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Landcare Research

Comparative detection probabilities, surveillance sensitivity and costs of four survey methods for managing invasive Bennett's wallaby in South Island, New Zealand

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Sustainable Farming Fund Project 405254 - Preventing the impacts and costs of wallaby range expansion

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1 Abstract

Invasive mammalian herbivores can have significant unwanted impacts on native vegetation and pastoral land. Bennett's wallaby (*Notamacropus rufogriseus*) were introduced into the South Island, New Zealand, in 1874. They have subsequently spread from their point of release and currently cause widespread damage to native vegetation, seedlings in exotic plantation forests, and pasture.

The council tasked with managing Bennett's wallabies aims to confine this pest to a delineated containment area. However, Bennett's wallaby have escaped this area and have established known or suspected new breeding populations in previously unoccupied areas which requires animals in these populations to be detected and removed. Critical to the success of operations that aim to eradicate outlying populations of a pest is confirming where they are and deciding when local eradication has been achieved so that control within the target area can be stopped.

Here, we determined the detection probabilities and derived surveillance system sensitivity of two methods that have traditionally been used for surveying Bennett's wallabies – helicopter surveys with observers and a ground hunter with detector dogs – and compared these results with those yielded from two novel methods – camera traps and helicopter surveys using a thermal imaging camera. We also estimated the cost of surveillance for each method.

Our results show that camera traps and ground hunters with dogs have the highest detection probabilities, surveillance sensitivities (under standardised search conditions) and cost-effectiveness. However, although these methods are useful for surveying small areas (c. 1,000 ha or less), capacity and time issues are likely to make it impractical for ground hunters with dogs to survey large areas (c. 10,000 ha or more). The helicopter-based methods that we assessed will be important for monitoring these larger areas.

Our detection parameter estimates can be applied during future surveillance following wallaby eradication attempts to determine when there has been sufficient surveillance to confidently declare wallabies are absent from an area.

2 Introduction

Invasive mammalian herbivores can have significant unwanted impacts on native vegetation and pastoral land (Hone 2007; Forsyth et al. 2015; Latham et al. 2017). In New Zealand, Bennett's wallabies (*Notamacropus rufogriseus*) were liberated in South Canterbury, South Island, in 1874, and dama (or tammar) wallabies (*N. eugenii*) in Bay of Plenty, North Island, in 1912 (Warburton 2005a, b). These species can negatively affect vegetation in native shrublands and forest, damage seedlings in exotic plantation forests, and graze and foul pasture (Warburton 2005a, b). Their impacts are predicted to become more widespread as they continue to expand their geographical ranges (Latham et al. 2019). Therefore, halting or reversing their geographical spread has become a priority for conservationists, affected landowners and management agencies (Latham et al. 2019).

Such containment can be a significant challenge for agencies tasked with managing pests with small distributions (c. tens of square kilometres), let alone pests such as wallabies that occupy many hundreds or even thousands of square kilometres (Russell et al. 2015).

Agencies tasked with managing Bennett's and dama wallabies in New Zealand have delineated containment areas that use natural boundaries, such as large rivers and mountain ranges, to prevent or limit the spread of wallabies to outside areas. However, both species have now escaped their respective containment areas and have established known or suspected new breeding populations in previously unoccupied areas (Latham et al. 2019).

Critical to the success of operations that aim to eradicate outlying populations of a pest is confirming where they are (which can be challenging if they occur at low densities; MacKenzie et al. 2005) and deciding when local eradication has been achieved so that control within the target area can be stopped (Ramsey et al. 2009, 2011; Anderson et al. 2013; Samaniego-Herrera et al. 2013). The problem is that absence of evidence of the pest does not necessarily indicate absence of the pest, especially when little survey effort has been made to collect evidence (Anderson et al. 2013). A cost-effective eradication programme should stop control efforts as soon as the pest has been eradicated, and should continue subsequent surveillance to build up confidence that eradication was indeed achieved (by calculating the probability of eradication or absence, *sensu* Ramsey et al. 2009; Anderson et al. 2013; Samaniego-Herrera et al. 2013).

Spatially explicit statistical models of wildlife disease–surveillance data have recently been developed for predicting the probability of freedom (epidemiological terminology for probability of eradication) of bovine tuberculosis (caused by *Mycobacterium bovis*) in New Zealand (Anderson et al. 2013, 2017). These models have proven effective for improving the cost efficiency of eradication programmes by reducing the likelihood of prematurely declaring success due to insufficient control effort and avoiding unnecessary costs due to excessive control and surveillance (Anderson et al. 2013).

This probability theory is highly applicable to eradication programmes targeting invasive pests, and similar spatial models have been adopted for and applied to pest removal from offshore islands; e.g., black rats (*Rattus rattus*) from Isla Isabel, Mexico (Samaniego-Herrera et al. 2013) and house mice (*Mus musculus*) from Isla Muertos, Mexico (Russell et al. 2017). Similar assessments will be critical for programmes aimed at eradicating pests over areas much larger than offshore islands, which, due to operational constraints, must be subdivided into smaller management zones; e.g. the Predator Free 2050 programme, whose aim is to eradicate key invasive mammalian predators from New Zealand (Russell et al. 2015). This is the type of approach that will be used to target wallabies as management agencies attempt to eradicate populations falling outside currently delineated containment areas and progressively shift the containment boundaries inward.

Different surveillance methods can be used to obtain data for estimating the probability of pest eradication, and these data have been used to determine the most cost-efficient surveillance strategies for enabling eradication to be confidently declared (Samaniego-Herrera et al. 2013; Anderson et al. 2017). For rodents, for example, kill-traps and PCRWaxTags® are often used to determine absence post-baiting and the trapping effort (trap density and trap nights) needed to achieve a desired probability of successful eradication (Samaniego-Herrera et al. 2013). For larger pest species, a different suite of survey methods is often used, including methods that are becoming increasingly available, affordable and practicable, such as camera traps and thermal imaging cameras (Swann et al. 2004; Havens and Sharp 2016).

Camera traps have proven useful for detecting invasive feral cats (*Felis catus*) (Glen et al. 2016) and quantifying the outcome of sustained control operations for introduced pests such as European rabbits (*Oryctolagus cuniculus*) (Latham et al. 2012) and feral pigs (*Sus scrofa*) (Bengsen et al. 2011). Similarly, studies have found that surveys using thermal imaging can result in higher rates of detection and detection probabilities for species such as red deer (*Cervus elaphus*), white-tailed deer (*Odocoileus virginianus*), European wild pig (*Sus scrofa*) and European rabbit compared with more traditional methods, such as spotlight counts (Focardi et al. 2001; Collier et al. 2007). The detection probability and cost-effectiveness of these new survey methods for wallabies need to be tested to determine their surveillance sensitivity relative to traditional methods such as spotlight transects, aerial observer surveys and detection dogs, and therefore their suitability for inclusion in probability-of-eradication modelling.

The probability of detecting an animal using a given surveillance method can be affected by the habitat where the animal occurs (Caughley 1977; Green et al. 2013). Collecting data on the detection probability of different methods when used in different habitats enables correction factors for habitat biases to be applied (Samuel et al. 1987; Green et al. 2013). More practically, it enables managers to determine which method would be most suitable for surveying a pest species in any given habitat.

This is an important consideration for Bennett's and dama wallabies in New Zealand, because they use a wide range of habitats, from open pasture and short tussock, to closed-canopy tall tussock, scrub and forest (Warburton 2005a, b). However, the suite of methods used to survey wallabies has been limited, and the effect of habitat on these methods has not been quantified. Spotlight transects and helicopter surveys are generally used in more open habitats like pasture and open scrub, whereas faecal pellet and live wallaby surveys, often using detector dogs, can have greater applicability across a wider range of habitats (Warburton and Frampton 1993; Williamson 1996). The habitat-based efficacy of traditional survey methods relative to new technologies (such as camera traps and thermal imaging) is largely unknown.

The objective of this study was to determine the detection probabilities and derived surveillance system sensitivity of two methods that have traditionally been used for surveying Bennett's wallabies – helicopter surveys with observers and a ground hunter with detector dogs – and to compare these results with those yielded from two novel methods – camera traps and helicopter surveys using a thermal imaging camera. Detection probabilities for each method were determined using wallabies marked with GPS collars programmed to record a near-continuous track log during the period in which surveys were conducted (0630–1200 hours). We estimated the effect of habitat on the probability of detection for each method at three study sites in South Canterbury by categorising each site into three broad categories: open (including pasture, short and tall tussock, and open scrub), closed scrub, and forest (including remnant native and plantation forests). We also estimated the cost of surveillance for each method. Based on detection probabilities for each method and their respective costs, we make recommendations for managers for increasing surveillance sensitivity to levels high enough to have confidence that a targeted population has been eradicated, or a suspected new population, if undetected, is not present (as opposed to not detected).

3 Methods

3.1 Study area

We determined detection probabilities for wallabies at three high-country stations (farms) farming sheep and beef cattle in South Canterbury. All three stations were located within the containment area delineated for Bennett's wallaby by Environment Canterbury (the management agency responsible for biosecurity in this region) (Latham et al. 2019). The densities of wallabies were high within most of the containment area at over two to three wallabies per hectare (Warburton 2005b). However, given that our management objective was to provide a method for proving eradication success, or determining the probability of absence for suspected new breeding populations occurring at low densities, we chose study areas with estimated low to moderate densities of wallabies. To do this, we used an index method known as the Guilford Score (Warburton 2005b), which is a visual assessment of faecal pellet abundance, tracks and wallaby sightings. A Guilford Score ≥4 is considered high; assessments of our study areas placed wallabies at c. 3 (range 2–4) on the Guilford Score.

Our first trial was at Glen Cary Station, Waimate District, in the southern part of the containment area, in May 2018. This site has a predominantly easterly aspect and is characterised by pasture at lower elevations (c. 450–600 m a.s.l.), tall snow tussocks (*Chionochloa* spp.) at higher elevations (c. 600–900 m a.s.l.), and scrub dominated by matagouri (*Discaria toumatou*) in gullies. There is a small block of *Pinus radiata* in a gully at c. 500–650 m a.s.l.

Our second trial was at Blue Cliffs Station, Waimate District, in the eastern central part of the containment area, from early August to mid-September 2018. This site is within a stream catchment that faces east, resulting in hill faces on the south side of the stream having a primarily northerly aspect and the north side of the stream having a primarily southerly aspect. The Blue Cliffs site is a mosaic of pasture and matagouri scrub (especially on north-facing slopes), tall snow tussocks at higher elevations (c. 600–700 m a.s.l.), New Zealand flax (*Phormium tenax*, especially on south-facing slopes), and patches of remnant native forest and scrub.

Our third trial was at Grampians Station, Mackenzie District, in the western central part of the containment area, from late February to early May 2019. This site is situated on the Mackenzie River, which flows in a northerly direction. This means that one set of hill-faces have a primarily eastern aspect and the other a primarily western aspect. The Grampians site was the highest elevation trial (c. 700–1,100 m a.s.l.) and is a mosaic of pasture, matagouri scrub, and tall snow tussocks and subalpine scrub at higher elevations.

