How can we detect introduced mammalian predators in non-forest habitats? A comparison of techniques

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Abstract: Efficient detection techniques will confirm the presence of a species at a site where the species exists, and are essential for effective population monitoring and for assessing the outcome of management programmes. However, detection techniques vary in their ability to detect different species. A wide range of mammalian predator species, most introduced into New Zealand since the late 18th century, have had a detrimental impact on the native flora and fauna. To date, there has been little research to compare the efficiency of detection techniques for these species, especially in non-forest habitats. We used nine commonly-available techniques to survey for the presence of mammalian predators at 19 sites on the open, non-forested banks of the Rangitata River, a large braided river in the South Island, New Zealand. We compared the relative efficiency of the techniques using three metrics: raw detection rates, Kaplan–Meier survival analysis, and probability of detection. Techniques varied in their ability to detect eight species of mammalian predator. The most efficient detection techniques included large tracking tunnels and hair tubes for feral cats (*Felis catus*), large tracking tunnels for European hedgehogs (*Erinaceus europaeus*), and WaxTags® for brushtail possums (*Trichosurus vulpecula*). Using our data to simulate a reduction in survey effort, we found that detection rates would be significantly reduced only when devices were at very low densities. We show also that 3–71 nights of monitoring are needed for a 90% probability of detection by our most efficient techniques. Our findings emphasise the merit of using more than one technique to detect a species, and we recommend that detection devices are left open for at least 10 nights. Finally, we highlight the need for further research to develop standardised monitoring protocols for introduced mammalian predators in New Zealand's non-forested habitats.

Keywords: Conibear trap; DOC250; *Erinaceus europaeus*; *Felis catus*; *Mus musculus*; *Mustela*; *Rattus*; *Trichosurus vulpecula*; wax tags

Introduction

A number of techniques are used to detect the presence of cryptic and usually nocturnal mammalian predator species. However, techniques vary in their ability to detect different species (e.g. Catling et al. 1997; Foresman & Pearson 1998; Lindenmayer et al. 1999; Gompper et al. 2006; O'Connell et al. 2006; Long et al. 2007). Efficient detection techniques reliably confirm the presence of a species at a site where the species exists (i.e. they have a high probability of detection). Without efficient detection techniques it is not possible to conduct the robust survey and monitoring protocols needed for reliable species and habitat management, for example to assess the change in relative abundance of a species over time, to quantify the effectiveness of a predator control programme, or to verify the pest-free status of an island.

Many mammalian predator species were introduced into New Zealand following the arrival of Europeans in the late 18th century. Feral cats (*Felis catus*), feral ferrets (*Mustela furo*), stoats (*M. erminea*), weasels (*M. nivalis*), Norway rats (*Rattus norvegicus*), ship rats (*R. rattus*), house mice (*Mus musculus*), European hedgehogs (*Erinaceus europaeus*) and brushtail possums (*Trichosurus vulpecula*) have all had a detrimental effect on the native flora and fauna (Towns & Daugherty 1994; Dowding & Murphy 2001; King 2005; Innes et al. 2010). Pacific rats or kiore (*Rattus exulans*) arrived with Polynesian settlers in the 13th century (Wilmshurst et al. 2008) but are now absent from most of the New Zealand mainland. Mammalian predators are monitored widely and often, but research has concentrated on comparing the efficiency of different monitoring techniques for relative abundance estimation (Brown et al. 1996; Blackwell et al. 2002; Warburton et al. 2004; McCulloch 2009), and comparisons of trap or bait efficacy (Montague 2002; Cameron et al. 2005; King et al. 2007a; Lal 2008). Despite realisation of the importance of being able to detect unwanted pest species (Dilks & Towns 2002; Russell et al. 2005, 2008), little work has been done to compare the efficiency of different detection techniques; Ji et al. (1999), King et al. (2007b), Sweetapple & Nugent (2011) and Nathan et al. (2013) are exceptions. Furthermore, research has focused on forest ecosystems, where the most common mammals are possums, stoats, ship rats and house mice (Brown et al. 1996; Blackwell et al. 2002; Warburton et al. 2004; Sweetapple & Nugent 2011). There has been little investigation of efficient detection techniques for introduced mammalian predators in other, more open ecosystems, where predator communities and behaviour of species might differ.

Braided rivers are globally uncommon, and in New Zealand are primarily found in the South Island where they support a unique species assemblage, including several threatened endemic birds, lizards and invertebrates (Department of Conservation 2006). Predation by introduced mammals is a major threat to braided river bird populations (Dowding & Murphy 2001). The suite of introduced mammalian predators

in braided river systems is dominated by feral cats, ferrets, stoats and hedgehogs (Keedwell & Brown 2001; Cameron et al. 2005; Cleland et al. 2007, 2008; Dowding & Ledgard 2009), which take braided river birds, chicks or eggs at nests (Pierce 1986; Keedwell et al. 2002; Sanders & Maloney 2002; Keedwell 2005; O'Donnell et al. 2010; Steffens et al. 2012). As a consequence, pest management programmes have been initiated on several braided rivers in an effort to conserve native fauna (Maloney et al. 2005; Steffens 2008; Dowding & Ledgard 2009; Schmechel 2010). Kill-trapping provides most of the data for assessing the presence and relative abundance of mammalian predators on rivers in New Zealand. However, there are no standardised monitoring protocols for most of the common mammalian predator species in non-forest habitat and the most efficient detection techniques are not known. Without efficient detection techniques, it is not possible to prioritise where to target pest management, or to assess the outcomes of predator control operations in braided river habitats (Cleland et al. 2008).

The purpose of this research was to identify efficient detection techniques for introduced mammalian predators in a non-forested environment in New Zealand. Our objectives were to (1) compare the relative efficiency of several commonly available techniques for detecting the suite of predator species present in an open braided river ecosystem and (2) quantify the monitoring effort needed to confirm the presence of each predator species. Following a pilot study (GP, unpubl. data), we limited our comparisons to nine techniques: three sizes of tracking tunnel, hair tubes, wax tags, two types of kill trap, and two search patterns. Alternative detection techniques, some of which were trialled in the pilot study, are summarised in Table 1.

Methods

Study area

Our study area was the Rangitata River (mid-point: 43°76' S, 171°22' E), South Canterbury, South Island, New Zealand. The Rangitata, 121 km long, has its source in the high-altitude Southern Alps, and is one of New Zealand's major rivers. The upper Rangitata flows as a wide braided river for about 50 km to the Rangitata Gorge. It is considered to be of outstanding importance for wildlife, especially as nesting habitat for birds (O'Donnell & Moore 1983). It is dominated by open shingle, indigenous matagouri (*Discaria toumatou*) and mat vegetation, and exotic dog rose (*Rosa canina*) and grasses. The more densely vegetated lower Rangitata begins below the Rangitata Gorge and continues at a steeper gradient compared with the upper river, for another 50 km to the coast south of Ashburton. The lower river's margins are mainly covered with invasive weed species such as gorse (*Ulex europaeus*), Scotch broom (*Cytisus scoparius*), blackberry (*Rubus fruticosus*) and willow (*Salix* spp.) (Butcher 2006). No formal pest control is carried out, but cats, brown hares (*Lepus europaeus*) and European rabbits (*Oryctolagus cuniculus*) are occasionally shot on the upper Rangitata (M. Prouting, Mesopotamia Station, pers. comm.) and possums and rabbits are infrequently controlled with 1080 poison adjacent to the river (B. Glentworth, Environment Canterbury, pers. comm.).

Our study was conducted at 19 sites along the banks of the Rangitata. Each site was surveyed once between spring (August–September) and early summer (December–January) 2008–2010. Nine sites were on the upper river and 10 on the lower river. The sites were selected on the basis of their accessibility. At each site we used a range of techniques to survey for mammalian predator presence along a 1.1-km transect, hereafter called 'survey line'. Survey lines were on average 2.7 km (SD ± 1.9) apart, but seven of the 10 lines that were closer than average were separated by the main or other river channels, which were expected to limit mammalian predator movement. Survey lines ran parallel to the main water flow (median 50 m from the river; range 20–292 m), with start points and direction (upriver or downriver) decided arbitrarily or because of logistical constraints; the only criteria were that mammalian predators did not have to cross water to reach the survey lines and that survey lines were placed near vegetation to maximise the likelihood of detection (Pascoe 1995; Alterio et al. 1998; Ratz 2000; Cameron et al. 2005; Shanahan et al. 2007; Recio et al. 2010, 2013). All sites had vegetation along the edge of the river, although plant species, density and structure varied, reflecting the range of vegetative cover along the whole of the Rangitata River. We assumed that

Table 1. Techniques for mammalian predator detection (including those trialled in a 2007 pilot study on the Rangitata River) not used in this study.

