of colours from yellow to red indicates the predicted number of possums (the initial distribution at month 1 was fixed at 0.4 possums per ha across the entire control area). The resurgence at month 13 follows a breeding event. g_0 and σ values were chosen to reflect low probability of capture and large home range ($g_{0\ mode}$ = 0.08 and σ = 140 m).

4.2 Effect of immigrants on possum numbers in the Halo area

The density of control devices inside the Halo area had a larger effect on possum density than the effectiveness of the semi-permeable dispersal barrier along SH1 (Figure 5). Outcome success declined with increasing trap spacing. Trapping scenarios with the lowest trap density (i.e. one device per 36 ha) could maintain possum density under 0.3 possums per ha (1.5% RTCI equivalent) in 95% of the simulations (Figure 5 – blue lines). However, the population did not stabilise, suggesting that the density could keep increasing for a few years before stabilising under such control scenarios. Trapping scenarios with a higher trap density (i.e. one device per 18 ha, Figure 5 – red lines; or one device per 25 ha, Figure 5 – green line) could maintain possums at a much lower density (below 0.06 possums per ha, or 0.3% RTCI equivalent).

A semi-permeable dispersal barrier along SH1 had minimal effect on reducing the population size within the Halo control area (Mt Cargill, Inner Halo and Heyward sectors), as modelled possum density with and without a dispersal barrier followed the same trends (Figure 5). The simulations illustrated in Figures 6 and 7 also suggest that possum density can be maintained at a low density within the Flagstaff area using a control network of one device per 25 ha, despite the area not being protected by a semi-permeable dispersal barrier along SH1.

The model showed that possum density outside the perimeter of the Halo area is likely to have a small effect on the final density within the Halo area. Intuitively, reducing possum density in areas surrounding the Halo control area would further reduce possum density inside the control area. However, the levels of reduction required in areas surrounding the Halo control area should typically aim for <2% RTCI to support a clear decrease in possum density within the control area (Mt Cargill, Inner Halo and Heyward sectors) (Figure 5). This effect was more apparent when the RTCI inside the Halo area was 0. A re-scaled image of scenarios with one device per 18 ha and one device per 25 ha is shown in Appendix 2, Figure A2.

These conclusions hold for all animal parameters, in particular for the most realistic parameter combinations (high trappability, small home range g_0 = 0.13, σ = 100 – Figure 5; and low trappability, large home range g_0 = 0.08, σ = 140 – Appendix 3, Figure A3).