The climate at all three sites is dominated by a dry (annual rainfall c. 300–600 mm), temperate continental climate. Summers are sunny and mild (average high c. 19–22°C; average low c. 7–10°C), and winters are cool (average high c. 5–12°C; average low c. –3–1°C). Snow can accumulate at all sites in winter. A suite of other mammalian herbivores occurred at all trial sites, including sheep and cattle, as well as brushtail possums (*Trichosurus vulpecula*), European rabbits, brown hare (*Lepus europaeus*), feral pigs, chamois (*Rupicapra rupicapra*), red deer and fallow deer (*Dama dama*). Hunting for sport, meat and pest control occurred at all trial sites, but was halted, insofar as was possible (i.e. some illegal hunting may have occurred), for about 3 months before we started our wallaby capture.

3.2 Wallaby capture and radio-collaring

We used two methods to capture wallabies: a net-gun fired from an MD 520N helicopter, and tunnel nets set at wallaby runs (i.e. well-used trails created by their large, soft-padded hindfeet) under farm fences. All wallabies netted using a helicopter were physically restrained, and a customised GPS radio-collar was fitted to them. We used a combination of physical and chemical immobilisation for wallabies captured using tunnel nets. These restraint methods were applied alternately for ground-netted wallabies and were used to compare the potential impacts to the welfare of captured animals. Chemical immobilisation was done using a low dose (1–4 mg kg^{-1}) of tiletamine–zolazepam (Zoletil®), as recommended by le Mar and McArthur (2000) and Mayberry et al. (2014).

Because we needed GPS collars that could collect a near-continuous track log (at 4–5 second intervals) during the period in which surveys were conducted, we used the expertise of a Manaaki Whenua – Landcare Research electronics expert to build bespoke store on-board GPS radio-collars. High-frequency GPS locations were critical as we needed to know the exact location of the collared wallabies in relation to the position of the surveyors when they passed within detection range (see below). The weight of the collars was c. 200 g. We only collared adult wallabies (≥9 kg) and therefore the weight of the collars did not exceed about 2.2% of wallaby body weight, well within the accepted international standard (Casper 2009; Latham et al. 2015).

All capture, handling and collaring protocols used in our study were approved by the Manaaki Whenua – Landcare Research Animal Ethics Committee (approval no. 17/11/03).

3.3 Survey methods

We estimated detection probabilities for four different methods (three mobile and one stationary) that were used to survey individually identifiable wallabies. We used the three mobile methods – helicopter surveys with observers, helicopter surveys using a thermal imaging camera, and a ground hunter with dogs – at all three trial sites. We deployed camera traps (the stationary method) at Blue Cliffs and Grampians, but not at Glen Cary.

We used the two helicopter-based survey methods in two ways. First, we conducted two and four surveys on Glen Cary and Blue Cliffs, respectively, with both survey methods (aerial observers and thermal imaging) running concurrently. This resulted in a survey design that was not optimised for either method; however, we used this design to determine the efficacy of using both methods concurrently for potentially improving surveillance sensitivity. Ideally, aerial observers need good ambient light during daytime and a height above ground level suitable for the study species, habitat and terrain (e.g. Jachmann 2002). Conversely, a cold background is needed for thermal imaging, as this makes the heat signature of any warm-blooded mammals stand out better against the cool signature of the environment (e.g. Graves et al. 1972; Havens and Sharp 1998; Ditchkoff et al. 2005). At our trial sites, early morning (before ambient light conditions were good) provided the coolest background environment within permissible flying hours. Further, as thermal imaging cameras have a smaller field of view than searching human observers, surveys conducted at a height above ground suitable for observers (using the helicopter to disturb wallabies) are likely to be too low for a thermal imaging camera, creating a narrow detection swath width (Havens and Sharp 1998), and thereby possibly reducing the surveillance sensitivity for the thermal imaging method unless additional paths are flown.

At Glen Cary and Blue Cliffs we flew aerial surveys between 0800 and 1200, and at a height above ground of 40–65 m. Conversely, at Grampians, we tailored (time of day and height above ground) helicopter flights to one or other of the aerial methods. We conducted seven surveys in total, but with both survey methods running concurrently (despite being optimised for only one). For aerial observers, we conducted two surveys that were tailored to good ambient light conditions (c. 0800–1100 hours) and at a height above ground of 10–50 m. We optimised five surveys for the thermal imaging camera, and these were done from 0730 to 1015 hours and at a height above ground of 60–75 m. All surveys were flown at a speed of 20–40 knots. We recorded track files for every helicopter survey and audio files for observer surveys that detailed the bearing and distance to detected wallabies. Footage from thermal imaging cameras was recorded and subsequently viewed to determine the number of wallaby detections and to estimate encounters with collared wallabies (see below).

We used two experienced personnel to conduct the ground hunter surveys: one hunter did three surveys at Glen Cary and three at Grampians, and the other did three surveys at Blue Cliffs. The ground hunters work for farmers and management agencies to survey and control wallabies using two or three dogs that had been trained specifically for that purpose. Ground hunter surveys at a trial site were done on consecutive days between 0745–1200 hours (Glen Cary and Blue Cliffs), or 0700–1100 hours (Grampians). The surveyors were asked to 'hunt' within the trial site using the same methods they would ordinarily use; i.e. covering as much of the site as possible within the survey period, using the topography, habitat and wind direction they deemed optimal. All dogs were muzzled to minimise the chance of harming wallabies.

The ground hunters carried GPS units and recorded their paths. All dogs had GPS collars, and a track file was recorded for every hunt for every dog. We used a human observer to assist the ground hunter with data recording so that the hunter could focus on selecting a route, observing his dogs and detecting wallabies. Once a wallaby was flushed or detected by the dogs or the hunter, the assistant used a range finder (Leupold RX-1000i TBR) and a compass to determine the distance to the detected wallaby and its bearing. We also recorded time and number of individuals, if more than one wallaby was seen at a location, and if an observed wallaby was wearing a GPS collar. By comparing information collected from ground hunts with the track logs from the GPS-collared wallabies, we were able to estimate which collared wallabies were detected during surveys.

We established 38 and 27 camera trap sites at Blue Cliffs and Grampians, respectively. We stratified Blue Cliffs into open pasture, tall tussock, scrub and remnant native forest, and randomly deployed camera traps in each habitat at a minimum distance of 60 m from the nearest camera trap. We used a systematic design at Grampians and deployed camera traps on a 300 m × 300 m grid. We primarily deployed Reconyx HyperfireTM PC900, but we also randomly deployed a small number of Bushnell® Trophy Cam HD Aggressor and Reconyx UltrafireTM XR6 at Blue Cliffs.

We deployed two trail cameras at each camera trap site: one camera was set to look along the nearest game trail and one was set at right angles to the game trail (about 2 m from the first camera). We fixed cameras to metal stakes (or trees at some camera trap sites in forest) 1.5 m above the ground and standardised their detection zone using the Walk Test or equivalent. Insofar as was possible, we faced cameras in a south-easterly, southerly, or south-westerly direction to avoid the glare of the sun. We programmed cameras to take photos day and night and left them *in situ* for c. 2 months. To maximise the chance of capturing an image of a wallaby moving in front of the zone of detection at pace, we programmed cameras to take five (or three for the Bushnell cameras) photos in rapid succession (one second delay between photos). We used standard mode for all other camera settings.

3.4 Identifying detections of collared wallabies

We estimated the conditional probability of detection (probability of detecting a collared wallaby given that the animal was at a point location within the field of view of the observer when the observer searched the area) as $P_{detection|presence}$ = P(Detection$^+$|Presence$^+$, Search$^+$) using data collected concurrently from GPS-collared wallabies and survey paths. The number of detections of collared wallabies by each survey method was identified by matching the time and spatial location of animals recorded by the observer with those of the GPS-collared animals; i.e. only a subset of the animals detected by the observer were collared. To do this, we wrote a script in R version 3.6.1 (R Core Team 2019) that searched for all GPS-collared wallaby locations that were within 50 m and 10 seconds from where the observer had seen an animal. We used a similar approach to identify which collared wallaby had been detected at each camera trap, but we used a distance threshold of 500 m and a time threshold of 3 hours, because trail cameras could take photos at any time of the day, when high-frequency GPS locations might not have been available.

We identified events where GPS-collared wallabies were present within the search path of the observer by matching the time and spatial location of the observer with those of the animals every 2–10 seconds (depending on the temporal resolution of the field-collected survey path). We used the same R script as above but set distance thresholds that varied depending on the survey method. We used 175 m and 150 m either side of the path for the ground hunter and helicopter observers, respectively. For both methods, the GPS-collared wallaby location had to fall within the field of view of the observer (i.e. within 120°–240° with respect to the forward direction of the moving observer). We chose these threshold distances based on the distribution of distances of animals seen by each method: less than 20% of animals were observed at distances greater than the thresholds. For the thermal imaging camera, we used a fixed threshold distance of 120–220 m to the right side of the helicopter path and a field of view of 20°–80° based on the position of the camera in the helicopter.

Once we identified the presence of GPS-collared wallabies within the search path of the observer based on spatial and temporal coincidence, we conducted a viewshed analysis in ArcGIS 10.5 (ESRI 2019). A viewshed is the geographical area that is visible from a specified location of an observer. It includes all surrounding points that are in line-of-sight with that location and excludes points that are beyond the horizon or obstructed by terrain and other features (e.g. buildings and trees). Thus, from the locations of GPS-collared wallabies identified based on matching time and distances to the survey paths, we further selected the subset that could realistically be seen based on the topography of the study areas. This subset represents the number of events when GPS-collared wallabies could have been detected by the different survey methods searching for them. We did not identify GPS-collared animals that could have been detected for camera traps; for this survey method we used a capture-mark-recapture approach to estimate $P_{detection}$ (see below).

Finally, we calculated an empirical $P_{detection|presence}$ for each survey method (except camera traps) as the ratio of number of detections of GPS-collared wallabies to the total number of GPS-collared wallabies that could have been detected.

3.5 Surveillance system sensitivity

Calculating an empirical $P_{detection|presence}$, as described above, provides an overall estimate of the probability of detection for each method, under the search effort conditions (e.g. distance or area covered) specific to each survey. In order to compare the effectiveness of all four methods under varying degrees of search effort (e.g. to apply estimates to future surveys), it is necessary to define detection probability as a function of search 'coverage' (i.e. the proportion of the total site area that is effectively searched; accounting for animals not being detected, for example, because they are out of range of observation). The detection probability for each survey can then be used to calculate the overall sensitivity of the surveillance system, SSe (i.e. the probability of detecting an animal given there is at least one present somewhere in the trial site), of a particular method (or a combination of methods) at each trial site. SSe is also required to calculate the probability of eradication at a site (Anderson et al. 2013), given no animals were detected during surveillance efforts. The approach for calculating SSe differs between survey methods, and we describe these approaches below.