Technique	References	Trialled in pilot study?	Reasons not used in this study
Small-diameter hair tubes	Horton et al. 2005; Gleeson et al. 2010	Yes	Interference by large predators
Faunatech hair funnel traps	Lindenmayer et al. 1999	Yes	Very low detection rates
Baited sand plots	e.g. Glen & Dickman 2003	Yes	Weather-prone; drying of substrate; very low detection rates
Spotlighting	e.g. NPCA 2009a	Yes	Some sites too vegetated; very low detection rates
Trail cameras	e.g. Meek et al. 2012	Yes	Equipment failure; financial cost of widespread use and loss from flooding
Predator dogs	Cheyne 2011	Yes	Limited availability
Electronic track pads	e.g. King et al. 2007b	No	Financial cost of widespread use and loss from flooding
Chew-track-cards	Sweetapple & Nugent 2011	No	Not fully-developed at start of study
Live traps	e.g. NPCA 2009a	No	Logistic constraints for daily checks

these differences would not affect the relative use of different survey devices by each species.

Detection techniques

The different survey techniques and designs are summarised in Table 2.

Tracking tunnels

We used three types of tracking tunnel: (1) a cat tracking tunnel (CTT), based on a design trialled in the Tasman Valley (Leseberg et al. 2005) and large enough to accommodate cats, consisting of a black corrugated plastic cover stapled on to a heavy wooden base (1000 × 200 × 200 mm; Fig. 1a); (2) the standard-sized tracking tunnel (TT), widely used in New Zealand for monitoring predator species (Gillies & Williams 2007), of similar construction (600 × 100 × 100 mm; Fig. 1a); (3) longer tracking tunnels (TTL) had unpainted metal covers that fitted over a wooden base (1000 × 100 × 100 mm; Fig. 1b). The longer tunnels were trialled to reduce incidences with the shorter tunnels of unidentifiable predators pawing bait out, and for protection of paper and ink from strong winds.

For all tracking tunnels, Black Track Ink (Pest Management Services, Wellington, NZ) was painted onto the central third of a corrugated plastic or plastic tray, bait placed in the middle of the tray, and tracking paper securely pinned to the un-inked third on either side (Fig. 1c). Bait consisted of a cube (CTT: 5-cm; TT and TTL: 2-cm) of fresh skinned hare or rabbit meat. Tracking tunnels were checked and rebaited on average every 3–4 days and papers were collected when mammalian or 'unidentified other' tracks were recorded. When more than 4 days elapsed between checks, we assumed the tracking tunnel was available for tracking for only 4 days because the bait was often unattractive (dried out or rotten) after this time. We used a cut-off of 4 nights for the bait's ability to attract a predator, but we do not know how accurate this was. If longer (as may be the case during cooler weather), then time to detection will be downwardly biased; conversely in the open riverbed following strong nor-west winds, bait attractiveness may have been much reduced.

Hair tubes

Hair tube (HT) design followed Landcare Research protocols (Horton et al. 2005) and consisted of a grey PVC tube large enough to accommodate a cat (150-mm diameter, 400 mm long; Fig. 1d). Slits were sawn near both ends of the tube and thick rubber bands, coated with TRAPPER® Glue (Bell Laboratories Inc., USA) thinned with toluene, were placed in the slits. Bait (a 5-cm cube of skinned fresh hare or rabbit meat) was suspended from a wire hook in the middle of the tube. Hair tubes were checked on average every 3–4 days and bait and bands were replaced at every check. Bands with hair attached were collected and stored in manila envelopes with filter paper to keep them dry for DNA analysis to identify species (Foran et al. 1997; Gleeson et al. 2010). It was possible to keep samples viable for up to 5 months this way. Mouse presence in the tubes was deduced from scat on the floor. As with tracking tunnels, we considered hair tubes to be open and available for collecting hair for a maximum of 4 nights between checks owing to the bait becoming less appealing after this time.

Wax tags

Wax tags are commonly used for monitoring rat and possum presence, indicated by species-specific bite marks in the wax (Thomas 1999; NPCA 2010). Peanut-butter-flavoured WaxTags® (Pest Control Research, Christchurch, NZ) were anchored ≤ 15 cm from the ground so that they remained accessible to hedgehogs (Fig. 1e). We aimed to check the wax tags once a week but, because of logistic constraints, checks were sometimes less frequent.

Kill traps

Two types of kill trap were chosen, on the basis of Department of Conservation (DOC) advice and the traps' humane status (National Animal Welfare Advisory Committee – NAWAC). The first was the 'Twizel' cat trap (DOC Current Best Practice Feral Cat Kill Trapping System 5) designed to kill cats humanely: a double-set ground trap with modified Steve Allan Conibear-like traps under a specially made black plastic Philproof™ cover (Wahlberg 2006; Fig. 1f). The second kill trap chosen was the DOC250 (a single-set trap designed to kill stoats, ferrets, rats and hedgehogs humanely; Poutu & Warburton 2005; Fig. 1g). Although no traps were set specifically for possums or weasels, these can be caught in the two traps we used (Cleland et al. 2008). In addition, Conibear traps can catch ferrets, stoats, hedgehogs and Norway rats (Anderson et al. 2006; Cleland et al. 2007, 2008). No traps were set for mice. Limited resources and complications from flooding meant that kill traps were only trialled at eight sites. We aimed to follow the DOC Tasman Valley trapping programme protocol (Leseberg et al. 2005). DOC250 traps were baited once with a 4-cm cube of salted hare or rabbit meat, and Conibear traps were baited once with an 8-cm cube of fresh skinned hare or rabbit meat. Traps were checked (but not rebaited) after 1 week and at the end of the month.

Table 2. Techniques for detecting mammalian predators on the banks of the Rangitata River, 2008–2010.

Technique	Number and spacing per line	Survey period	Number of sites
1. Cat tracking tunnel	3 at 400 m	21 nights	19
2. Standard tracking tunnel	3 at 400 m	21 nights	19
3. Longer tracking tunnel	3 at 400 m	21 nights	19
4. Hair tubes	3 at 400 m	21 nights	19
5. WaxTag®	12 at 100 m	24 nights	19
6. Conibear traps	3 at 400 m	c. 30 nights	8
7. DOC250 traps	6 at 200 m	c. 30 nights	8
8. Search Edge	1 search	-	16
9. Search Inland	1 search	-	10