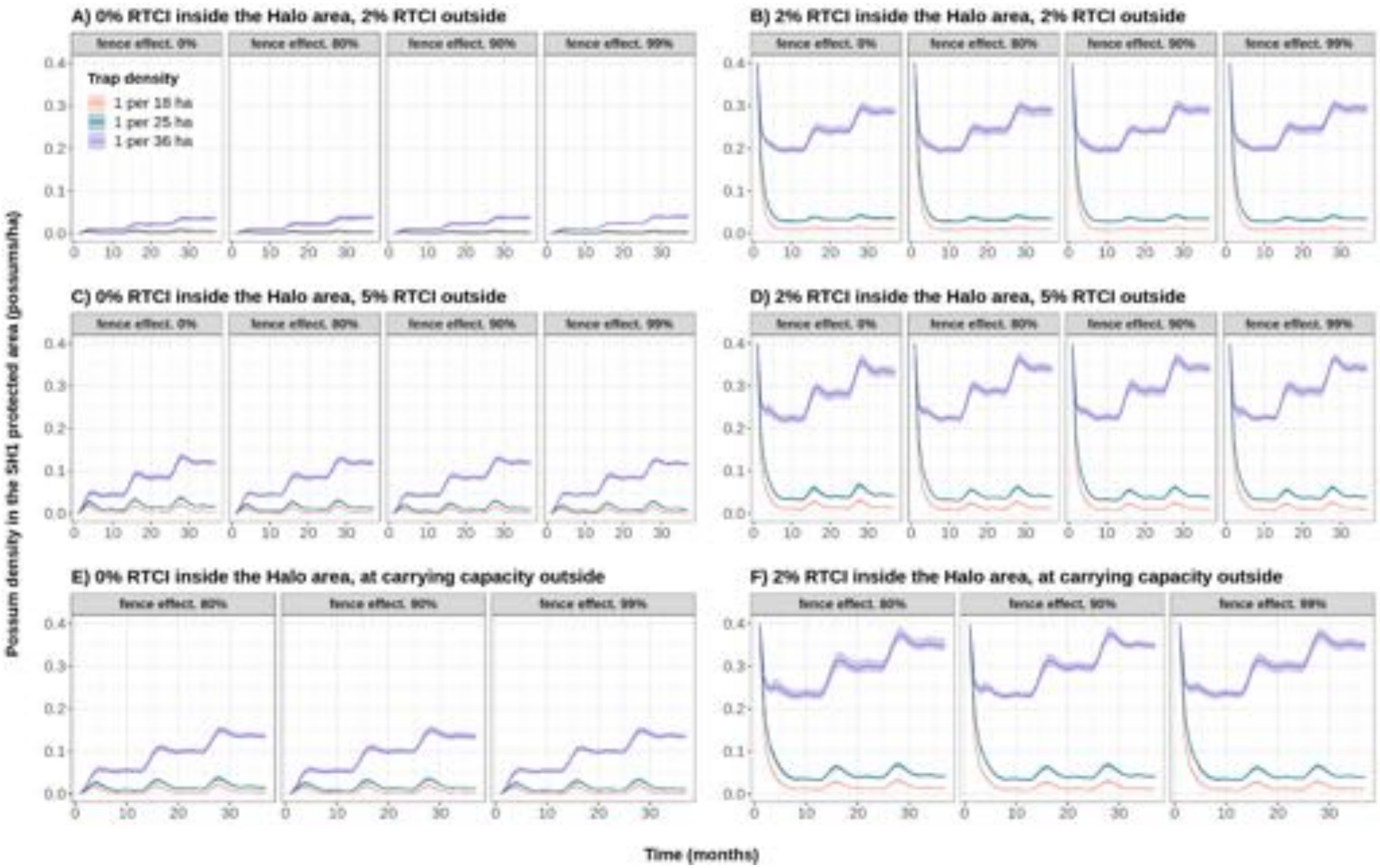

Figure 5. Modelled possum density over time in the SH1 protected area (Mt Cargill, Inner Halo and Heyward sectors). Outcomes of three control scenarios are displayed: one device per 18 ha (red), one device per 25 ha (green), and one device per 36 ha (blue). The left column (A, C, E) represents scenarios for which the initial density in the SH1 protected area was set to 0, and the right column (B, D, F) represents scenarios for which the initial density was set to 0.4 (2% RTCI). The first row (A, B) represents scenarios for which the possum density surrounding the Halo area was fixed at 2% RTCI, the second row (C, D) represents scenarios for which the possum density surrounding the Halo area was fixed at 5% RTCI, and the third row (D, E) represents scenarios for which the possum density surrounding the Halo area was fixed at carrying capacity. Panels are shown for different semi-permeability of a dispersal barrier along the SH1: 0% (no dispersal barrier), 80%, 95% and 99% effective at preventing immigration. g_0 and σ values were chosen to reflect a low probability of capture and large home range ($g_{0\ mode}$ = 0.08 and σ = 140 m).

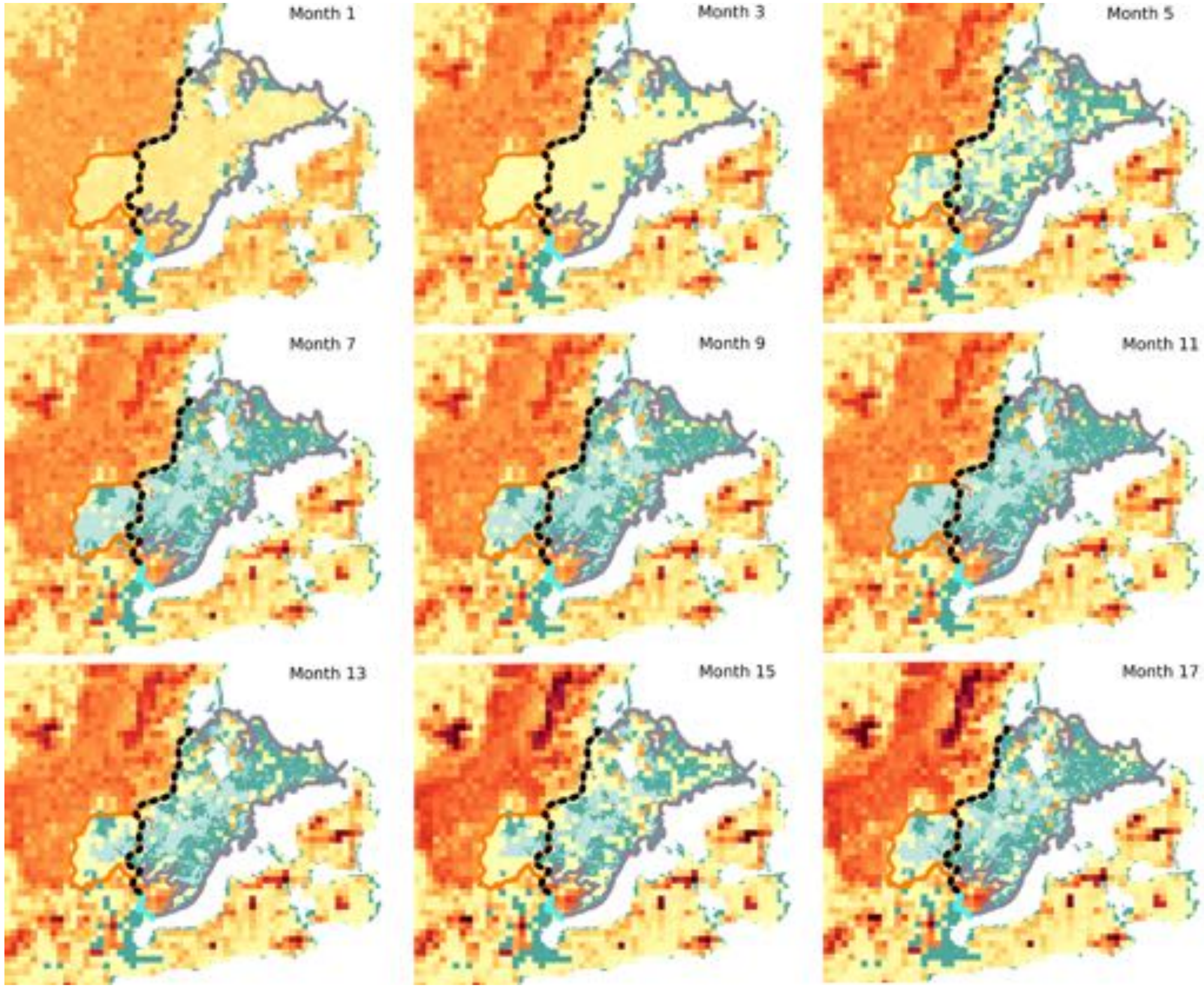

Figure 6. Predicted mean number of possums in the Halo control area and surrounding area in the *absence* of a semi-permeable dispersal barrier. The results are averaged over 100 simulations. The gradient of colours from yellow to red indicates the predicted number of possums. The initial distribution in the Halo control area was fixed at 0.4 possums per ha (i.e. c. 2% RTCI) and an overall 5% RTCI outside. Results are shown for simulations in which