3.5.1 Stationary surveillance methods

Surveillance system sensitivity for camera traps is calculated following the methods of Anderson et al. (2013). The survey site is first discretised with a uniform grid, with a total of N grid cells (where the grid cell size should be small relative to the species home-range size). The grid cell is the fundamental suveillance unit of the analysis. The overall surveillance system sensitivity SSe is the average over all N grid cell sensitivities SeU_i. That is, each grid cell *i* has an associated surveillance sensitivity SeU_i, which is the probability of a wallaby being detected if its home-range centre is located in cell *i* and is a function of the search effort in that cell from one or more camera traps. For surveillance using *J* camera traps, grid cell-level surveillance sensitivity is given by:

$$SeU_i = 1 - \prod_{j=1}^{J}(1 - SeU_{ij}),$$

where SeU_{ij} is the sensitivity of camera trap *j* for detecting an animal with home-range centre in grid cell *i*. This is calculated as the probability of detection over *TN* trap nights (here, we define one trap night to be a 24-hour period):

$$SeU_{ij} = 1 - \left(1 - g_0 \times \exp\left(\frac{-d_{ij}^{\,2}}{2\sigma^2}\right)\right)^{TN},$$

where d_{ij} is the distance from camera trap *j* to the centre of grid cell *i*; g_0 is the probability of detecting a wallaby in a single night if the camera trap is placed at its home-range centre; and σ is the spatial-decay parameter (in metres) for a wallaby's home-range kernel. For computational reasons, this detection kernel is truncated such that $SeU_{ij} = 0$ if $d_{ij} > 4\sigma$; in other words, a camera trap cannot detect an animal if its home-range centre is more than 4σ metres away. An estimation of σ is given by $r/2.45$, where r = the radius of the 95% home range.

We obtained σ from the GPS-collared wallaby locations by estimating each wallaby's home-range area (i.e. the area an animal occupies 95% of the time) using kernel density estimation (Seaman and Powell 1996), and then assuming that this home range area is equal to $\pi(2.45\ \sigma)^2$. That is, we assumed that the probability of wallaby presence at a location is, on average, bivariate normally distributed around the home-range centre. An estimate for g_0 was obtained from camera trap data by fitting a half-normal detection function to sightings and re-sightings of marked (GPS-collared) wallabies at camera traps, along with sightings of unmarked (non-collared) wallabies, using the SECR package in R (Efford 2019) for spatially explicit capture-recapture analysis. The SECR model can be fitted to estimate both g_0 and σ, but there were insufficient resightings of marked wallabies in our datasets to infer reliable estimates of both parameters. Therefore we fixed σ at the mean value obtained directly from the GPS locations and estimated only g_0. SECR also provides an estimate of the density of the wallaby population, however density is not relevant in the context of surveillance for confirming eradication (i.e. zero density) so we do not report those estimates here.

3.5.2 Mobile surveillance methods

For each of the three surveillance methods with a moving searcher (ground hunter with dog, helicopter observer, and helicopter-mounted thermal imaging camera) we calculated system-level *SSe* over a total of *J* surveys as:

$$SSe = 1 - \prod_{j=1}^{J}\left(1 - SSe_j\right)$$

where SSe_j is the surveillance sensitivity for survey j (i.e. the probability of detecting a wallaby in the survey area given that one is present). In contrast to the grid-cell approach used with the stationary camera traps (above), the surveillance unit with mobile devices is the individual wallaby on the landscape.

We account for search effort by defining SSe_j as a function of effective search coverage c_j (the proportion of the total site area A, in m^2, that is effectively searched in survey j):

$$SSe_j = 1 - \exp(-c_j),$$

such that surveillance sensitivity increases with increasing coverage. This function, termed the exponential detection function, or 'random search formula' (Koopman 1946, 1980), is commonly applied in search theory (e.g. Glen and Veltman 2018). It performs well as an unbiased estimator for real search effectiveness, accounting for random variations in search parameters arising due to, for example, search transects that are not perfectly straight, equally spaced and parallel. An important underlying assumption of this exponential detection function is that search effort is applied uniformly across the survey area (Frost 2000).

Coverage c_j is calculated in two ways. Initially, for simplicity, we assume a constant probability of detection (given presence) over the entire coverage (i.e. detection probability does not decrease with lateral distance from observer, but is constant up to a maximum perpendicular distance on either side of the observer). We therefore calculate coverage as

$$c_j = \left(\frac{d_{path} \times w}{A}\right) \times P_{detection|presence},$$

where d_{path} is distance surveyed (i.e. effort, in metres), w is the maximum width of the search swath (in metres), and ($d_{\text{path}} \times w/\text{A}$) measures the proportion of the total site area that is effectively searched. For ground hunters and aerial observers we use $w = 350$ m and $w = 300$ m, respectively (as per threshold distances used to calculate empirical $\text{P}_{detection|presence}$ for each method; see section 3.4). The effect of using alternative values of w for each of these two survey methods was investigated in a sensitivity analysis. For the thermal imaging camera we set $w = 100$ m (i.e., the approximate camera swath). If d_{path} is unknown, it can be estimated simply as a product of average speed and time spent searching. Note that $\text{P}_{detection|presence}$ is not itself a function of time or survey effort; it is the instantaneous probability of detecting an animal given there is one present within a distance of $w/2$ meters from the observer. This instantaneous (and constant) probability is then applied uniformly across the width w and length d_{path} of the search path when calculating coverage c.

To quantify the effect of habitat on the probability of wallaby detection by each method, we estimated $\text{P}_{detection|presence}$ by fitting a Bernoulli model (see Appendix 1, Supplementary Methods) to the GPS-collared wallaby detection data y_w (where $y_w = 0$ if a collared animal could have been detected but was not; $y_w = 1$ if the animal was detected), with fixed effects for three habitat categories (open [intercept], scrub and forest) and uninformative priors:

$$y_w \sim Bernoulli(P_{detection|presence,w}),$$

$$logit(P_{detection|presence,w}) = \beta_0 + \beta_1 Scrub_w + \beta_2 Forest_w,$$

$$\beta_0, \beta_1, \beta_2 \sim \mathrm{N}(0,100).$$

We also estimated an overall probability of detection (given presence) for each method by fitting an intercept-only model without habitat effects.

This approach for estimating *SSe* allows for a direct comparison among methods (for a given effort d_{path} and survey site area *A*), but does not account for a decay in detection probability as a function of lateral distance from the observer. To address this, we also calculated c_j for the ground hunter and helicopter observer, using $c_j = (d_{\text{path}} / \mathrm{A}) \times R$. This follows the approach described in Glen and Veltman (2018), where *R* is the 'effective swath width' (also referred to as 'effective sweep width', Robe and Frost 2002) in metres, a measure of detectability describing a critical search swath width for which the number of undetected animals inside the swath equals the number of detected animals outside the swath. More formally, it is the sum of detection probabilities over all lateral distances to the right and left of an observer.

Using the effective swath width allows us to treat a survey as if it were a complete census of the effective search swath ($d_{\text{path}} \times \mathrm{R}$). We obtained estimates for *R* graphically by plotting the cumulative number of non-detections against increasing lateral distance from observer, from zero up to the maximum lateral distance (i.e. an increasing function of distance). Cumulative detections were then plotted against lateral distance, from the maximum distance decreasing to zero (i.e. a decreasing function of distance). The point at which these two curves intersect is approximately half the effective swath width *R* (Robe and Frost 2002). We did not include the thermal imaging camera in this analysis because we assumed detection probability does not decay with lateral distance for this method, resulting in this method hads a fixed area of detection (120–220 m), and thus detection probability does not decay with lateral distance.

3.5.3 Surveillance sensitivity from multiple methods

If a combination of surveillance methods is deployed simultaneously at the same trial site, an overall surveillance system sensitivity can be calculated as:

$$SSe = 1 - \prod_k (1 - SSe_k),$$

where SSe_k denotes the surveillance system sensitivity of method *k*.

3.6 Cost per unit of *SSe* of each survey method

Surveillance sensitivity *SSe* is a function of the detection sensitivity of the survey method and the search coverage (i.e. it is dependent on the search effort; e.g. d_{path} or number of camera trap nights, and the size of the site), but does not incorporate information on costs. Therefore, we next evaluated the cost-effectiveness of each method for declaring wallabies eradicated from a particular site with a probability of 0.95.

To compare the costs per unit of surveillance sensitivity, we standarised all estimated SSe to a hypothethical 100-ha square study area that was searched using the minimum effort required by each method to physically cover the full area in a single survey (i.e. for mobile methods $d_{path} \times w/A = 1$). For all calculations, we assumed that no wallabies were detected during any of the hypothetical surveys; i.e. the aim of the surveys is to confirm eradication (at a 95% level of confidence). This entailed five 1 km-long transects for the ground hunter with dogs, four 1-km transects for the helicopter observer, ten 1-km transects for the thermal imaging camera, and 16 camera traps located on a 300 m × 300 m square grid. For the camera traps, this design assumes that each device surveys a circular area of c.170 m radius, which approximates the size of a wallaby home range in our study areas (Table 5).

We assumed the following costs: NZ$1,800 per hour of helicopter flight, NZ$50 per hour for the ground hunter with dogs, and NZ$50 per hour for a contractor setting camera traps. For the helicopter observers, we assumed a flight speed of 60 km hr^{-1} and a swath of 300 m, which equates to surveying 1,800 ha hr^{-1} or NZ$1 ha^{-1}. For the thermal imaging camera, we assumed the same flight speed but a swath of 100 m, which equates to surveying 600 ha hr^{-1} or NZ$3 ha^{-1}. For the ground hunter with dogs, we assumed a speed of 4 km hr^{-1} and a swath of 200 m, which equates to surveying 80 ha hr^{-1} or NZ$0.625 ha^{-1}. For the camera traps, costs are only incurred at deployment and retrieval, with no additional costs per night that the camera is left at site. Accordingly, we assumed that one contractor could set up the 16 cameras in a single 8 hour day, and then retreive them in a single 8 hour day, which equates to NZ$8 ha^{-1}. We calculated SSe for each of the above survey designs in the hypothetical area, using the estimated parameters (i.e. constant $P_{detection|presence}$ for the mobile methods and the estimated g_0 and σ for the camera traps).

For camera traps, the number of trap nights required to achieve 95% probability of wallaby absence (P_{free}) was found by simulating the model described in section 3.5.1 for the 100–ha area, to find the minimum number of trap nights to satisfy:

$$\frac{Prior}{1 - SSe(1 - Prior)} \geq 0.95 \quad \text{(Anderson et al. 2013)},$$

using an uninformative mean prior probability of wallaby absence ($Prior$) of 0.5.

For each mobile surveillance method, we estimated how many repeats J^* of surveys with equivalent SSe are needed to achieve a 95% probability of wallaby absence in the 100-ha area, using the formula:

$$J^* = \log_{1-SSe}\left(\frac{0.05 \times Prior}{0.95 \times (1 - Prior)}\right).$$

The number of repeats J^* required was then multiplied by the cost of each repeat (see above). This represents the cost of surveillance per hectare for each survey method to achieve the 95% threshold to confidently declare local (within the 100-ha survey area) eradication of wallabies.

3.7 Decision support system

The equations described above have been packaged into a web-based interface using the R package Shiny; the app is freely available at https://landcare.shinyapps.io/Wallaby_Detection_App_beta

On the app, council staff can input the shapefiles of the study area and of the paths that were surveyed for wallabies (either by helicopter observers or ground hunters with dogs). Conversely, the point locations of camera traps and the number of nights they were active for can be used as inputs. The app then estimates the *SSe* for each survey. In this way, council staff can use the app *a priori*, to design search paths or camera trap placements that will provide sufficient *SSe* to achieve their target P_{free}, or *a posteriori*, to estimate the level of confidence in wallaby absence in an area given surveillance efforts conducted to date without any detections.

4 Results

We radio-collared eight (one female, seven males), 15 (10 females, five males), and 15 (six females, nine males) at Glen Cary, Blue Cliffs and Grampians, respectively. Of these, 30 collared wallabies provided usable GPS data (i.e. a near-continuous track log during the survey periods, and remained in the study area for all, or part, of our surveys). The average recorded weight of 27 collared wallabies was 11.8 kg (range 9–15 kg).