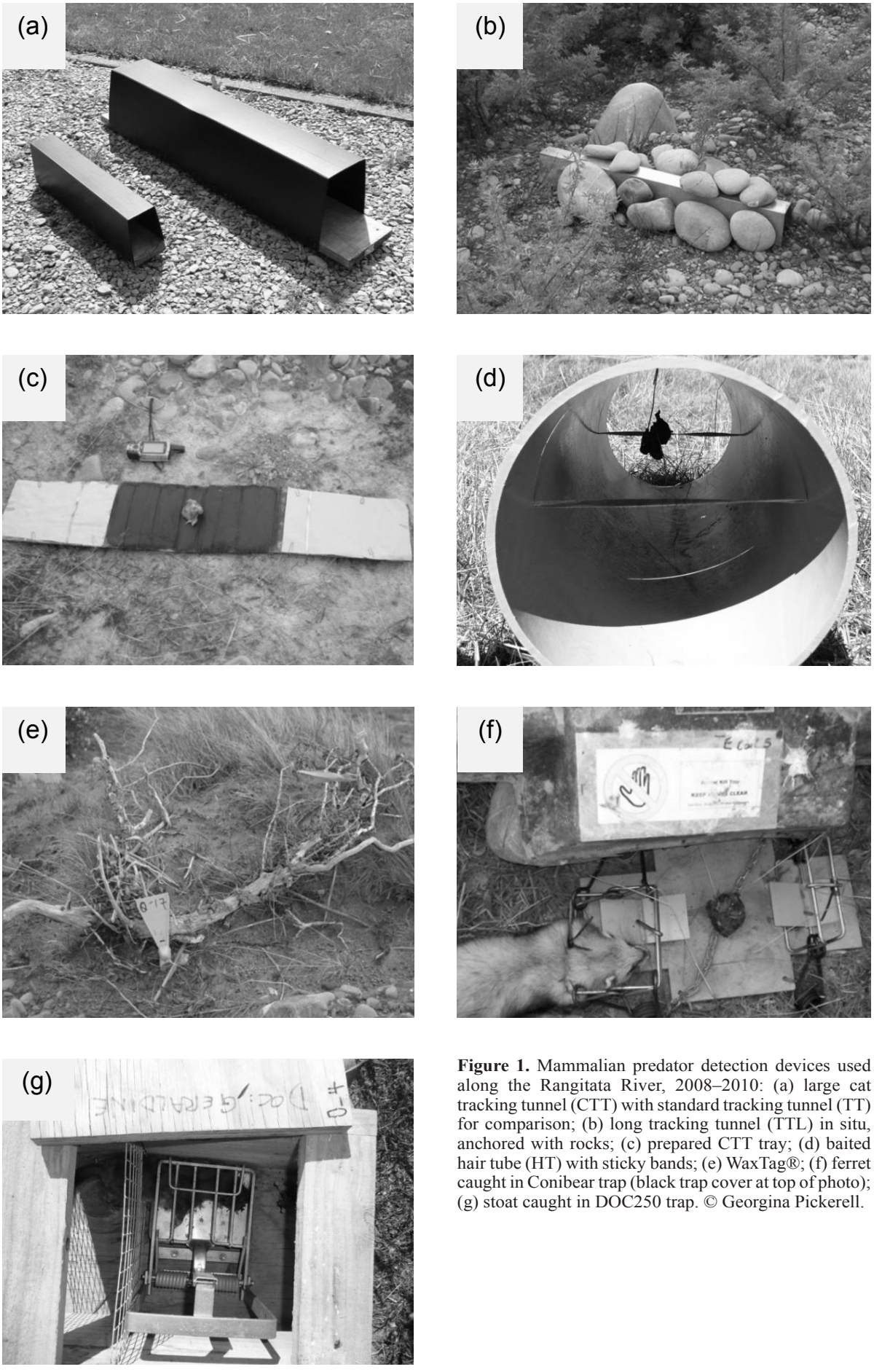


Figure 1. Mammalian predator detection devices used along the Rangitata River, 2008–2010: (a) large cat tracking tunnel (CTT) with standard tracking tunnel (TT) for comparison; (b) long tracking tunnel (TTL) in situ, anchored with rocks; (c) prepared CTT tray; (d) baited hair tube (HT) with sticky bands; (e) WaxTag®; (f) ferret caught in Conibear trap (black trap cover at top of photo); (g) stoat caught in DOC250 trap. © Georgina Pickerell.

Systematic searches

We trialled two methods of systematic searching for predator sign: edge transects and inland plots. For edge transects, the river channel edge nearest to where the other detection techniques were positioned was walked once by one person at c. 3 km per hour. Fresh scat and tracks of mammalian predators were carefully looked for up to 10 m from the channel in areas of bare wet sand or silt, where tracks showed up well. Edge transects were searched at only 16 sites because three sites had a combination of dense channel-edge vegetation and deep water that prevented access to the channel. For inland plots 10 circular plots, 10 m in diameter and 100 m apart in a line parallel to the river edge, were searched once for fresh scat and footprints. Plots were in the vicinity of the other detection devices and contained a mixture of vegetation types. Because of logistic constraints, systematic searching of inland plots was carried out at only 10 sites. Any sign that was not readily identified in the field was photographed for later verification.

All devices were well-anchored to the ground with rocks, and in some cases metal pegs. With the exception of wax tags, devices were placed at least 10 days prior to being opened and were not pre-baited. On opening, the plastic tray, ink and paper (tracking tunnels) or sticky elastic bands (HT) were placed in the device along with the bait. WaxTags® were placed and simultaneously opened at the commencement of the survey session.

Survey line composition

Each survey line consisted of three CTT, alternating with three HT (Fig. 2). In addition, one TTL was placed within an average of 15 m of each CTT and one TT was placed a similar distance from each HT. This resulted in a cluster of detection devices every 200 m, with each cluster designed to detect the full range of mammalian predators expected to be present. WaxTags® were placed near and between these clusters. We placed kill traps near the non-capture technique we were comparing them with: one Conibear trap in the vicinity of each CTT, and a DOC250 trap in the vicinity of each TT and TTL. Monitoring devices within a line were not considered to be independent of one another and we assumed that all devices were equally available to detect mammals.

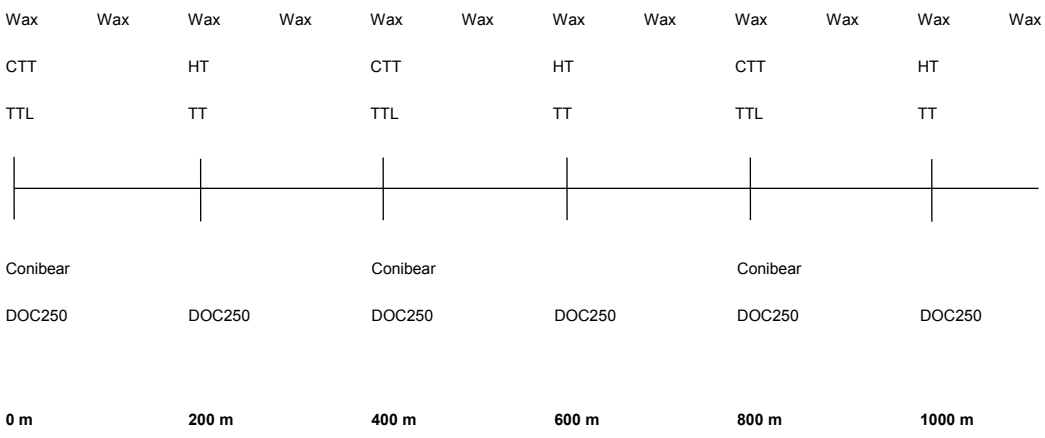
Sampling regime

All techniques on a line were trialled simultaneously except kill traps, which were opened after the other survey methods had finished. Tracking tunnels and HT were run for a minimum of 21 'good tracking' nights, i.e. nights when the ink in the tracking tunnels and the sticky elastic bands in the hair tubes were free of wind-blown sand and/or floodwater. If devices were covered in sand or had been flooded at the time of checking we assumed they had been operable only for half of the time since the previous check, unless the exact time of gales or high water was known. WaxTags® and kill traps were assumed to be always operational unless they had been affected by floods.

Large floods disrupted monitoring in 2008 and 2009; one line was surveyed for 10 tracking nights only, and monitoring on others was temporarily suspended until devices could be accessed and replaced if necessary. There was no disruption to monitoring in 2010. Flooding and bad weather meant we surveyed for periods longer than the techniques required at 14 sites because the data were needed for another study; we used the extra data in one of our analyses reported below.

Identification of predators

Footprints in tracking tunnels were identified based on Ratz (1997) and Gillies & Williams (2002), with unidentified prints sent to Craig Gillies (DOC, Hamilton) for clarification. In 2008 and 2009, hair samples were sent to EcoGene (Auckland, NZ) for DNA analysis to identify species. DNA from hair samples was extracted using a Corbett X-tractor Gene robot and ready-made reagents from Qiagen® following the manufacturer's instructions. Species identification was accomplished by amplification of a highly conserved region of the mitochondrial cytochrome b gene common across a wide range of vertebrates (primers CB-J-10612 and CB-N-10920; Kocher et al. 1989) (R. Howitt, EcoGene, pers. comm.). In 2010, hair samples were identified to species by setting in 50% polyvinyl acetate (PVA) glue and examining the scale casts under a microscope (Brunner & Coman 1974; Teerink 1991). WaxTag® chew marks were identified according to an unpublished guide and examples provided by Malcolm Thomas (Pest Control Research, Christchurch, NZ). In addition, some tags were sent to Mr Thomas for identification of bite marks. Species that



Key: CTT = cat tracking tunnel; TT = standard tracking tunnel; TTL = longer tracking tunnel; HT = hair tube; Wax = WaxTag®; Conibear and DOC250 are kill traps.