control devices were deployed at one device per 25 ha. g_0 and σ values were chosen to reflect a low probability of capture and large home range ($g_{0\ mode}$ = 0.08 and σ = 140 m).

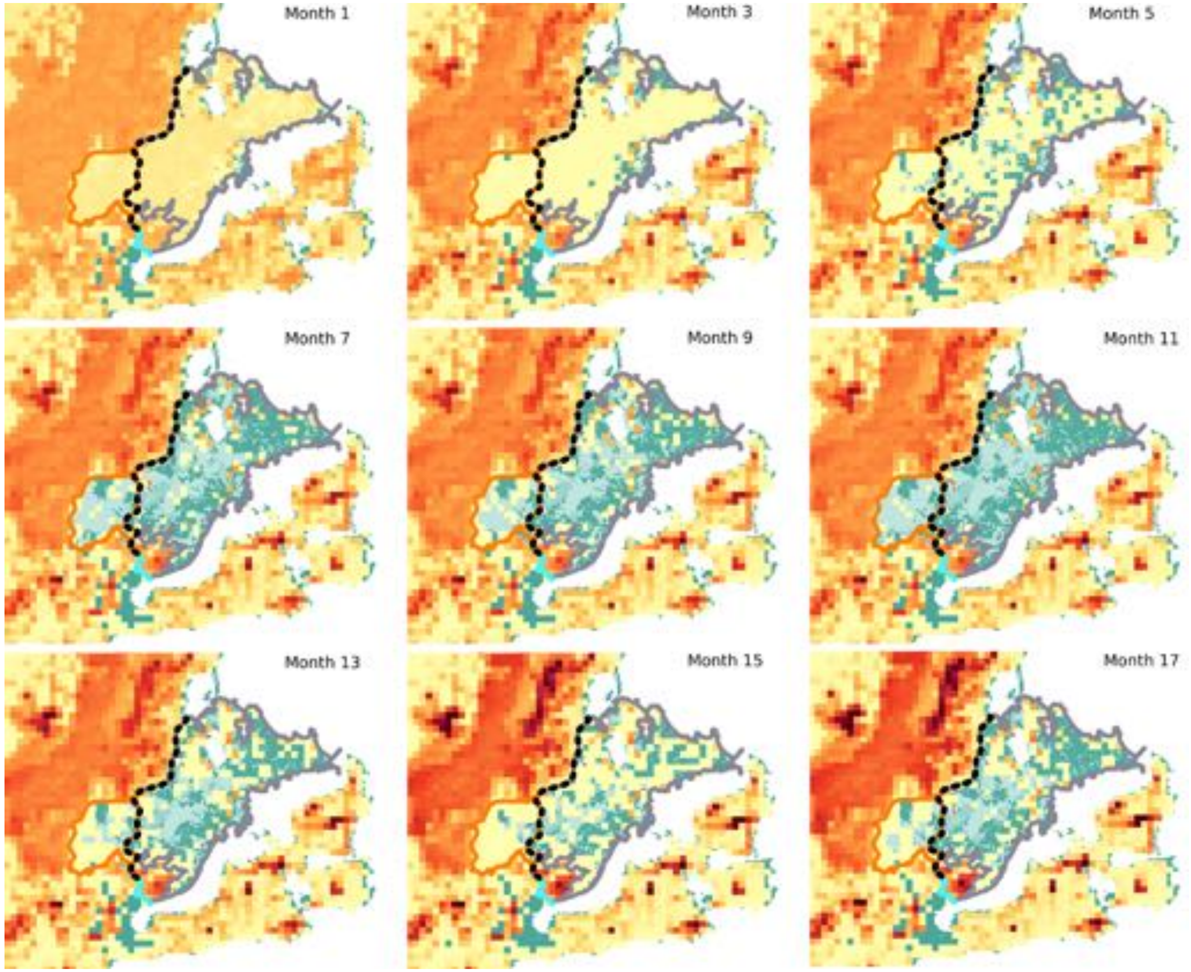

Figure 7. Predicted mean number of possums in the Halo control area and surrounding area in the *presence* of a semi-permeable dispersal barrier 90% effective at preventing dispersing animals from invading the Halo. The results are averaged over 100 simulations. The gradient of colours from yellow to

red indicates the predicted number of possums. The initial distribution in the Halo control area was fixed at 0.4 possums per ha; i.e. c. 2% RTCI and 5% RTCI outside. Results are shown for simulations in which control devices were deployed at one device per 25 ha. g_0 and σ values were chosen to reflect a low probability of capture and large home range ($g_{0\ mode}$ = 0.08 and σ = 140 m).