Six GPS collars were retrieved at Glen Cary, comprising 465,655 locations (Figure 1). However, one collar had no usable data as it failed to obtain fixes after being deployed. Of the five GPS-collared wallabies with usable data, one animal (ID 3) showed repeated large-distance movements in the south-east corner of the study area (Figure 1). This animal was outside of the area surveyed by the ground hunter and only overlapped a small portion of the helicopter paths.

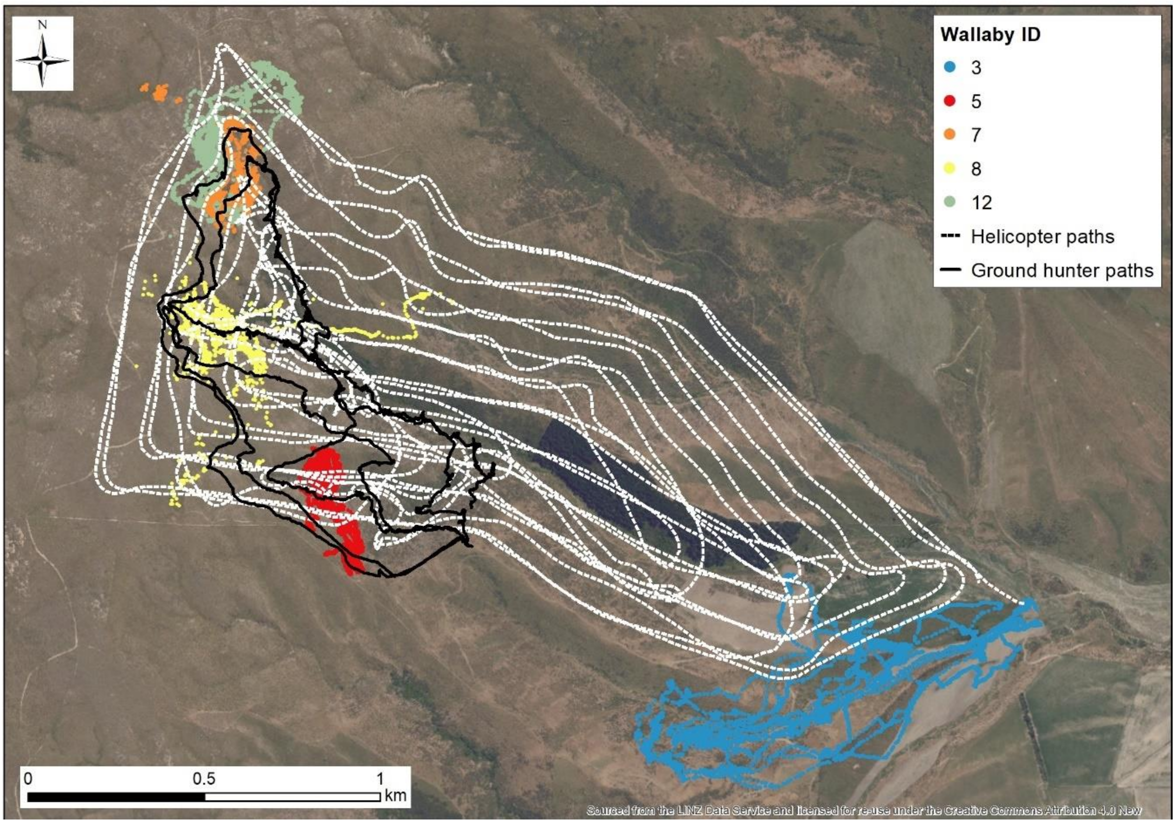

Figure 1. GPS-collared wallaby locations and ground hunter and helicopter paths at trial site 1, Glen Cary Station.

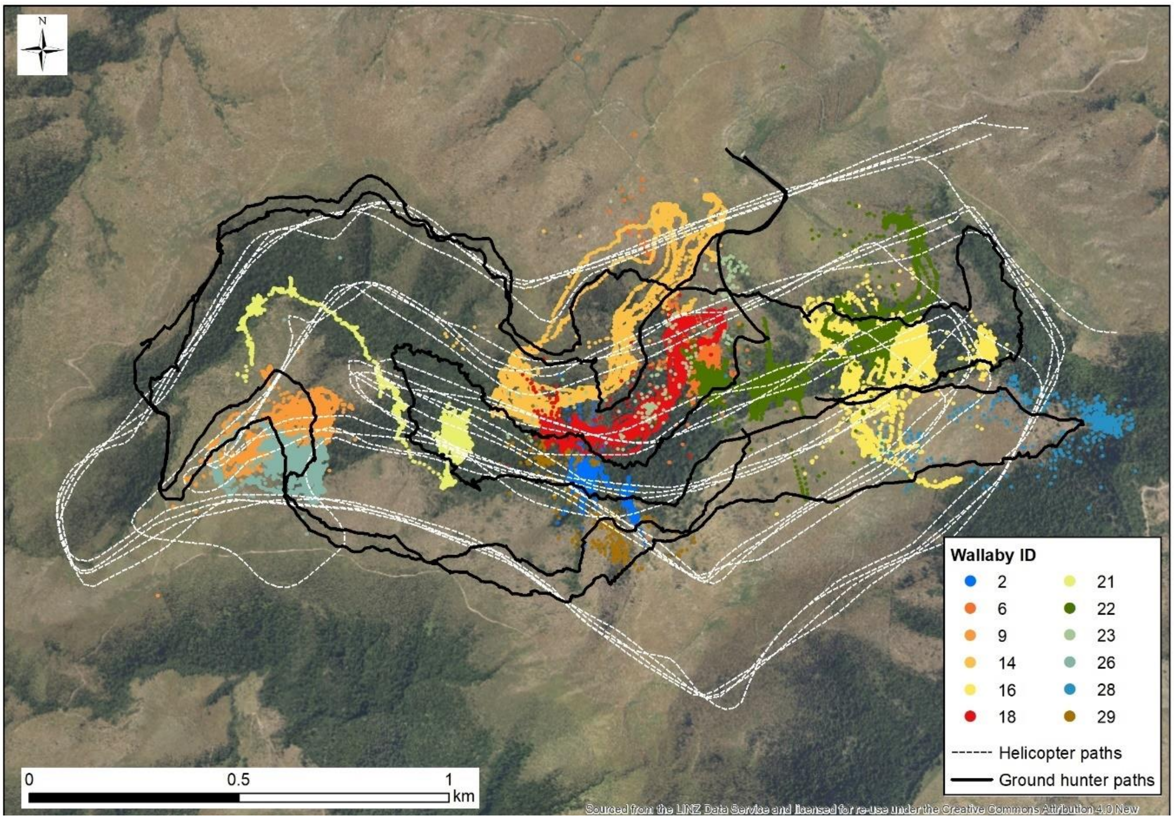

Figure 2. GPS-collared wallaby locations and ground hunter and helicopter paths at trial site 2, Blue Cliffs Station.

Fifteen GPS collars were retrieved from Blue Cliffs, but three collars had no usable data. The remaining 12 retrieved collars yielded 931,438 locations, and all wallabies wearing those collars stayed within the area surveyed by the ground hunter and the helicopter (Figure 2). Thirty-eight camera trap sites (76 trail cameras) captured 56,054 images of wallabies (37% of all images taken). All camera trap sites, except one interfered with by cattle, captured photos of wallabies. GPS-collared wallabies were recorded in a total of 1,347 photos at 11 camera trap sites.

Fifteen GPS collars were retrieved from Grampians, but two collars had no usable data. The remaining 13 retrieved collars yielded 905,815 locations and all wallabies wearing those collars remained within the area surveyed by the helicopter (Figure 3), although wallaby 9 was not within the area surveyed by the ground hunter. A total of 27 camera trap sites (54 trail cameras) captured 26,395 images of wallabies (16% of all images taken). All camera trap sites captured images of wallabies; GPS-collared wallabies were recorded on a total of 146 photos across eight camera trap sites.

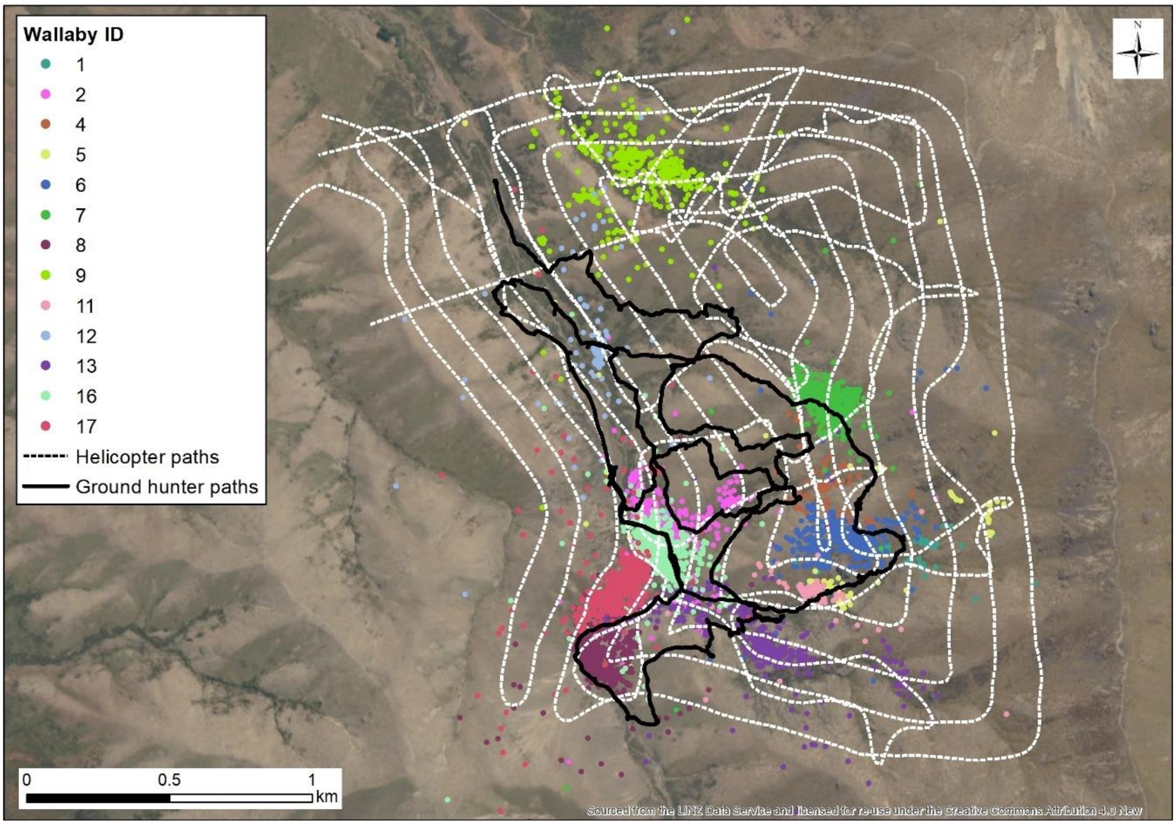

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Figure 3. GPS-collared wallaby locations and ground hunter and helicopter paths in trial site 3, Grampians Station. Only low-frequency GPS locations and two of the seven helicopter paths are shown.