Figure 2. Diagram showing the relative placement of mammalian predator detection devices along a 1.1-km survey line on the banks of the Rangitata River, 2008–2010.

could not be identified, e.g. because of indistinct ink prints or poor hair samples, were recorded as 'Unidentified' and excluded from analyses.

Comparing detection techniques

For each species, we used data only from sites where the species was known to be present, based on the results of any survey technique or on incidental evidence – such as fresh footprints or a sighting – during the survey session. We compared the detection rates of each species by the different techniques, with three metrics:

1) *Raw detection rates*. We looked at the proportion of lines where a species was known to be present and was detected by a given technique.

2) *Time to first detection*. We used Kaplan–Meier (K–M) survival analysis (Kaplan & Meier 1958) to assess the time to detection (an 'event') of a species. This metric was used only for the repeatedly checked devices (CTT, TT, TTL, HT and WaxTags®). The time to detection was defined as the number of days a technique took to first identify the presence of a species at a site. Detection time was assigned to the mid-point between checks. Estimates of time to detection may be biased upwards for wax tags, which were checked less frequently compared with other techniques. This approach accommodates right-censored data, allowing us to use data from all survey lines, regardless of the length of time that line was open. Data were right-censored if monitoring finished on a line before a predator species had been detected by that technique. K–M survival analysis assumes that the probability of recording an event is independent and constant over the survey period. For each species, K–M estimates for each technique were compared using the Gehan–Breslow test, a weighted estimation for Cox regression, implemented within the package 'coxphw' (Ploner & Heinze 2009) in R 2.14.2 (R Development Core Team 2011). The Gehan–Breslow test is the most conservative of the modified Wilcoxon tests and places most weight on earlier events when the sample size is largest. K–M estimates were then converted to cumulative incidence estimates by subtracting 'survival' rates from 1. Cumulative incidence curves revealed how many nights of monitoring were needed by each technique before a species was detected on any given percentage of lines.

3) *Probability of detection* (POD; MacKenzie et al. 2002). This metric assumes detections of a species are independent across surveys and techniques and that detectability and site occupancy do not change during the course of the survey (e.g. Gompper et al. 2006; O'Connell et al. 2006; Long et al. 2007). The advantages of this analysis are two-fold: missing data can be accommodated, e.g. if a particular technique was not used at a site in a particular year, or monitoring was carried out for less than the specified time and a species had not been detected within that time. The other advantage is that it can be used to compare all nine techniques. Given that a species was present at a site, its presence or absence as determined by a particular detection technique is represented as a series of '1's and '0's, respectively. For example, 100101010 denotes the detection history of a species on one survey line as detected using techniques 1, 4, 6 and 8, but not detected with techniques 2, 3, 5, 7 or 9 (Table 2). We used the programme PRESENCE 3.1 (Hines 2006) to construct two single-season models for each species: one where POD varied between techniques and one where it did not. Occupancy rates were kept constant in both models. Maximum likelihood techniques were used to fit the models and models were selected based on their Akaike Information Criteria (AIC) value (Burnham & Anderson 2002). Akaike weights were then used to produce model-averaged POD estimates and their associated standard errors (Burnham & Anderson 2002). PRESENCE frequently warned that models had failed to converge. However, we considered all models to be valid because the model convergence was accurate to more than two significant digits, meaning the warnings can be ignored (Hines 2011). In some models, estimates near 0 or 1 had very large standard errors, which are acceptable because when real parameters are 0 or 1 their associated standard errors are undefined, and standard errors of the estimated parameters are therefore expected to be large (Hines 2011).

Each survey line was considered to be independent in analyses. However, it is possible that some animals' home ranges included multiple lines. Many predator species can have linear home ranges of 5 km or more (stoats: Murphy & Dowding 1994; cats: Pierce 1987; Norbury et al. 1998a, b; hedgehogs: Moss 1999 cited in Moss & Sanders 2001) although these may vary depending on season, prey density, habitat type, etc. Logistic constraints prevented our survey sites being >5 km apart. Two lines surveyed in consecutive years overlapped in their placement by 350 m, and two sites had parallel survey lines (558 m apart on average) operating at the same time but separated by a series of spring-fed channels. DNA results (GP, unpubl. data) showed that the same cat was present on the overlapping lines in the two years, and a different individual cat was present at two other lines 2.93 km apart in the same year, so for cats on four out of 19 survey lines the assumption of independence was not supported. The resulting underestimated standard errors might affect conclusions for this species.

Investigating survey effort

We used the K–M and POD approaches to evaluate two components of the survey effort needed to detect a predator species at a site. We were interested to know (1) how detection rates would be affected if we reduced our survey effort by using fewer devices per survey line, and (2) with the same number of devices as in our study, how many nights of monitoring would be needed to obtain high detection rates for each species; following Conway et al. (2004) we used a 90% POD level. We limited our investigations to those techniques that had worked well, i.e. had recorded a given species on over 60% of lines where it was present (Table 3).

Number of devices per site

We subsampled our data to investigate effects of reducing the number of CTT, TT, TTL, HT and WaxTags® per survey line. We generated new detection histories for: (1) two CTT, TT, TTL or HT placed 800 m apart per line by using the results from the 1st and 3rd devices on each line; (2) one CTT, TT, TTL or HT per line by randomly selecting the result from either the 1st, 2nd or 3rd device on each line; (3) six WaxTags®, placed 200 m apart, by randomly selecting one of two combinations of wax tags – odd-numbered or even-numbered; and (4) three WaxTags® at 400-m intervals by randomly selecting results from one of four combinations of wax tags: 1st, 5th, 9th or 2nd, 6th, 10th and so on. We repeated the K–M analyses to compare these new detection rates for each species with the original.

Number of nights

For each species, we used the following equation to convert POD per survey (Table 4) to POD per night (MacKenzie & Royle 2005):

Table 3. Raw detection rates (number of survey lines where a species was detected by technique / number of lines where technique was used and where that species was known to be present) of mammalian predator species on the Rangitata River, 2008–2010, using nine detection techniques. The best techniques for each species are highlighted in bold text.

Species	Total no. lines detected	Cat tracking tunnel	Standard tracking tunnel	Longer tracking tunnel	Hair tube	WaxTag®	Conibear trap	DOC250 trap	Search – Edge	Search – Inland
Cat	19	**0.947 (18/19)**	0.632 (12/19)	0.421 (8/19)	**0.947 (18/19)**	0.056 (1/18)	0.625 (5/8)	0.000 (0/8)	0.375 (6/16)	0.200 (2/10)
Ferret	13	0.692 (9/13)	0.615 (8/13)	0.538 (7/13)	**0.769 (10/13)**	0.000 (0/12)	0.400 (2/5)	0.400 (2/5)	0.000 (0/11)	0.000 (0/7)
Stoat	8	0.250 (2/8)	**0.500 (4/8)**	0.250 (2/8)	**0.500 (4/8)**	0.000 (0/8)	0.000 (0/4)	**0.500 (2/4)**	0.000 (0/7)	0.000 (0/4)
Weasel	3	**0.667 (2/3)**	**0.667 (2/3)**	0.000 (0/3)	0.333 (1/3)	0.000 (0/3)	0.000 (0/3)	0.333 (1/3)	0.000 (0/2)	0.000 (0/1)
Hedgehog	18	**0.941 (16/17)**	0.471 (8/17)	0.529 (9/17)	0.000 (0/17)	0.778 (14/18)	0.375 (3/8)	0.625 (5/8)	0.000 (0/15)	0.500 (5/10)
Norway rat	11	0.200 (2/10)	0.200 (2/10)	0.000 (0/10)	0.091 (1/11)	**0.300 (3/10)**	0.000 (0/6)	0.000 (0/6)	0.222 (2/9)	0.167 (1/6)
Mouse	17	0.562 (9/16)	0.588 (10/17)	**0.750 (12/16)**	0.125 (2/16)	0.467 (7/15)	0.000 (0/7)	0.000 (0/7)	0.000 (0/14)	0.111 (1/9)
Possum	10	0.111 (1/9)	0.111 (1/9)	0.111 (1/9)	0.000 (0/9)	**0.900 (9/10)**	0.000 (0/4)	0.000 (0/4)	0.222 (2/9)	0.333 (1/3)
Unidentifiable mustelid	8	0.250 (2/8)	0.500 (4/8)	0.250 (2/8)	0.125 (1/8)	0.000 (0/8)	0.000 (0/4)	0.000 (0/4)	0.000 (0/6)	0.000 (0/4)
Unidentified	19	0.056 (1/18)	0.778 (14/18)	0.278 (5/18)	0.278 (5/18)	0.474 (9/19)	0.000 (0/8)	0.000 (0/8)	0.000 (0/16)	0.000 (0/10)
Total no. species*		**8**	**8**	**6**	**6**	**5**	**3**	**4**	**3**	**5**