4.3 Effect of variable trappability on predicted control outcomes

The model showed that a relatively small but consistent variation between possums in trappability (variance ≤ 0.01) (Figure 2) is unlikely to affect control outcomes (Figure 8). Under the assumption of small variation in trappability, a surveillance network at one device per 18 ha (Figure 8 – red lines) or one device per 25 ha (Figure 8 – green lines) could maintain possum density under 0.3 possums per ha (1.5% RTCI equivalent).

However, if the population exhibits larger variation in individual trappability (variance > 0.01), the simulations suggested that it would be unlikely that possum density inside the Halo would be maintained below 0.4 possums per ha (2% RTCI equivalent) because a substantial proportion of the population is not trappable. This was particularly apparent when RTCI inside the Halo area was 2%. Trapping scenarios starting with a 0% RTCI inside the Halo area could maintain possum density under 0.4 possums per ha (2% RTCI equivalent) in 95% of the simulations (Figure 8 – blue lines). However, the population did not stabilise, suggesting that the density could keep increasing for a few years before stabilising under such scenarios.

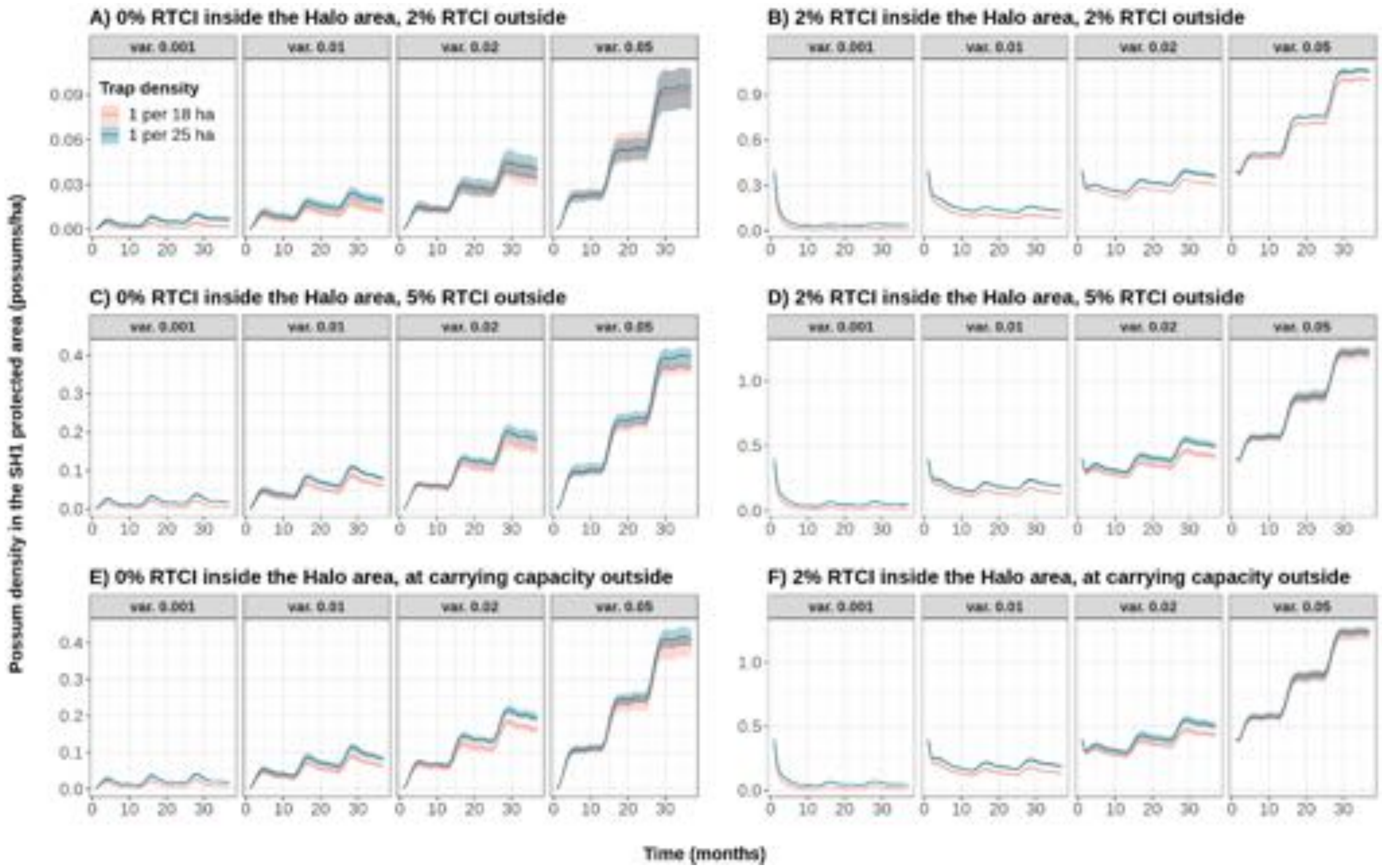

Figure 8. Modelled possum density over time in the SH1 protected area (Mt Cargill, Inner Halo and Heyward sectors). Outcomes of two control scenarios are displayed: one device per 18 ha (red) and one device per 25 ha (green). The left column (A, C, E) represents scenarios for which the initial density in the SH1 protected area was set to 0, and the right column (B, D, F) represents scenarios for which the initial density was set to 0.4 (2% RTCI). The first row (A, B) represents scenarios for which the possum density surrounding the Halo area was fixed at 2% RTCI, the second row (C, D) represents scenarios for which the possum density surrounding the Halo area was fixed at 5% RTCI, and the third row (D, E) represents scenarios for which the possum density surrounding the Halo area was fixed at carrying capacity. Panels are shown for different levels of variability in the probability of capture g_0, from a relatively homogeneous population (variance = 0.001) to a highly heterogeneous population (variance = 0.05). Mean g_0 and σ values were chosen to reflect a low probability of capture and large home range ($g_{0\ mode}$ = 0.08 and σ = 140 m). Please note that the panels have different y-axis scales.