4.1 Detection probabilities

Of the GPS-collared wallabies available to be seen when a survey took place, the ground hunter with dogs generally detected most or all of the individual animals (Table 1). The helicopter observer was also able to detect most available individuals, except at Blue Cliffs, where only two of the seven individual animals were detected. The thermal imaging camera detected the lowest proportion of individuals available to be seen in each trial, except for trial 3, where the camera traps detected only 46% of available individuals.

The empirical detection probabilities (given presence) for each mobile survey method from each trial site are summarised in Table 2; a more detailed description of the number of wallabies detected during each individual survey in each trial site is presented in Appendix 1.

The take-home message from the empirical $P_{detection|presence}$ for the three mobile survey methods is that the ground hunter with dogs consistently had a higher probability (0.47–0.62) of detecting GPS-collared wallabies that were in the study area and available to be seen than either of the aerial methods (Table 2). However, these empirical $P_{detection|presence}$ estimates do not consider extent of coverage or relative costs of each method. The detection probabilities for the thermal imaging camera were generally higher than those for the aerial observers at two trial sites; however, the thermal imaging camera failed to detect any collared wallabies at Glen Cary (Table 2). Combining the two aerial survey methods (helicopter observers and thermal imaging camera), detection probabilities were intermediate between those for each method alone.

Table 1. Number of different GPS-collared wallabies (i.e. not events) seen at three trial sites in Canterbury, South Island, New Zealand, compared with the number of different GPS-collared wallabies that were available to be seen

Trial site	Method	Number of individual GPS-collared wallabies seen	Number of individual GPS-collared wallabies available to be seen	Proportion of individual animals seen
1. Glen Cary Station	Ground hunter with dogs	3	3	1
	Helicopter observers	3	4	0.75
	Thermal imaging camera	0	4	0
2. Blue Cliffs Station	Ground hunter with dogs	3	4	0.75
	Helicopter observers	2	7	0.28
	Thermal imaging camera	1	4	0.25
	Camera traps	8	12	0.67
3. Grampians Station	Ground hunter with dogs	5	7	0.71
	Helicopter observers	8	9	0.89
	Thermal imaging camera	6	9	0.67
	Camera traps	6	13	0.46

Table 2. Number of encounters (distance range, m, in parenthesis) and empirical detection probabilities ($P_{detection|presence}$) for each mobile survey method at three trial sites in Canterbury, South Island, New Zealand. Empirical detection probabilities (given presence) are calculated by determining the number of events when collared wallabies were seen compared to the number of events when they could have been seen. For the aerial combined method it is not possible to estimate the number of wallabies seen because some of the animals seen by each individual method could be duplicates

Trial site	Method	Number of wallabies seen	Number of events when collared wallabies were seen	Number of events when collared wallabies could have been seen	Empirical $P_{detection|presence}$
1. Glen Cary Station	Ground hunter with dogs	178 (4–324)	7 (43–205)	15 (33–205)[1]	0.47
	Helicopter observers	45 (30–200)	7 (19–77)	28 (3–143)[2]	0.25
	Thermal imaging camera	36 (142–190)[3]	0	7 (162–218)[4]	0
	Aerial combined	–	7	31	0.23
2. Blue Cliffs Station	Ground hunter with dogs	94 (0–510)	11 (21–190)	18 (21–190)[1]	0.61
	Helicopter observers	26 (10–100)	2 (90–96)	27 (7–150)[2]	0.08
	Thermal imaging camera	34[3] (120–220)	1 (213)	8 (142–219)[4]	0.13
	Aerial combined	–	3	30	0.1
3. Grampians Station	Ground hunter with dogs	122 (5–315)	16 (13–229)	26 (13–229)[1]	0.62
	Helicopter observers	195 (5–500)	16 (11–376)	99 (8–376)[2]	0.16
	Thermal imaging camera	272 (120–220)[3]	11 (123–218)	39 (123–218)[4]	0.28
	Aerial combined	–	26	115	0.23

[1] Estimate based on a maximum detection distance for wallabies of 175 m and a field of view between 240° and 120° with respect to the heading of the ground hunter. An objective correction for topography was applied using a viewshed analysis, but no habitat-based correction was applied.

[2] Estimate based on a maximum detection distance for wallabies of 150 m and a field of view between 240° and 120° with respect to the heading of the helicopter. An objective correction for topography was applied using a viewshed analysis, but no habitat-based correction was applied. The audio recording for the second run for the helicopter observer in Blue Cliffs Station was corrupted, so it was not considered in analyses.

[3] Includes animals that were not unequivocally identified as wallabies: 3 in Glen Cary Station, 11 in Blue Cliffs Station, and 88 in Grampians Station.

[4] Estimate based on a distance for detecting wallabies of 120–220 m and a field of view of 20°–80° with respect to the heading of the helicopter. No correction was applied for the periods when the video footage was 'washed-out' due to sun exposure; instead, we assumed this is a drawback of the method.

4.1.1 Distribution of distances that wallabies were seen

Figure 4 shows the distribution of distances that wallabies were seen by observers from the helicopter at all three trial sites. At Glen Cary and Blue Cliffs stations, nearly all wallabies that were seen by helicopter observers were within a comparatively small distance from the helicopter (0–100 m). Conversely, at the trial site with the most open habitat, Grampians Station, wallabies were frequently seen out to c. 250 m, and even as far as 500 m.

Figure 5 shows the distribution of distances that wallabies were seen by ground hunters at all three trial sites. At all sites, few wallabies were seen at distances >200 m from the ground hunter. There was a noticeable drop in the number of wallabies seen beyond 50 m at Blue Cliffs (Trial 2); this may be attributable to more structurally complex habitat than at the other two sites, or a different ground hunter.

We did not conduct similar analyses for thermal imaging cameras or camera traps, as both of these methods have fixed detection zones (or windows of detection).

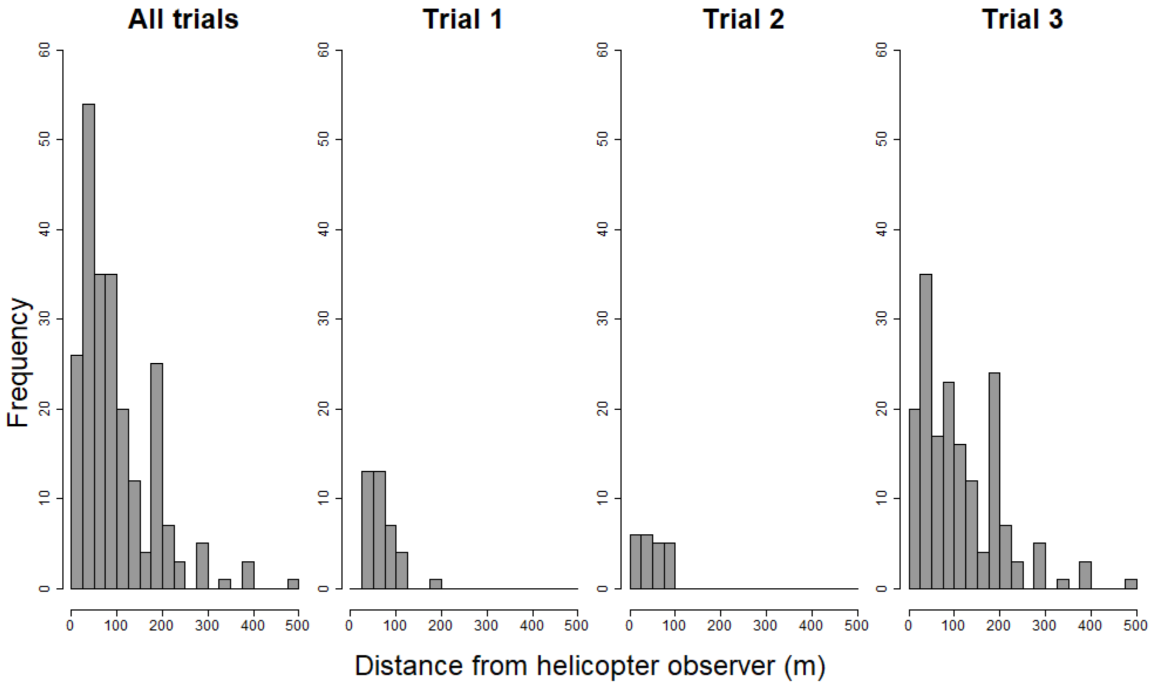

Figure 4. Frequency distribution for the number of wallabies seen as a function of distance (m) from the helicopter at each trial site and for all trials combined. Trial 1: Glen Cary Station; trial 2: Blue Cliffs Station; trial 3: Grampians Station.

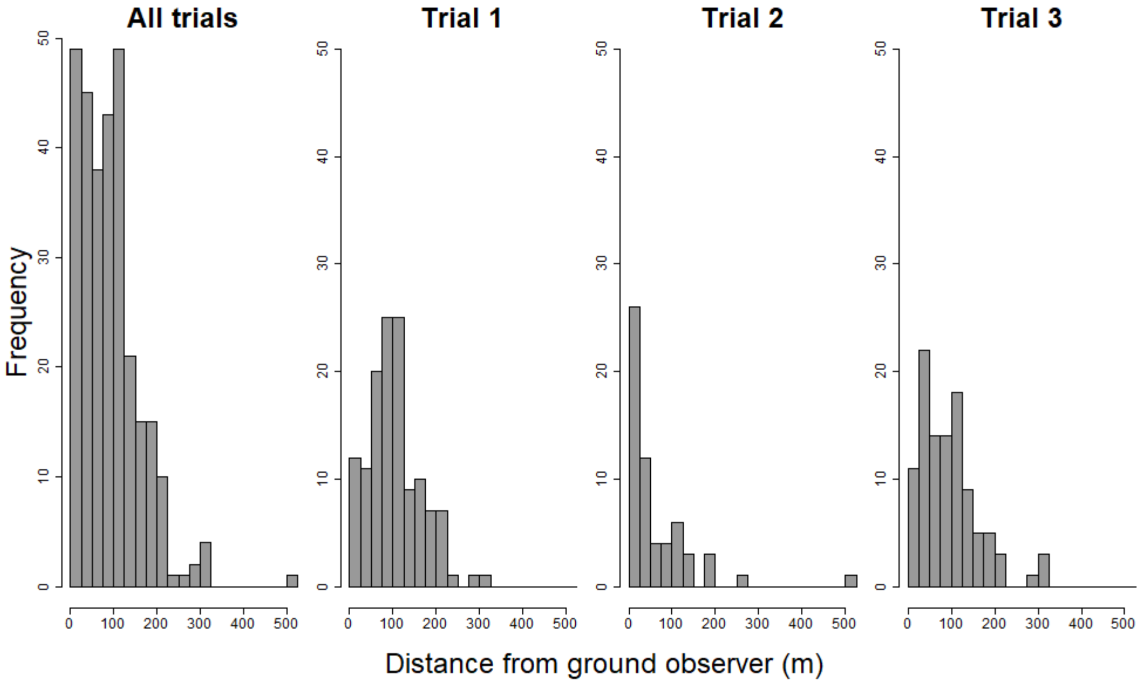

Figure 5. Frequency distribution for the number of wallabies seen as a function of distance (m) from the ground hunter at each trial site and for all trials combined. Trial 1: Glen Cary Station; trial 2: Blue Cliffs Station; trial 3: Grampians Station.