*Excluding 'Unidentifiable mustelid' and 'Unidentified'

$$POD_{night} = 1 - (1 - POD_{survey})^{1/n}$$

where n = number of nights per survey (i.e. 21, 24 or 30). POD_{night} was then used to determine the number of nights of monitoring a technique needed to achieve a 90% POD. Where $POD_{survey} = 1$ we substituted 0.99999999 into our calculations to eliminate an improbable result of $POD_{night} = 1$.

Results

Species detected

Our techniques detected eight out of nine possible species of introduced mammalian predator (Table 3). Although rat prints could not be assigned to species, the presence of Norway rat was confirmed from DNA results and kill trap data, and subsequently all rat sign was assumed to be Norway rat; ship rats were the only unrecorded predator species. Weasels were confirmed from only three survey lines in only one year and the resulting small sample size makes inference unreliable, although we have included the results here. Footprints of ferrets and stoats, and stoats and weasels, can overlap in size and it is then not possible to assign prints to a species with certainty. In these cases, the species were recorded as 'Unidentifiable mustelid' and excluded from our analyses. Most unidentifiable mustelid prints were either ferrets or stoats. For size comparisons, we assumed we were unlikely to see prints of juvenile ferrets or stoats before November.

Efficiency of detection techniques

The three metrics we used to compare techniques gave similar results. Probability of detection (POD) analysis showed that the model that best described weasel and Norway rat detection rates was the model with constant POD; i.e. no particular detection technique worked better than any other did. For the other species, the best model was one where detection probability varied with technique (Table 4). The Gehan–Breslow tests did not converge if a technique had failed to detect a species (Table 5), and therefore no comparison was possible with the other techniques for that species.

Cat tracking tunnels (CTT) and standard tracking tunnels (TT) were the only techniques that recorded all eight of the species present on the 19 survey lines (Table 3). Searching the channel edge proved the least reliable technique, detecting only three species at 16 sites. CTT were especially efficient at detecting cats and hedgehogs (Tables 3–5). Kaplan–Meier survival analysis (K–M) estimated the CTT detection rate for cats as 68% after 5 nights and almost 95% after 13 nights, and for hedgehogs as 94% after 21 nights (Fig. 3). CTT also performed well at detecting ferrets, with detections on over half the lines within 6 nights. TT were moderately good at detecting cats, ferrets, stoats and mice (raw detection rates: 50–63%, Table 3; POD: 45–67%, Table 4); at least 12 nights were needed for a >50% detection rate of these species (Fig. 3). Notably, TT had the highest rate of unidentifiable results of any of the techniques we tested. Longer tracking tunnels (TTL) were the most efficient technique for detecting mice but performed comparatively less well for other species.

Hair tubes (HT), like CTT, were a very efficient technique for detecting cats (Fig. 3; Tables 3–5). Two of the three metrics showed also that HT were the most efficient technique (although not significantly so) for detecting ferrets, with >50% detection within 5 nights and 77% detection after 19 nights. HT were also one of the better techniques for detecting stoats, although our sample size was small and detection rates did not exceed 0.5. We cannot say with confidence that hedgehogs did

Table 4. Model-averaged probability of detection estimates, with standard errors (SE), of two candidate models with constant site occupancy (ψ(.)) and detection probabilities that are either constant (p(.)) or vary with technique (p(method)). $\hat{p}$ = estimated probability of detection (given presence) using each technique for mammalian predators on the Rangitata River, 2008–2010. Abbreviations: CTT = cat tracking tunnel; TT = standard tracking tunnel; TTL = longer tracking tunnel; HT = hair tube; Wax = WaxTag®; Conibear = Conibear trap; DOC250 = DOC250 trap; Edge = search channel edge; Inland = search inland plots.

Species	Model	Model weight	$\hat{p}$CTT	$\hat{p}$TT	$\hat{p}$TTL	$\hat{p}$HT	$\hat{p}$Wax	$\hat{p}$Conibear	$\hat{p}$DOC250	$\hat{p}$Edge	$\hat{p}$Inland
Cat	ψ(.), p(method)	1.000	1.000	0.667	0.444	1.000	0.059	0.625	0.000	0.400	0.200
	ψ(.), p(.)	0.000	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534
	model-avg est		**1.000**	**0.667**	**0.444**	**1.000**	**0.059**	**0.625**	**0.000**	**0.400**	**0.200**
	SE		0.000	0.111	0.117	0.000	0.057	0.171	0.000	0.126	0.126
Ferret	ψ(.), p(method)	1.000	0.749	0.666	0.582	0.832	0.000	0.498	0.498	0.000	0.000
	ψ(.), p(.)	0.000	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439
	model-avg est		**0.749**	**0.666**	**0.582**	**0.832**	**0.000**	**0.498**	**0.498**	**0.000**	**0.000**
	SE		0.125	0.136	0.142	0.108	0.000	0.250	0.250	0.000	0.000
Stoat	ψ(.), p(method)	0.813	0.250	0.500	0.250	0.500	0.000	0.000	0.500	0.000	0.000
	ψ(.), p(.)	0.187	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237
	model-avg est		**0.248**	**0.451**	**0.248**	**0.451**	**0.044**	**0.044**	**0.451**	**0.044**	**0.044**
	SE		0.135	0.190	0.135	0.190	0.073	0.073	0.248	0.073	0.073
Weasel	ψ(.), p(.)	0.920	0.261	0.261	0.261	0.261	0.261	0.261	0.261	0.261	0.261
	ψ(.), p(method)	0.080	0.667	0.667	0.000	0.333	0.000	0.000	0.333	0.000	0.000
	model-avg est		**0.293**	**0.293**	**0.240**	**0.267**	**0.240**	**0.240**	**0.267**	**0.240**	**0.240**
	SE		0.126	0.126	0.106	0.107	0.106	0.106	0.107	0.106	0.106
Hedgehog	ψ(.), p(method)	1.000	0.941	0.471	0.529	0.000	0.778	0.375	0.625	0.067	0.500
	ψ(.), p(.)	0.000	0.480	0.480	0.480	0.480	0.480	0.480	0.480	0.480	0.480
	model-avg est		**0.941**	**0.471**	**0.529**	**0.000**	**0.778**	**0.375**	**0.625**	**0.067**	**0.500**
	SE		0.057	0.121	0.121	0.000	0.098	0.171	0.171	0.064	0.158
Norway rat	ψ(.), p(.)	0.961	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141
	ψ(.), p(method)	0.039	0.200	0.200	0.000	0.091	0.300	0.000	0.000	0.222	0.167
	model-avg est	**-**	**0.143**	**0.143**	**0.136**	**0.139**	**0.147**	**0.136**	**0.136**	**0.144**	**0.142**
	SE		0.043	0.043	0.043	0.042	0.046	0.043	0.043	0.044	0.044
Mouse	ψ(.), p(method)	1.000	0.562	0.588	0.750	0.125	0.400	0.000	0.000	0.000	0.111
	ψ(.), p(.)	0.000	0.342	0.342	0.342	0.342	0.342	0.342	0.342	0.342	0.342
	model-avg est		**0.562**	**0.588**	**0.750**	**0.125**	**0.400**	**0.000**	**0.000**	**0.000**	**0.111**
	SE		0.124	0.119	0.108	0.083	0.126	0.000	0.000	0.000	0.105
Possum	ψ(.), p(method)	1.000	0.125	0.125	0.125	0.000	1.000	0.000	0.000	0.250	0.333
	ψ(.), p(.)	0.000	0.227	0.227	0.227	0.227	0.227	0.227	0.227	0.227	0.227
	model-avg est		**0.125**	**0.125**	**0.125**	**0.000**	**1.000**	**0.000**	**0.000**	**0.250**	**0.333**
	SE		0.117	0.117	0.117	0.000	0.000	0.000	0.000	0.153	0.272

not visit the hair tubes, just that neither DNA nor hair scale analysis detected their presence. WaxTags® were easily the best of our techniques at detecting possums (Fig. 3; Tables 3–5), with 90% detection within 5 nights. WaxTags® were also good at detecting hedgehogs. Although no method was good at detecting Norway rats, WaxTags® performed slightly better than the other techniques.