5 Discussion

The model simulations suggested that a low-density control network of one automatic multi-capture trap per 25 ha or one multi-capture trap per 18 ha could maintain and further reduce possum population density to a low level (<2% RTCI) within the Halo control area (Flagstaff, Mt Cargill, Inner Halo and Heyward sectors) if all possums had a similar probability of capture.

While the model predicted markedly lower possum density across the entire Halo area using any of the three spatial control strategies, possum eradication was unlikely. Some population recovery is expected to occur within the Halo control area due to breeding and immigration from the surrounding uncontrolled area. It is important to note that no control devices were modelled to the south of the Halo area (Figure 1 – uncontrolled area). In this area, the modelled possum population was left undisturbed, creating a source of immigrants to the Flagstaff, Inner Halo and Mt Cargill sectors. The number of animals remaining within the Halo control area was nevertheless very low, with a control grid of one device per 25 ha or one device per 18 ha. For coarse control grids (one device per 36 ha), simulations showed that possum recovery exceeded population reductions, resulting in net population increases over an annual cycle. It is therefore not recommended to use a control grid of one device per 36 ha for maintaining the Halo possum population at an RTCI target of 2% or below.

It has been suggested that intensive control along SH1 (i.e. a "semi-permeable dispersal barrier") could compliment the effectiveness of control in the interior of the Halo area by reducing immigration from surrounding uncontrolled areas. However, the model predicted that such a barrier would have minimal effect on reducing possum numbers within the Halo area. One possible explanation is that a low-density control network of one device per 18 ha or one device per 25 ha is sufficient to mitigate immigration into the targeted area. Similar effects were observed in a simulation model for the Cape to City control area in Hawke's Bay (Lustig et al. 2019). In particular, simulations showed that using a buffer zone of high-density control at the periphery of the Cape to City control area could limit immigration to the control area, provided the buffer was larger than the average possum dispersal distance. However, a buffer zone of high-density control was less effective at reducing the long-term population size than homogeneously distributed trapping inside the control area (Lustig et al. 2019).

The density of possums in areas surrounding the Halo project had a significant effect on possum recovery within the Halo control area, but this could be managed using a control network of one deviceper 18 ha or one device per 25 ha within the Halo area. Overall, reducing possum density in areas surrounding the Halo area or using a semi-permeable dispersal barrier to prevent immigration from those areas both had little predicted effect on maintaining possum populations within the Halo area at a low density. However, a transition from sustained possum control at low density, to achieving elimination of possums from the Halo area, would benefit from prioritising control in areas surrounding the Halo project over the use of a semi-permeable dispersal barrier along SH1. Indeed, the simulations showed that reducing possum density in those surrounding areas to an equivalent of 2% RTCI or below could prolong treatment persistence in the interior of the

Halo control area (Figure 5). This effect was more apparent when starting from a initial zero density.

The validity of any model rests on its assumptions. Possum density at the edge of the Halo area and dispersal are the two factors that are likely to have the greatest impacts on the level of reinvasion. However, dispersal is challenging to model because of the difficulty of gathering the empirical data needed to inform model parameters, particularly for juveniles. For example, we did not take account of possible stochastic effects on dispersal that might result from events such as variations in food availability. Consequently, it is likely that the model does not generate the possible range of immigrant possum densities observed empirically. Nevertheless, the model is still useful in predicting possible spatial patterns of reinvasion.

The degree of individual variation in the trappability parameters g_0 and σ is particularly important when estimating the trapping effort needed to maintain the Halo possum population at an RTCI target of 2% or below. Empirical studies suggest that the probability of capture is more sensitive to changes in σ than g_0 (D. Anderson, MWLR, pers. comm.). σ varies with possum density, and g_0 varies with σ. Patterns of movement by possums from analysis of GPS data across multiple habitats showed that there is considerable variability in σ across possums in a population (D. Anderson & C. Arienti, MWLR, pers. comms.), which results in substantial variations in g_0. The simulated range of values for g_0 (and σ) in this study spanned the possible range of observed values (D. Anderson, MWLR, pers. comm.), but we do not know the degree to which trappability varies between possums in the Halo area.

Priority should be given to validating these parameters since they form the basis for all subsequent analyses. In particular, the results of the model confirmed that it can be disproportionally difficult to control a population of possums that exhibit a high level of variability in the probability of detection/capture between individuals. Control that relies on possum investigation and contact with a control device may fail to sample individuals that are less active or too wary to approach the control device (low g_0).

6 Conclusions and recommendations

- A low-density control network of one automatic multi-capture trap per 25 ha or one multi-capture trap per 18 ha could maintain and further reduce possum population density to a low level (<2% RTCI) within the Halo control area if all possums have a similar probability of capture. It is, however, not recommended to use a control grid of one device per 36 ha for maintaining the Halo possum population at an RTCI target of 2% or below.
- Reinvasion is likely to become significant a year after OSPRI’s departure from the Halo area, but the level of immigration can be mitigated by a control network of one device per 25 ha or one device per 18 ha within the Halo area.
- The simulated use of a semi-permeable dispersal barrier along SH1 had minimal effect on reducing the possum population size within the Halo control area. A transition from sustained possum control at low density to achieving elimination of possums from the Halo area would benefit from prioritising control in areas surrounding the Halo project over the use of a semi-permeable dispersal barrier along SH1.