4.2 Surveillance sensitivity

Using the datasets of detection and non-detection events (with associated habitat type) for GPS-collared animals over all trial sites, we estimated surveillance system sensitivities for mobile methods, as described in section 3.5.2.

Table 3 shows $P_{detection|presence}$ estimates (and associated uncertainty) for each habitat type and for all habitats combined. Because search distances and survey areas varied among trials and surveys, we used these $P_{detection|presence}$ estimates, along with pre-defined maximum swath widths, *w,* to calculate a standardised *SSe* for a 1-km search transect in a hypothetical 100-ha survey area. This allowed a comparison of surveillance sensitivity per kilometre search transect across the four mobile survey methods (but note that swath width still differs between methods, so *SSe* is not standardised per unit search area).

Of these methods, the ground hunter–dog team had the highest standardised *SSe* in all three habitat types (overall *SSe* = 0.172, Table 3), with the aerial combined method having the next highest sensitivity across all habitat types (overall *SSe* = 0.061). For open and scrub habitat, the helicopter observer method was more sensitive (*SSe* = 0.037 and *SSe* = 0.047, respectively) than the thermal imaging camera (*SSe* <0.001 and *SSe* = 0.025, respectively), although these two methods were equally sensitive to detecting wallabies in forested habitat (*SSe* = 0.012). It is possible that the low detection probability of the thermal imaging camera in open habitat reflected a higher rate of image 'wash-out' due to sun exposure in these habitat types. The thermal imaging camera had the highest median $P_{detection|presence}$ (0.219 for all habitats combined) out of the aerial methods, however its relatively small swath width (w = 100 m) meant that when surveillance sensitivity was assessed per kilometre search transect, the helicopter observer method (w = 300 m) was more sensitive. Standardised *SSe* was insensitive to choosing larger values of maximum swath width w (Appendix 1, Supplementary Table 4 and Supplementary Figure 1), though, as expected, $P_{detection|presence}$ estimates decreased with increasing w.

Table 3. Detection probability ($P_{detection|presence}$) and derived standardised surveillance system sensitivity (*SSe*) for the four mobile survey methods, assuming a constant probability of detection over the entire coverage. Estimates of $P_{detection|presence}$ were obtained for three different habitat categories (open, scrub and forest), and for all habitats combined (i.e. an intercept-only model with no habitat effect) (in bold). The uncertainty in estimated $P_{detection|presence}$ is given by the 95% credible interval; i.e. there is a 95% chance that $P_{detection|presence}$ falls within this interval. Maximum swath width (w) and standardised *SSe* (calculated using $c = (d_{\text{path}} \times w/A) \times P_{detection|presence}$) for a 1-km search transect in a 100-ha survey area are also given. $P_{detection|presence}$ is an instantaneous probability of detecting an animal (given it is present within a distance of $w/2$ meters from the observer). Survey effort (e.g. amount of time spent searching) is incorporated via d_{path} when calculating coverage c

Method	**Habitat**	**$P_{detection|presence}$**		**w (m)**	**Standarised *SSe***
		Median	**95% CI**		
Ground hunter with dogs	Open	0.308	0.018–0.842	350	0.102
	Scrub	0.514	0.352–0.676		0.165
	Forest	0.630	0.383–0.836		0.198
	All	**0.538**	**0.405–0.667**		**0.172**
Helicopter observers	Open	0.126	0.031–0.303	300	0.037
	Scrub	0.162	0.101–0.238		0.047
	Forest	0.039	0.002–0.187		0.012
	All	**0.144**	**0.094–0.206**		**0.042**
Thermal imaging camera	Open	0.004	0.000–0.229	100	<0.001
	Scrub	0.251	0.139–0.393		0.025
	Forest	0.122	0.004–0.511		0.012
	All	**0.219**	**0.122–0.341**		**0.022**
Aerial combined	Open	0.107	0.026–0.261	370	0.039
	Scrub	0.193	0.135–0.261		0.069
	Forest	0.072	0.011–0.221		0.026
	All	**0.170**	**0.122–0.226**		**0.061**

Table 4. Effective swath width *R* and derived surveillance system sensitivity (*SSe*) for the ground hunter with dogs and helicopter observer survey methods in each trial site and for all trials combined. To compare the two methods, a standardised *SSe* was calculated using c = (d_{path}/A) × *R* (i.e. we assumed a decay in detection probability as a function of lateral distance from the observer) for a 1-km search transect in a 100-ha survey area. The helicopter observer method in trial site 2 had insufficient detections to allow estimation of *R*, but these data were included when estimating *R* for all three trials combined

Method	Trial	*R* (m)	Standarised *SSe*
Ground hunter with dogs	1	201.0	0.182
	2	204.4	0.185
	3	183.0	0.167
	All	**196.0**	**0.178**
Helicopter observers	1	67.5	0.065
	2	–	–
	3	50.1	0.049
	All	**49.6**	**0.048**

Table 4 shows estimates for effective swath width *R* and derived standardised surveillance system sensitivity (for a 1-km search transect in a 100-ha survey area) for the ground hunter with dogs and helicopter observers, assuming a decay in detection probability as a function of lateral distance from the observer. The helicopter observer method in trial site 2 had insufficient detections to allow estimation of *R*, but these data were included when estimating *R* for all three trials combined. The resulting standardised *SSe*, for all trial sites combined, was very similar to that estimated using the constant detection probability approach (Table 3), with the ground hunter method yielding a higher standardised *SSe* than the helicopter observers (0.178 and 0.05, respectively).

Finally, the detection probability parameters for camera traps, for each trial and for all trials combined, are shown in Table 5. There was considerable variation in home-range size between individuals (Appendix 1, Supplementary Table 2), with an overall mean home-range area of 11.2 ha (SD = 12.5 ha) corresponding to a mean spatial decay parameter σ = 68.2 metres (SD = 36.8 m). Both trials with deployed camera traps yielded the same mean g_0 estimate equal to 0.1. Results for an alternative trail camera deployment, with only a single camera deployed at each camera trap site, also yielded a mean g_0 = 0.1 (Appendix 1, Supplementary Table 3).

Table 5: Detection parameter estimates for surveillance using camera traps. Summary statistics for home-range area (ha) and spatial-decay parameter σ (metres) were estimated from GPS-collared wallaby locations at three different trial sites using kernel density estimation to obtain a 95% occupancy area for each animal. The probability of detection, on a single night, for a camera trap located at a wallaby's home-range centre (g_0), and associated standard error, was estimated from the marked and unmarked animal detections using spatially explicit mark-recapture techniques (with σ fixed at the mean value obtained from kernel density estimation). For consistency, we estimated g_0 for a camera trap survey consisting of 80 trap nights (the actual number of trap nights differed between the two trial sites)

Parameter	Trial	Mean	SD	SE	n	Range
Home-range area (ha)	1	10.17	12.90	5.77	5	3.41–33.18
	2	8.09	7.68	2.22	12	0.87–26.14
	3	15.37	15.59	4.32	13	0.61–55.24
	All	**11.21**	**12.52**	**–**	**–**	**–**
σ (m)	1	65.02	38.17	17.07	5	42.49–132.63
	2	58.64	30.46	8.79	12	21.42–117.74
	3	81.06	41.33	11.46	13	18.03–171.14
	All	**68.24**	**36.78**	**–**	**–**	**–**
g_0	2	0.105	–	0.0097	–	–
	3	0.104	–	0.0093	–	–
	Mean	**0.105**	**–**	**–**	**–**	**–**

4.3 Cost of *SSe* of each survey method

The estimated costs of surveillance per hectare for each method are presented in Table 6. This is the cost per hectare to achieve a 95% probability of wallaby absence (from an uninformative mean prior probability of wallaby absence of 0.5). The ground hunter with dogs is the most cost-effective method, with a cost of less than $4 per ha. The camera traps would cost more than twice this to achieve the same level of confidence in absence. The aerial observers and thermal imaging camera are more than 5 and 10 times more expensive, respectively, than the ground hunter.

Table 6. Estimated costs of surveillance to achieve a 95% probability of wallaby eradication for each of four survey methods. The costs are derived for a hypothetical 100-ha square area but should be applicable to other areas of different sizes and shapes

Variable name	Ground hunter with dogs	Helicopter observers	Thermal imaging camera	Camera traps
Speed (km/h)	4	60	60	–
Swath (m)	200	300	100	–
Hectares surveyed per hour	80	1,800	600	6.25
Cost per hour (NZ$)	50	1,800	1,800	50
Cost per hectare (NZ$)	0.63	1.00	3.00	8.00
Cost per 100 hectares (NZ$)	62.5	100.0	300.0	800.0
SSe from full coverage of 100-hectare survey area	0.45	0.13	0.20	0.81
Desired probability of wallaby absence	0.95	0.95	0.95	0.95
Prior probability of wallaby absence	0.5	0.5	0.5	0.5
Number of repeat surveys required (nights for camera traps)	5	21	14	180
Surveillance cost per 100 hectares (NZ$)	313	2100	4200	800
Surveillance cost per hectare (NZ$)	**3.13**	**21.00**	**42.00**	**8.00**

5 Discussion

Bennett's and dama wallabies in mainland New Zealand have shown significant range expansions between when they were introduced around the start of the 20th century and 2016 (when last quantified), with spread occurring as a result of natural dispersal and illegal liberations (Latham et al. 2019). Both species of wallaby have escaped their respective containment areas, and effective management is needed to halt or reverse their range expansions to prevent their unwanted impacts from also spreading.

Our study contributes to two national and regional management objectives for mitigating the spread of wallabies: progressively removing (locally eradicating) wallaby populations that are located outside the containment area, and, if that is achievable, progressively containing them within an increasingly smaller containment area (Latham et al. 2019). Key to these objectives is having reliable and affordable tools for estimating probability of local eradication.

Here we assessed the detection probabilities (given a wallaby was available to be detected), corresponding surveillance sensitivities (under standardised search conditions) and cost-effectiveness for three mobile survey methods and one stationary survey method that are used (or their suitability is currently being investigated) for surveying wallabies in New Zealand (Warburton and Frampton 1993; Mowbray 2011; Latham et al. 2019). We found that the ground hunter with dogs consistently had the highest *SSe* (for a standardised search effort) in all three habitat types, while *SSe* were much lower for the helicopter-based methods. Surveillance sensitivity for helicopter observers was highest in open and scrub habitats but low in dense vegetation, whereas thermal imaging cameras performed poorly on aspects or in habitats prone to 'wash-out' caused by solar radiation, which we found was most common in open habitats. Conversely, we found thermal imaging cameras performed comparatively well in forest, possibly because of the larger temperature difference between warm-bodied animals and the cool temperate forest floor. However, as canopy closure increases, presumably $P_{detection|presence}$ (and derived *SSe*) will decrease as canopy vegetation obscures the ability to view objects on the forest floor (Graves et al. 1972; Wäber and Dolman 2015; Hambrecht et al. 2019). By the end of each trial, camera traps had identified half to two-thirds of the different GPS-collared wallabies that were available to be seen.