Although the Conibear trap's detection rate of cats was >60%, this was lower than CTT and HT levels. Also, detection rates for ferrets and hedgehogs using this technique were typically lower than for the non-capture methods, but standard errors were large (Tables 3, 4). DOC250 traps detected ferrets, stoats, weasels and hedgehogs. This technique's moderate detection rate for stoats equalled the highest of the non-capture methods for that species, and it was the third best technique for detecting hedgehogs, with a detection probability of 62.5% after 30 nights.

Searching the channel edge detected cats, Norway rats and possums, but detection rates were not high for any of these species using this technique (Tables 3, 4). Searching inner plots resulted in low detection rates for all species except hedgehogs. However, we could not search the occasional plot owing to very dense vegetation, which may have negatively biased the results.

Survey effort

Number of devices per line

Simulating fewer devices on our survey lines predicted reduced detection rates but, for most species and devices, this reduction was statistically significant only when the number of devices reached the lowest levels simulated (Table 6). This indicates that a moderate reduction in survey effort may not harm the ability to detect a species.

Number of nights

Our simulations showed that the better techniques would require between 3 and 71 nights of monitoring to achieve 90% POD of a species (Fig. 4). Fewer than 20 nights were needed in only four cases: CTT and HT detecting cats, CTT detecting hedgehogs, and WaxTags® detecting possums. The simulations emphasised also the differences in detection efficiencies between the non-capture and kill-trap techniques. Three CTT or HT per line were predicted to take 3 nights for a 90% POD of cats, compared with 71 nights with three Conibear traps. A 90% POD for hedgehogs would take 18 nights with three CTT, but 71 nights with six DOC250 traps.

Table 5. Comparing the efficiency of five non-capture techniques for detecting the presence of mammalian predators on the Rangitata River, 2008–2010. *P*-values are for Gehan–Breslow tests comparing pairs of Kaplan–Meier survival analysis curves (*$P \leq 0.05$). Sample size is in brackets. Abbreviations: CTT = cat tracking tunnel; TT = standard tracking tunnel; TTL = longer tracking tunnel; HT = hair tube; NC = non-convergence.

Species		Standard tracking tunnel	Longer tracking tunnel	Hair tube	WaxTag®
Cat (*n* = 19)	CTT	0.002*	<0.001*	0.634	<0.001*
	TT		0.076	0.007*	0.003*
	TTL			<0.001*	0.017*
	HT				<0.001*
Ferret (*n* = 13)	CTT	0.440	0.169	0.958	NC
	TT		0.546	0.445	NC
	TTL			0.165	NC
	HT				NC
Stoat (*n* = 8)	CTT	0.327	0.744	0.247	NC
	TT		0.423	0.860	NC
	TTL			0.374	NC
	HT				NC
Hedgehog (*n* = 18)	CTT	0.092	0.068	NC	0.794
	TT		0.972	NC	0.087
	TTL			NC	0.093
	HT				NC
Norway rat (*n* = 11)	CTT	0.801	NC	0.384	0.964
	TT		NC	0.536	0.709
	TTL			NC	NC
	HT				0.264
Mouse (*n* = 17)	CTT	0.782	0.243	0.003*	0.310
	TT		0.282	0.001*	0.221
	TTL			<0.001*	0.042*
	HT				0.017*
Possum (*n* = 10)	CTT	0.831	0.940	NC	0.033*
	TT		0.887	NC	<0.001*
	TTL			NC	<0.001*
	HT				NC

Table 6. Comparing the efficiency of mammalian predator detection techniques deployed at different densities along a 1.1-km survey line on the banks of the Rangitata River. Simulations were restricted to non-capture techniques that were most efficient at detecting a species. *P*-values are for Gehan–Breslow tests comparing pairs of Kaplan–Meier survival analysis curves (*$P \leq 0.05$; **$P \leq 0.10$). Grey shaded cells = not applicable. Abbreviations: CTT = cat tracking tunnel; TT = standard tracking tunnel; TTL = longer tracking tunnel; HT = hair tube.

Species	Technique	Number of devices per survey line			
		3 versus 2	3 versus 1	12 versus 6	12 versus 3
Cat	CTT	0.476	0.007*		
	TT	0.437	0.163		
	HT	0.079**	0.024*		
Ferret	CTT	0.707	0.001*		
	HT	0.751	0.028*		
Hedgehog	CTT	0.732	0.021*		
	WaxTags®			0.218	0.008*
Mouse	TTL	0.675	0.091**		
Possum	WaxTags®			0.203	0.043*