- Small levels of inter-individual variation in the detection/capture probability can substantially hinder the efficacy of the management scenarios tested. Control that relies upon possum investigation and contact with a control device may fail to sample individuals that are less active or too wary to approach the device (low g_0). Priority should be given to validating trappability parameters. Active control methods (such as shooting) may be particularly useful to target the last survivors with a low trappability.

7 Acknowledgements

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Appendix 1 – Model parameterisation

We used the most recent field-based estimates to calibrate life-history and control parameters. Values are reported in Table A1 and were extracted from Lustig et al. 2019. The probability that an adult in the grid cell *(x,y)* was captured within *k* nights of trapping was expressed as:

$$P_{adult} = 1 - e^{-2\pi g_0 \sigma^2 k \rho_{(x,y)}}$$

where g_0 is the probability of capture by a trap placed at the centre of the animal's home range, σ is the spatial decay parameter for a normal home-range kernel to model decline in encounter probability with distance between the home range centre and trap, and ρ is the density of traps (i.e. traps per unit area) in the grid cell.

Dispersing juveniles had a probability of being trapped in each grid cell they travelled through during the dispersal phase, which was expressed as:

$$P_{juveniles\ (x,y)} = 1 - e^{-A g_1 \rho_{(x,y)}}$$

where g_1 is the probability of a juvenile being captured by a trap, and A is the area covered by a dispersing juvenile as it passes through one grid cell. More specifically, we assume that juveniles encounter a trap if it is within a distance *W* of the animal's path. Therefore, the area A covered by a juvenile was given by:

$$A = VW\partial t, \text{ with } \partial t = \frac{Rt_{max}}{d_{max}}$$

where *R* is the spatial resolution, *V* the mean velocity of a juvenile during dispersal, d_{max} the maximal dispersal distance, and t_{max} the maximal time of dispersal. More details about trapping probability are given in Lustig et al. 2019.

Table A1. Animal and trappability parameter values (source: Lustig et al. 2019)

Parameter	Abbreviation	Value	
Spatial parameters			
Spatial resolution	R	500 m	
Life history parameters			
Life expectancy	l	12 years	
Reproduction rate	r	0.77 (0.51–1.05) / year	
Maximum dispersal distance	d_{max}	12,000 m	
Control parameters (two columns correspond to two scenarios)			
Probability of capture of an adult	g_0	0.08	0.13
Spatial decay parameter	σ	140 m	90 m
Probability of capture of a juvenile	g_1	0.08	0.13
Area covered by a dispersing juvenile per grid cell	A	0.037 ha	0.037 ha

Appendix 2 – Modelling possum abundance under different control scenarios

We first simulated the model assuming a closed system, meaning no immigration from outside the south and west of the eradication area (i.e. we assumed a perfect barrier to immigration along SH1 and Leith Stream). Simulations were run with a starting possum density of 0.4 possums per hectare across the Halo area, equivalent to an RTCI of 2% (Ramsey et al. 2005). This density reflects the control targets in the area for the preceding TB control operations conducted by OSPRI. Individual possums were randomly located within the Halo area.