Once standardised to a single survey achieving full physical search coverage of an indicative hypothetical 100-ha area, to allow comparison between all (stationary and mobile) survey methods (see '*SSe* from full coverage of 100-ha survey area' in Table 6), we found that camera traps had the highest surveillance sensitivity per survey (based on 16 camera traps deployed at a spacing of 300 m × 300 m and left *in situ* for 80 nights), followed by the ground hunter with dogs, the thermal imaging camera and, finally, the helicopter observers. To achieve a 95% probability of eradication within the hypothetical 100-ha area, effort would have to be increased to 180 nights for camera traps, and five, 14 and 21 repeat surveys for the ground hunter with dogs, the thermal imaging camera and the helicopter observers, respectively.

An alternative to leaving camera traps *in situ* for an additional 100 nights would be to increase the density of camera traps (Meek et al. 2014); however, this comes at a greater additional cost (for purchase and deployment). A possible disadvantage to using camera traps as a survey method for proof of eradication is that, unlike all of the mobile methods, if one or more wallabies are detected at camera traps, no attempt can be made to kill them until an observer has viewed the photos and control staff are deployed to attempt to belatedly locate and kill them. However, if the surveillance method is the same as the control method (e.g. ground hunter with dogs), then the probability of detection might decrease as wallabies become educated to the selected method and better able to avoid detection.

The total cost of surveillance per hectare to achieve a 95% probability of eradication was substantially lower (c. NZ $4.00) for the ground hunter with dogs than for the other survey methods. Camera traps were also substantially cheaper (c. NZ $8.00) than either of the helicopter-based methods (>NZ $20.00), but this excludes the cost of viewing captured photos and entering the data. The cost of a contractor for viewing c. 160,000 images captured at the Grampians and subsequent data entry was c. NZ $3,500 (equivalent to about 2 hours of helicopter flight time), corresponding to a per hectare cost of c. NZ $43. However, as image recognition software is increasingly being used to reliably identify photos that contain images of animals and even determine species (Fegraus et al. 2011; Yu et al. 2013; Falzon and Glen 2018), the cost associated with image anlysis and data entry is expected to become trivial for a large management programme like that for Bennett's wallaby.

The thermal imaging camera also captured footage that needed to be viewed, but again, relative to the hourly rate of hiring a helicopter and thermal imaging camera operator, these costs are negligible. We maintain that detection probabilities (given presence) and surveillance sensitivities of aerial-based methods would need to improve substantially before the total cost of surveillance per hectare to achieve a 95% probability of eradication became competitive with the ground hunter with dogs, or camera traps.

The $P_{detection|presence}$ and associated costs for mobile surveillance methods reported in the results were estimated for a pre-defined swath width that was appropriate for our particular surveying conditions (e.g. the aircraft's height above ground described in Methods). Our sensitivity analysis (Appendix 1, Supplementary Table 4 and Supplementary Figure 1) show how $P_{detection|presence}$ and derived *SSe* vary for different swath widths. This allows the surveillance sensitivity and associated surveillance costs to be calculated for future surveys under different conditions (by pre-defining a suitable swath width and using the corresponding $P_{detection|presence}$ estimate). On the other hand, obtaining direct estimates for effective swath width, *R*, as we reported for the ground hunter and helicopter observer methods, does not require swath width to be pre-determined. Based on these estimates, the survey paths for ground hunter and helicopter observer methods should be spaced ≤200 m and 50 m apart, respectively, in order to achieve full effective coverage of a search area. Similarly, surveillance sensitivities and associated costs can be calculated for different arrangements of trail cameras and number of trap nights using the standardised camera trap parameters g_0 and σ.

There were a few limitations to our study design, especially for the aerial methods, perhaps most importantly in our use of thermal imaging cameras. We fixed the thermal imaging camera in the helicopter and flew at a constant height above ground, and this enabled us to calculate the size of the swath (or field of view of the camera) within which collared wallabies could be detected. There is a perception among thermal imaging camera operators that 'hunting' with the camera (i.e. moving the camera manually to search areas of perceived best habitat) leads to higher detection rates (and therefore presumably higher detection probabilities) than using it in a fixed position. We are unaware of any studies that have assessed this, but we acknowledge that if using a 'hunting' strategy with a thermal imaging camera results in higher $P_{detection|presence}$ than a fixed camera approach, we will have introduced a directional bias into our comparison. We were constrained to using a fixed camera in the helicopter because at present there is no readily available technology capable of calculating the size of the searched swath for a camera (or its direction) that is manually operated. When the technology permits, we recommend quantifying the efficacy of using a hunting strategy with a thermal imaging camera as a research priority.

As mentioned, the thermal imaging camera also experienced image wash-out due to high solar radiation in some surveys or some parts of the study areas, especially if weather conditions were not optimal (cold and overcast; Graves et al. 1972). We did not correct for this wash-out by omitting affected sections of surveyed transects. Our rationale was that this is a limitation of thermal imaging cameras that needs to be acknowledged (e.g. Cilulko et al. 2013) and it is no different from, for example, a ground hunter's dogs tiring towards the end of a search period and covering an increasingly smaller swath around the GPS path walked by the hunter. If changes in New Zealand Civil Aviation Authority legislation enable use of thermal imaging cameras at night, either mounted in a helicopter or on a drone (unmanned aerial vehicle), then it is likely that wash-out will not affect surveys for this method (e.g. Witczuk et al. 2018; Kays et al. 2019). We recommend testing the efficacy of aerially deployed thermal imaging at night as a research priority.

Another limitation of our study was that we surveyed with helicopter observers and a thermal imaging camera operating concurrently. At Glen Cary and Blue Cliffs, flights were not optimised for either method, whereas at the Grampians flights were tailored specifically to only one of the helicopter-based survey methods. Our results, although based on a small sample size of one, suggest that optimising methodology for just one survey method marginally increased that method's empirical $P_{detection|presence}$ relative to its non-tailored $P_{detection|presence}$ (see Appendix 1, Supplementary Table 1). Therefore, the $P_{detection|presence}$ and corresponding surveillance sensitivities derived from all tailored and non-tailored surveys combined (Table 3) can be considered conservative estimates for these methods.

However, even with the majority of surveys being non-tailored, the overall surveillance sensitivity (per kilometre search transect) for the combined aerial surveillance (i.e. helicopter observer and thermal imaging operating concurrently) was still larger than either method individually, although this improvement was admittedly small. Nevertheless, given the greater efficacy for detecting wallabies in denser cover using thermal imaging and the comparatively high efficacy of helicopter observers in open and scrub terrain, we recommend that aerial surveys using thermal imaging cameras should also accommodate data collection by helicopter observers if light conditions are suitable and even if surveys are flown at a height above ground marginally too high for the observers. In the case of surveying for proof of eradication, it is irrelevant which method detects a wallaby; a detection of even one animal (e.g., a female with a pouch young) means eradication has not been achieved and more control is needed.

So how can our results be operationalised? If an attempt is made to eradicate a known population of wallabies outside of the containment area and we want to confirm that they have been eradicated with a probability of 95%, our results show that ground hunters with dogs and camera traps are most cost-effective out of the methods we assessed (for a single survey achieving full physical coverage of a hypothetical 100-ha site), and they perform well in all habitats.

There are important limitations to their use, however. A ground hunter and dogs can cover less distance than a helicopter (c. 4 km per hour and c. 60 km per hour, respectively). If the size of the area being assessed for wallaby absence is large (e.g. >50,000 ha) it will be challenging for the current few trained ground hunters and dogs to survey the area within a timeframe that permits eradication to be quickly, but confidently declared. More ground hunters and dogs can be trained, but there will have to be enough work and funding to ensure they remain committed to the industry.

Similarly, at a grid spacing of 300 m × 300 m, many camera traps (8,000) would have to be deployed to cover the above area of 50,000 ha (e.g. at a density of 16 camera traps per 100 hectares). This is clearly unaffordable, and although camera traps could be deployed only in good wallaby habitat, or quickly rotated to new areas if no detections occur, the limitations associated with camera traps confirming presence or eradication are obvious.

Therefore, despite the expense associated with the use of helicopters and operators of thermal imaging cameras, they will likely fill an important role for surveying large areas that present logistical challenges for the other methods. It is possible that some lower level of confidence that wallabies have been eradicated or are absent (e.g. 80–90%) could be used as thresholds in large, low-risk areas.

We have extended spatial models developed for predicting the probability of freedom of bovine tuberculosis from livestock and wildlife in New Zealand (Anderson et al. 2013, 2017) to assess their applicability for determining the probability of eradication for invasive, medium-sized, ground-dwelling mammals. This approach has high applicability for management objectives related to eradication or progressive containment of invasive mammals around the world; e.g. for coypu (or nutria, *Myocastor coypus*) in the United States (Myers et al. 2000; Kendrot 2011), and for Javan mongoose (*Herpestes javanicus*) in Hawaii, United States, and Okinawa Island, Japan (Barun et al. 2011).

Our approach for estimating probability of eradication from various survey methods will also be critical for New Zealand's Predator Free 2050 programme and its aim of eradicating brushtail possums (*Trichosurus vulpecula*), rats (*Rattus* spp.) and stoats (*Mustela erminea*) from New Zealand by 2050 (Russell et al. 2015). Indeed, given the lofty goal – some argue unachievable ambition with current control methods (Parkes et al. 2017) – of the Predator Free 2050 programme, eradication of invasive wallabies from New Zealand would be a good case study for determining the feasibility of the predator-free initiative. Wallabies are currently confined to much smaller, more accessible areas than possums, rats and stoats, but agencies tasked with their management face many of the same technological and social issues faced by the predator-free initiative.

6 Summary

We have compared the sensitivities of four surveillance methods for detecting wallabies in three different New Zealand habitats, along with their associated cost-effectiveness. Our results show that camera traps and ground hunters and dogs have the highest detection probabilities, surveillance sensitivities (under standardised search conditions) and cost-effectiveness. However, although these methods are useful for surveying small areas (c. 1,000 ha or less), capacity and time issues are likely to make it impractical for ground hunters with dogs to survey large areas (c. 10,000 ha or more). The helicopter-based methods that we assessed will likely be important for monitoring these larger areas. In conclusion, our detection parameter estimates can be applied during future surveillance following wallaby eradication attempts to determine when there has been sufficient surveillance to confidently declare wallabies are absent from an area.