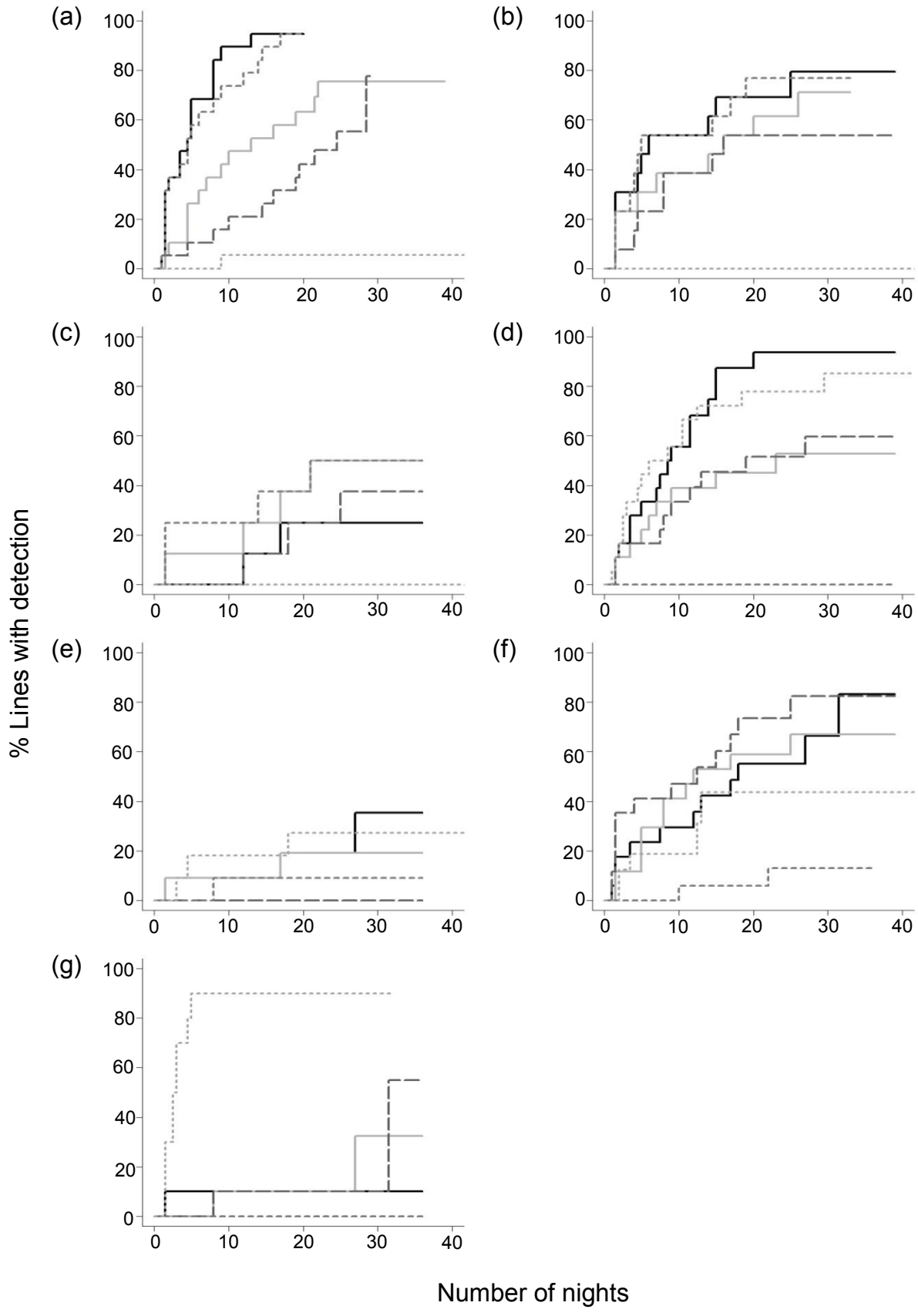


Figure 3. Cumulative incidence curves showing detection rates of survey lines on the banks of the Rangitata River, 2008–2010, for (a) cats (n = 19); (b) ferrets (n = 13); (c) stoats (n = 8); (d) hedgehogs (n = 18); (e) Norway rats (n = 11); (f) mice (n = 17); (g) possums (n = 10) using five different techniques: 3 cat tracking tunnels (———), 3 standard tracking tunnels (———), 3 longer tracking tunnels (— — —) or 3 hair tubes (– – – – –) at 400 m; 12 WaxTags® (--------) at 100 m; 95% confidence intervals are omitted for clarity. Horizontal axes are limited to 40 nights as there were no new detection events after this time.

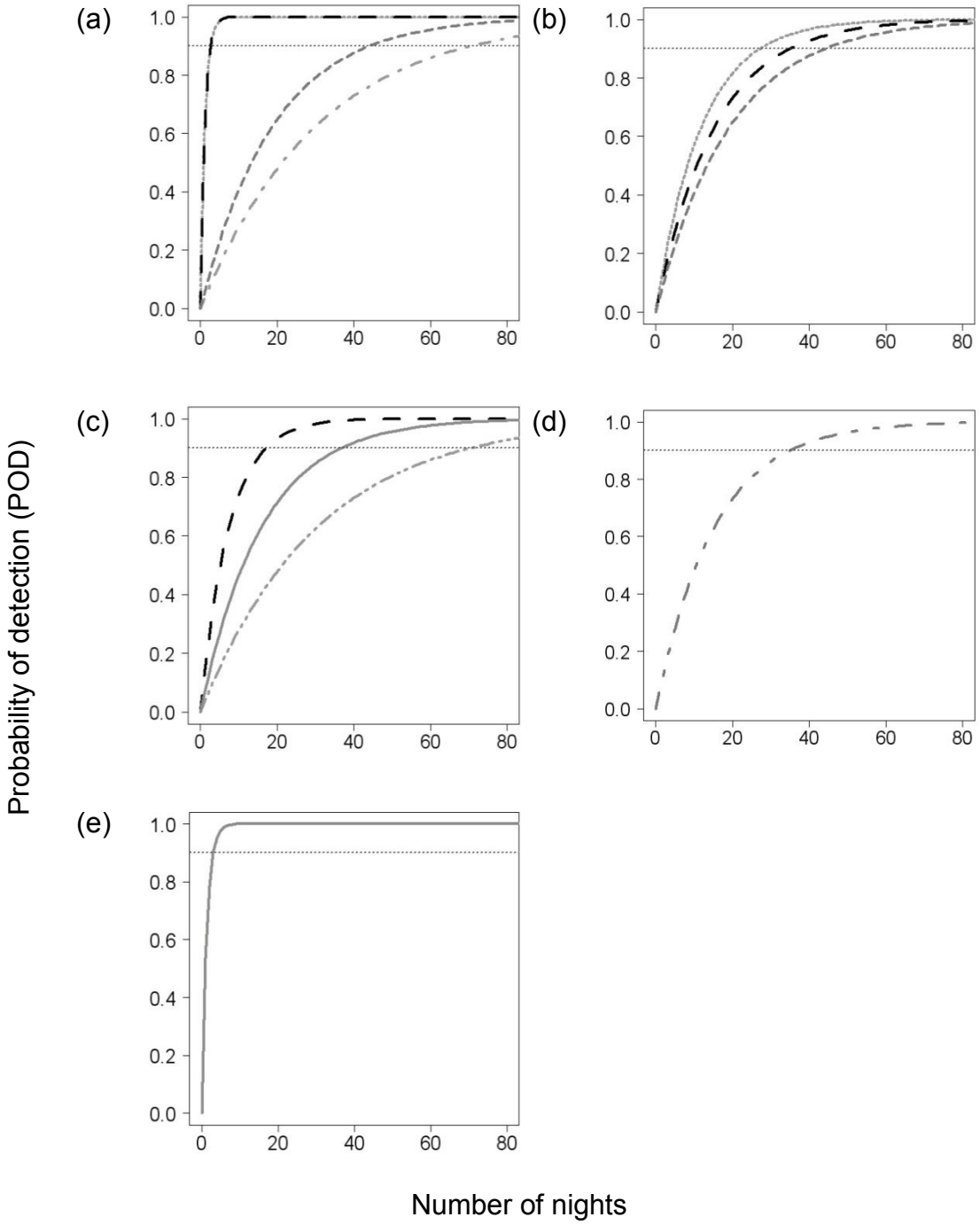


Figure 4. Number of nights of monitoring needed per technique for a 90% probability of detecting a mammalian predator on the banks of the Rangitata River: (a) cats; (b) ferrets; (c) hedgehogs; (d) mice; (e) possums. Techniques: 3 cat tracking tunnels (— — —), 3 standard tracking tunnels (- - - - -), 3 longer tracking tunnels (— - - — —) or 3 hair tubes (·····) at 400 m; 12 WaxTags® (————) at 100 m; 3 Conibear traps (— - — - —) at 400 m; or 6 DOC250 traps (— - - — - -) at 200 m. Devices were placed linearly**.**

Discussion

Relative efficiency of the detection techniques

The nine survey techniques varied in their ability to confirm the presence of mammalian predator species that were known to be present at a site and each technique had advantages and disadvantages in the braided river environment.The severe weather conditions that can occur on braided rivers mean some detection techniques may not work efficiently all the time. Large cat tracking tunnels (CTT) and standard-sized tracking tunnels (TT) were the only techniques that detected all eight species. These two tunnel types, placed 200 m apart, were closer to other types of monitoring devices on a line than they were to each other. Although this result indicates animals might have shown a preference for these devices, differences in detection efficiency also can be attributed to features that limited a technique's ability to detect all the species. The most obvious examples of this are the Conibear and DOC250 traps, which mice are too light to trigger, and the hair tubes (HT), in which small animals can avoid the sticky bands.

Non-capture devices

Some techniques detected certain species particularly well. The detectability of cats, hedgehogs and ferrets using non-capture techniques was notably high at a time of year when trapping studies have reported low catch rates of these species (Moller et al. 1996; Cleland et al. 2007, 2008; Lal 2008). Three large CTT spaced approximately 400 m apart were particularly efficient at detecting cats, and they also proved reliable for detecting hedgehogs – much better than the standard-sized TT – and ferrets. Sullivan (2010) also found the CTT better than TT at detecting hedgehogs in her trial at the Ashburton Lakes. We know of only one prior study where large CTT were used to monitor cats. In 2005 and 2006, one wooden CTT was placed at the end of each established TT monitoring line in the Tasman Valley and opened for 3 nights (Cleland et al. 2007) in accordance with standardised protocols for indexing population sizes (Gillies & Williams 2007). These CTT (and other TT) detected so few of the target predator species compared with nearby kill traps that the monitoring lines were subsequently discontinued (R. Maloney, DOC, pers. comm.). We suggest that the CTT were not opened and rebaited for long enough in this Tasman Valley monitoring programme. Since the start of our study, CTT have been trialled at other sites including a wetland (Sullivan 2010), tussock-dominated high country, and coastal scrub; they have detected cats and other species when left open for at least 10 nights (J. Smith, Landcare Research, pers. comm.; J. Young, Yellow-eyed Penguin Trust, pers. comm.).