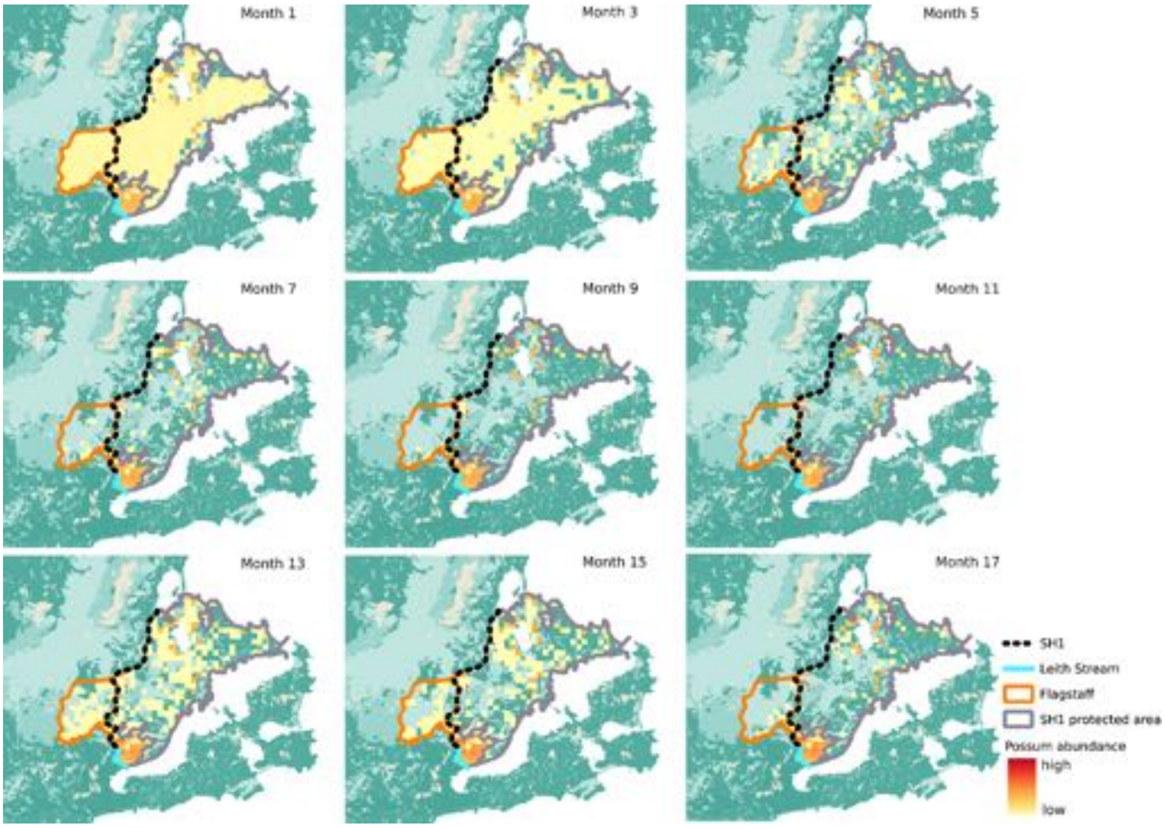

Figure A1. Modelled possums density in the Halo control area. Results are shown for simulations in which control devices were deployed at one device per 25 ha (proposed layout). The gradient of colours from yellow to red indicates the predicted number of possums at different times (the initial distribution at month was fixed at 0.4 possums per ha across the entire control area). g_0 and σ values were chosen to reflect a low probability of capture and large home range ($g_{0\ mode}$ = 0.08 and σ = 140 m).

Appendix 3 – Effect of immigration on suppression of possum numbers in the Halo area

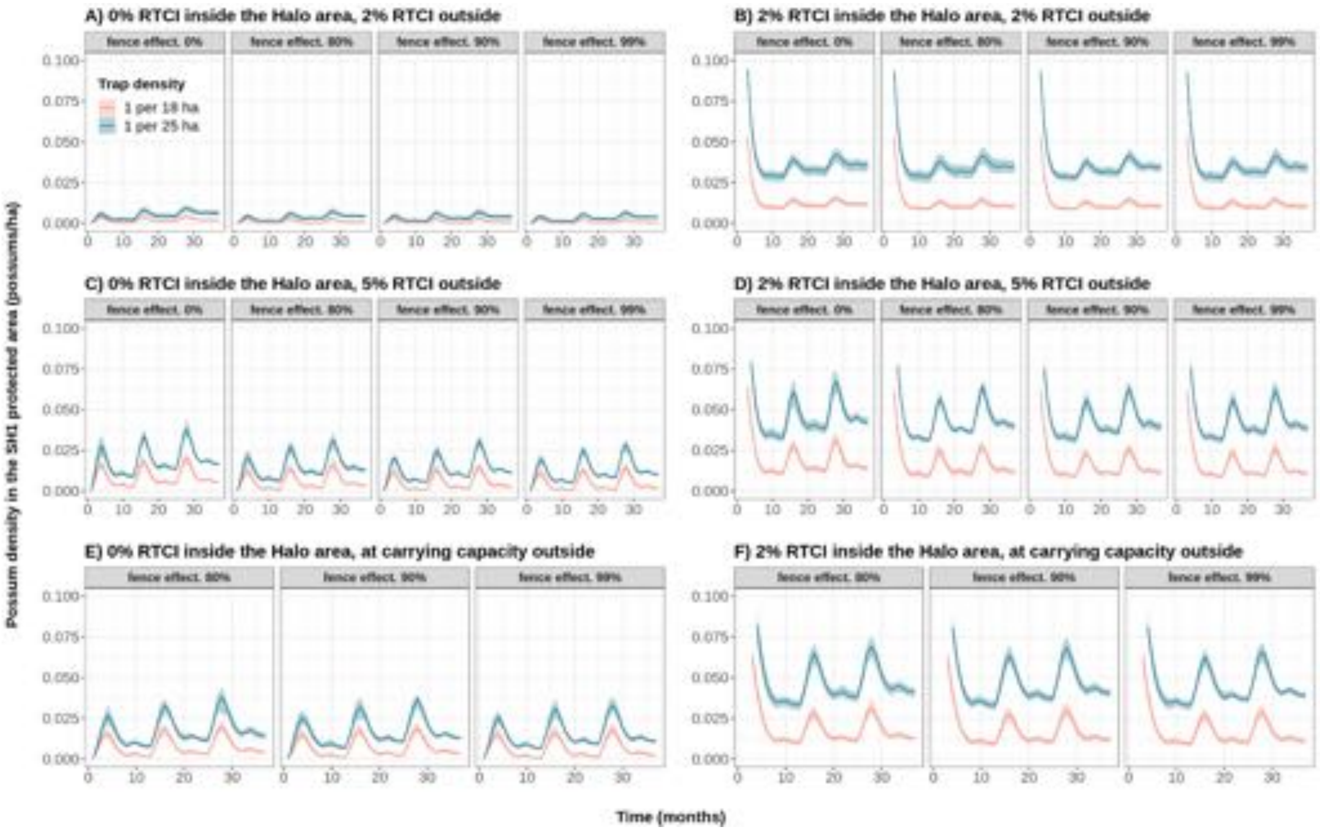

Figure A2. Modelled possum density over time in the SH1 protected area (Mt Cargill, Inner Halo and Heyward sectors). Outcomes of wo control scenarios are displayed: one device per 18 ha (red) and one device per 25 ha (green). The left column (A, C, E) represents scenarios for which the initial density in the SH1 protected area was set to 0, and the right column (B, D, E) represents scenarios for which the initial density was set to 0.4 (2% RTCI). The first row (A, B) represents scenarios for which the possum density surrounding the Halo area was fixed at 2% RTCI, the second row (C, D) represents scenarios for which the possum density surrounding the Halo area was fixed at 5% RTCI, and the third row (D, E) represents scenarios for which the possum density surrounding the Halo area was fixed at carrying capacity. Panels are shown for different semi-permeability of a dispersal barrier along the SH1; i.e. for a dispersal barrier 0% (no dispersal barrier), 80%, 95% and 99% effective at preventing reinvasion.