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Appendix 1 – Supplementary information

Supplementary tables

Supplementary Table 1. Number of encounters with wallabies during each individual survey (i.e. ‘Day’ or ‘Run’) for each survey method at each trial site. Probability of detection given wallaby presence, $P_{detection|presence}$, is calculated by determining the number of events when collared wallabies were seen compared to the number of events when they could have been seen. The audio recording file from Run 2 of the aerial observer in Blue Cliffs Station was corrupted

Trial Site	Method	Day/Run	Number of wallabies seen	Number of events when collared wallabies were seen	Number of events when collared wallabies could have been seen	Empirical $P_{detection|presence}$	Area covered (ha)	Distance covered (km)
1. Glen Cary Station	Ground hunter with dogs	Day 1	71	1	3[1]	0.33	106	5.4
		Day 2	49	1	1[1]	1.0	71	4.4
		Day 3	58	5	11[1]	0.46	112	5.7
	Helicopter observers	Run 1	26	1	12[2]	0.09	311.1	35.7
		Run 2	19	6	16[2]	0.38	319.7	30.8
	Thermal imaging camera	Run 1	23[3]	0	3[4]	0	–	35.7
		Run 2	13	0	4[4]	0	–	30.8
2. Blue Cliffs Station	Ground hunter with dogs	Day 1	34	1	2[1]	0.50	170.6	6.0
		Day 2	28	2	4[1]	0.50	193.8	6.9
		Day 3	32	8	12[1]	0.67	126.2	6.0
	Helicopter observers	Run 1	20	2	11[2]	0.18	288	14.9
		Run 2	NA	NA	5[2]	–	273	13.8
		Run 3	2	0	9[2]	0	271	13.3
		Run 4	4	0	7[2]	0	272	13.4
	Thermal imaging camera	Run 1	18[3]	0	3[4]	0	–	14.9
		Run 2	7[3]	1	3[4]	0.33	–	13.8
		Run 3	3[3]	0	2[4]	0	–	13.3
		Run 4	6[3]	0	0[4]	–	–	13.4

Trial Site	Method	Day/Run	Number of wallabies seen	Number of events when collared wallabies were seen	Number of events when collared wallabies could have been seen	Empirical $P_{detection|presence}$	Area covered (ha)	Distance covered (km)
3. The Grampians Station	Ground hunter with dogs	Day 1	47	3	5[1]	0.60	113.4	5.34
		Day 2	25	1	9[1]	0.11	104.1	5.28
		Day 3	50	12	12[1]	1.0	136.3	5.41
	Helicopter observers	Run 1	31	3	15[2]	0.20	589.3	40.3
		Run 2	18	0	13[2]	0.17	542.3	41.7
		Run 3	15	1	12[2]	0.09	526.6	41.4
		Run 4*	34	6	10[2]	0.60	411.7	21.5
		Run 5	27	3	18[2]	0.17	584.0	43.8
		Run 6	14	1	22[2]	0.05	589.2	44.7
		Run 7*	56	2	9[2]	0.22	556.3	27.0
	Thermal imaging camera	Run 1	79[3]	3	9[4]	0.33	–	40.3
		Run 2	46[3]	1	5[4]	0.20	–	41.7
		Run 3	20[3]	2	6[4]	0.33	–	41.4
		Run 4*	8[3]	0	3[4]	0	–	21.5
		Run 5	27[3]	2	7[4]	0.29	–	43.8
		Run 6	63[3]	1	6[4]	0.17	–	44.7
		Run 7*	29[3]	2	3[4]	0.67	–	27.0

[1] This estimate is based on a maximum detection distance for wallabies of 175 m and a field of view between 240° and 120° with respect to the heading of the ground hunter. An objective correction for topography was applied using a viewshed analysis, but no habitat-based correction was applied.

[2] This estimate is based on a maximum detection distance for wallabies of 150 m and a field of view between 240° and 120° with respect to the heading of the aerial observer. An objective correction for topography was applied using a viewshed analysis, but no habitat-based correction was applied.

[3] Includes animals that were not unequivocally identified as wallabies: three animals in Glen Cary station (all in Run 1); 11 animals in Blue Cliffs Stations (six in Run 1, one in Run 2, two in Run 3, and two in Run 4); 88 animals in The Grampians Station (40 in Run 1, 17 in Run 2, seven in Run 3, seven in Run 5, and 17 in Run 6).

[4] This estimate is based on a distance for detecting wallabies of between 120 and 220 m and a field of view between 20° and 80° with respect to the heading of the helicopter and the angle at which the thermal imaging camera was fixed; i.e., where it could 'see'. We did not apply a correction for the survey periods when the thermal imaging camera video footage was 'washed-out' due to sun exposure; instead, we assumed that this was a drawback of the thermal imaging camera method and thus should be included in the estimation of detection probability.

[*] Indicates runs tailored for the helicopter observer only.

Supplementary Table 2. Home-range area (ha) and spatial-decay parameter σ (metres) estimated from GPS locations for each wallaby at each trial site. Kernel density estimation was used to obtain a 95% occupancy area for each animal

Trial	Wallaby ID	Home-range area (ha)	σ (metres)
1. Glen Cary Station	3	33.18	132.63
	5	3.52	43.21
	7	3.41	42.49
	8	5.17	52.36
	12	5.58	54.40
2. Blue Cliffs Station	2	1.02	23.21
	6	0.87	21.42
	9	3.53	43.25
	14	12.66	81.93
	16	6.51	58.74
	18	5.28	52.93
	21	2.58	37.00
	22	7.46	62.88
	23	26.14	117.74
	26	1.45	27.73
	28	16.36	93.14
	29	13.21	83.69
3. The Grampians Station	1	38.54	142.95
	2	10.11	73.21
	4	14.10	86.46
	5	55.24	171.14
	6	8.19	65.88
	7	4.61	49.44
	8	4.65	49.68
	9	22.91	110.21
	11	8.46	66.97
	12	0.61	18.03
	13	18.70	99.59
	16	6.41	58.29
	17	7.23	61.92

Supplementary Table 3. Parameter estimates for surveillance with camera traps, under an alternative deployment with only a single camera at each camera trap site. Detection data for this single-camera deployment were subsetted from the original double-camera detection dataset by selecting one of the two cameras at random for each camera trap site. The probability of detection on a single night, for a camera located at a wallaby's home-range centre (g0) and associated standard error were estimated from the marked and unmarked animal detections using spatially explicit mark-recapture techniques. For consistency, we estimated g0 for a camera trap survey consisting of 80 trap nights (the actual number of trap nights differed between the two trial sites)

Parameter	Trial	Mean	SE
g_0	2	0.096	0.0101
	3	0.099	0.0101
	Mean	**0.114**	**–**

Supplementary Table 4. Sensitivity analysis for maximum swath width, *w* (m), for the ground hunter with dogs and the helicopter observers' survey methods. The mean probability of detection (given presence), $P_{detection|presence}$ (and associated 95% credible interval), and standardised surveillance system sensitivity for a 1-km search transect in a 100-ha survey area (*SSe*) are given for different values of *w*. The thermal imaging camera method had a fixed swath width of 100 m, so was not included in the sensitivity analysis

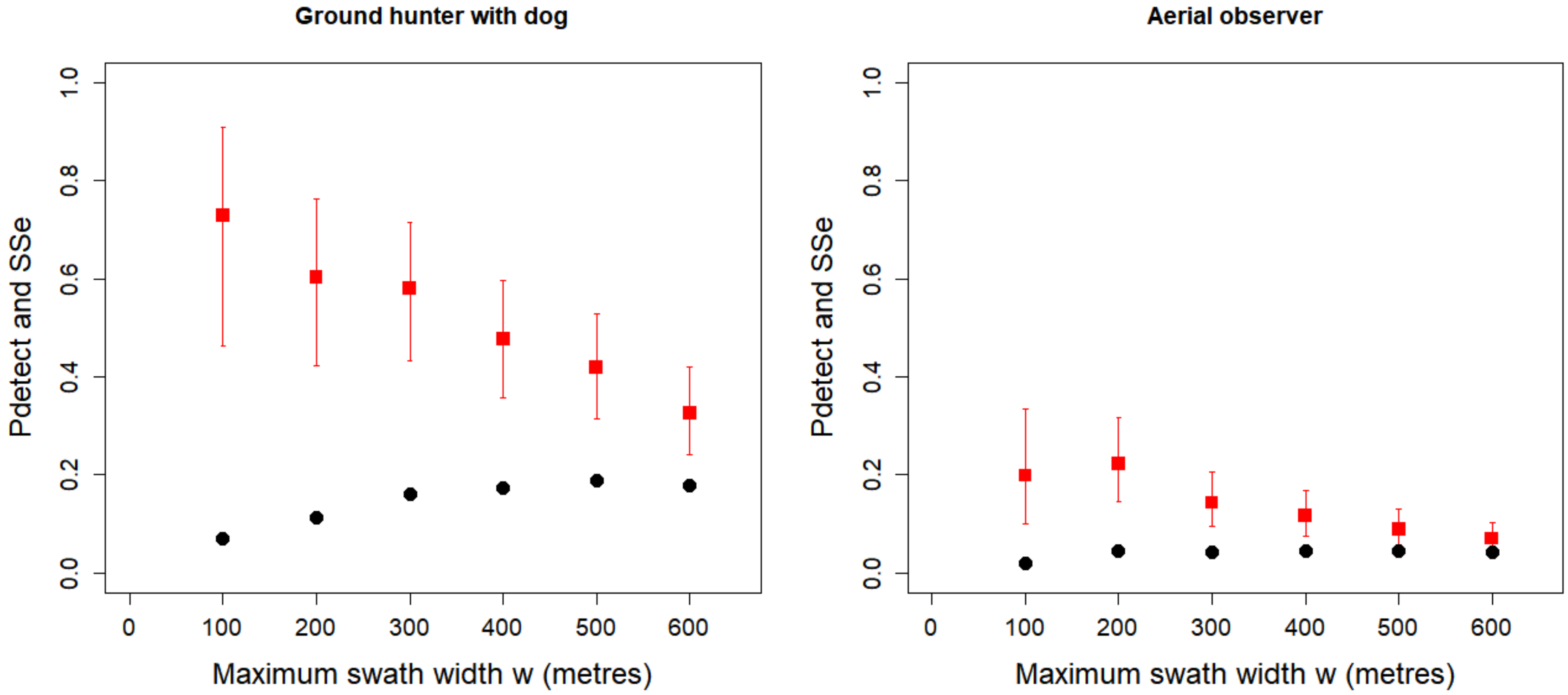
W **(m)**	**Ground hunter with dog**			**Helicopter observers**		
	$P_{detection|presence}$		**Standardised *SSe***	$P_{detection|presence}$		**Standardised *SSe***
	Mean	**95% CI**		**Mean**	**95% CI**	
100	0.730	0.462–0.908	0.070	0.198	0.100–0.334	0.020
200	0.604	0.422–0.766	0.114	0.222	0.145–0.316	0.043
300	0.579	0.432–0.717	0.160	0.144	0.095–0.206	0.042
400	0.477	0.357–0.597	0.174	0.116	0.076–0.168	0.045
500	0.419	0.315–0.529	0.189	0.089	0.058–0.130	0.044
600	0.325	0.240–0.419	0.177	0.070	0.046–0.102	0.041

Supplementary Methods

Estimation of habitat effects on probability of detection given wallaby presence for mobile surveillance methods

To estimate the effects of habitat category on $P_{detection|presence}$ for each mobile survey method, the Bernoulli model outlined in section 3.5.2 was fitted in a Bayesian framework using MCMC simulation with uninformative priors to obtain posterior mean parameter estimates and 95% credible intervals. Models were fitted using JAGS software with three chains, initialised at a value of zero for each β coefficient parameter, and run for 400,000 iterations (then thinned by an interval of 10 iterations) after a burn-in period of 10,000 iterations.

Supplementary Figures



Supplementary Figure 1. Sensitivity analysis for maximum swath width, *w* (m), for the ground hunter with dogs and the helicopter observers' survey methods. The mean probability of detection (given presence), $P_{detection|presence}$ (and associated 95% credible interval, red squares) and standardised surveillance system sensitivity for a 1-km search transect in a 100-ha survey area (*SSe,* black circles) are shown for different values of *w.* The thermal imaging camera method had a fixed swath width of 100 m so was not included in the sensitivity analysis. As *w* increases, $P_{detection|presence}$ decreases because more events when collared wallabies could have been seen are included in the expanding swath, but there are few or no additional positive detections. *SSe* decreases for smaller *w* because, despite a larger $P_{detection|presence}$, the search coverage is substantially reduced.