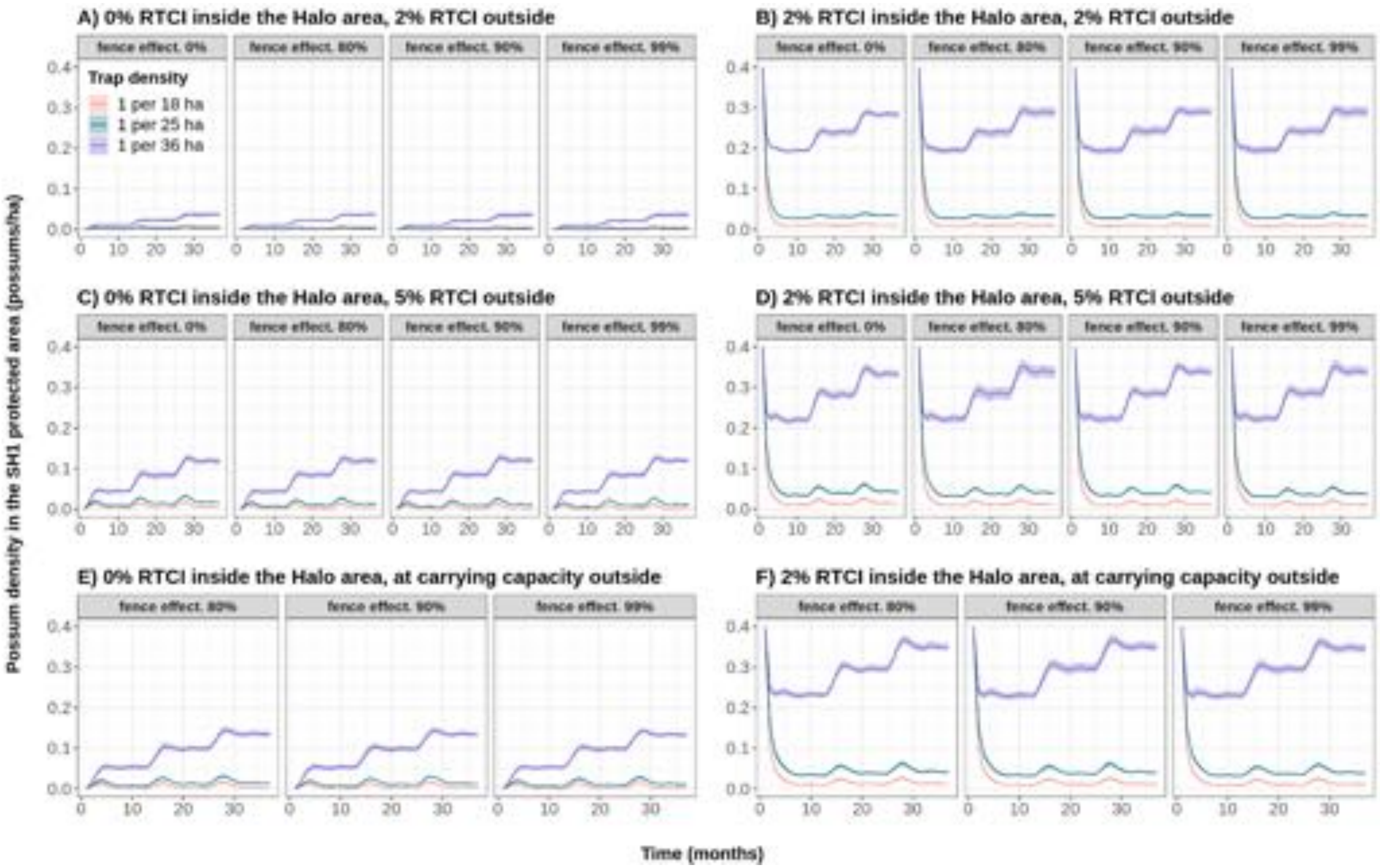

Figure A3. Modelled possum density over time in the SH1 protected area (Mt Cargill, Inner Halo and Heyward sectors). Outcomes of three control scenarios are displayed: one device per 18 ha (red), one device per 25 ha (green), and one device per 36 ha (blue). The left column (A, C, E) represents scenarios for which the initial density in the SH1 protected area was set at 0, and the right column (B, D, E) represents scenarios for which the initial density was set at 0.4 (2% RTCI). The first row (A, B) represents scenarios for which the possum density surrounding the Halo area was fixed at 2% RTCI, the second row (C, D) represents scenarios for which the possum density surrounding the Halo area was fixed at 5% RTCI, and the third row (D, E) represents scenarios for which the possum density surrounding the Halo area was fixed at carrying capacity. Panels are shown for different semi-permeability of a dispersal barrier along SH1; i.e. for a dispersal barrier 0% (no dispersal barrier), 80%, 95% and 99% effective at preventing reinvasion. g_0 and σ values were chosen to reflect a high probability of capture and small home range ($g_{0\ mode}$ = 0.13 and σ = 100 m).