Hair tubes had an equally high cat-detection probability as CTT, and they were also good for detecting ferrets. The diameter of the HT we used was too large to easily pick up hairs from stoats, weasels, rats and mice; a smaller diameter tube is used by Landcare Research for stoat research (Horton et al. 2005), but we found in a 2007 trial that larger animals frequently interfered with the bait in these smaller tubes (GP, pers. obs.). Using three TT at 400-m intervals did not detect any species particularly well, and they had a much higher incidence of unidentifiable results than the other techniques. Our probability of detection cannot be compared with those from established protocols for monitoring rodents and mustelids where 10 or 5 TT are spaced along a transect at 50-m or 100-m intervals, respectively (Gillies & Williams 2007).

Mice are not considered important predators of braided river birds, but they are known to take eggs and chicks in other environments (Angel et al. 2009). We found the best of our techniques for detecting them was the longer tracking tunnels (TTL), possibly the result of a predator avoidance strategy by the mice, as larger predators entered this type of tracking tunnel least frequently. Mouse detectability with TTL was 41% after 4 nights, which may have been improved had we used a higher density of TTL and baited with peanut butter (Nathan et al. 2013). TTL may have detected larger predators inefficiently because the length of the TTL relative to its cross-sectional area either (1) physically stopped predators reaching the ink pad, or (2) meant that the device was not 'open' enough to attract a predator inside (O'Farrell et al. 1994; Wilson et al. 2007). WaxTags® were the only device that detected possums well, with detection after 5 nights on all but one line where possums were present. Peanut butter may be superior to meat as a lure for possums. These tags also detected hedgehogs well, and were one of the better techniques for detecting Norway rats as Sullivan (2010) also found in the Ashburton Lakes area. As more WaxTags® were used per line compared with the other techniques, their detection rate would have been relatively enhanced for species with small home ranges. However, Nathan et al. (2013) found that mouse detectability was higher in TT baited with peanut butter than at peanut-butter-flavoured WaxTags®.

Kill traps

Kill traps were deployed on fewer lines compared with the non-lethal techniques, and therefore sample sizes were small. With the exception of stoats, the kill traps appeared less efficient than the non-capture methods at detecting species, although associated standard errors were large. However, there were only three instances where a species was known to be present solely from kill-trap data: two lines where a stoat was detected by a DOC250 and one line where hedgehogs were detected by both types of kill trap. If anything, we had expected kill traps to be more efficient than tracking tunnels, as Cleland et al. (2007) found in the Tasman Valley. We set twice as many DOC250s as each of the tracking tunnel types, HT and Conibear traps, which should have favoured the detection of species with small home ranges. Also, because kill traps were opened after at least 3 weeks of rebaiting of the nearby tracking tunnels and HT, animals should have become habituated to the easy availability of food. One disadvantage of the kill traps was that they were baited only once, so as the meat spoilt, their attractiveness was likely to decline. However, a pilot study in 2007 using the same kill traps, but rebaiting every 3–4 nights with fresh meat, showed detection probabilities were still lower than those for tracking tunnels and HT (GP, unpubl. data). Use of DOC150 and DOC200 traps may have increased the detectability of rats, weasels and stoats, but these traps do not meet the National Animal Welfare Advisory Committee (NAWAC) standards for ferrets (Poutu & Warburton 2005). Likewise, we were restricted from using Fenn Mark VI traps (FHT Works, Worcestershire, England), which Gillies et al. (2003) found caught the most ferrets and cats, because of their NAWAC status. Soft-jaw Victor leg-hold traps (Woodstream Corporation, USA) are known to have a higher catch rate than the Conibear setup we used (Cleland et al. 2007, 2008; Lal 2008), but logistical constraints prevented us from carrying out the required daily checks.

Searching

Incidental sightings of tracks and scat in all areas of the river during the course of the study identified the presence of all predator species except mice and weasels. Therefore, systematic searching for sign had the potential to be a good detection technique. Furthermore, we expected animals' activities to be concentrated along the channel edge, being a linear feature and probably a barrier to further movement. However, searching for prints and scat along the channel edge detected only three species and provided just one unique detection (i.e. a species was not detected using any of the other techniques): a Norway rat. Reasons for this lack of success may have been that the channel edge was sometimes far from vegetative cover, and varied in the amount of suitable substrate available to be tracked. Searching inland plots detected more species, possibly because these sites tended to be more vegetated.

Reasons for poor detection rates

No matter which technique we used, Norway rat and stoat detection was poor. Norway rats are notoriously neophobic (Thorsen et al. 2000; Clapperton 2006) and stoats are hard to detect at low population densities (Choquenot et al.

2001). Using the edge search method proved invaluable for ascertaining the presence of Norway rats on islands in the Rangitata River (GP, pers. obs.). On Frégate Island, Thorsen et al. (2000) also found Norway rat presence was more commonly ascertained from incidental sightings of their footprints, especially near water. Our poor detection rates may have been due in part to the techniques we used. Our choice of bait may have reduced detection of some species; rodents and possums are usually attracted to non-meat lures (Ji et al. 1999; Clapperton 2006; NPCA 2009b). The use of peanut-butter-flavoured WaxTags® was intended to circumvent this. We did not use peanut butter as bait in the tracking tunnels or hair tubes as we did not want to make these devices so attractive to mice and possums that detection of carnivorous mammals was inhibited. The spacing of our devices will also have affected their ability to detect species with small home ranges: intervals of 25–50 m are recommended for rodent detection (Cunningham & Moors 1996).

Comparing analytical methods

The three metrics we used to assess the detection efficiency of nine monitoring techniques gave comparable results, but the raw detection rates did not allow differences between techniques to be evaluated. Kaplan–Meier (K–M) and probability of detection (POD) analysis were both useful in assessing how well particular survey techniques worked for each species, although we could not use the K–M approach to compare between all techniques. Another drawback with the K–M method is that bias increases with the proportion of data that are censored, meaning later survival estimates are less accurate than earlier ones. However, most of the detection events by our more efficient techniques occurred relatively early in the survey period, with little data censored. Therefore, this is unlikely to affect the results of these techniques. In addition, the Gehan–Breslow test placed more weight on detection events that occurred earlier in the survey period, which would reduce the likelihood of type I and II errors. POD analysis allowed us to compare all nine techniques, but variance estimates are undefined when real detection rates are close to 0 or 1 (Hines 2011). In addition, when a technique detected a species on the most lines, and other techniques did not detect that species on additional lines, the POD_{survey} estimate of the first technique was 1, regardless of whether the first method had detected the species on all the lines where it was known to be present. This POD_{survey} overestimate occurred with CTT and HT detections of cats, and WaxTag® detection of possums, but it does not affect our conclusions regarding the relative efficiency of the different techniques for detecting these species because POD_{survey} results were supported by the findings of the other two metrics we used to analyse our data.

Survey effort

A technique's detection ability depends in part on the number of devices used, but extra devices per site leads to a trade-off between increased detection probability and the cost (labour, materials and time) of servicing these devices. Our choices of the number of detection devices and their spacing along a survey line were based partly on recommended densities of tracking tunnels and traps for mustelids (NPCA 2007), with unknown efficiencies. Simulating a reduction in the number of tracking tunnels, hair tubes or wax tags per survey line indicated that the detection efficiency of a technique would be significantly reduced only when a single tracking tunnel or HT, or three WaxTags®, were used per line. Therefore, densities of devices could be reduced from the levels we used, although higher density offers some insurance against malfunction or loss. The likelihood of detecting a species also depends in part on the length of the survey period. For our best techniques, we estimated between 3 and 71 nights of monitoring would be needed for a 90% POD. Therefore, short survey periods are unlikely to result in high detection probabilities for most species and, when a high POD is desired, it is unsuitable to use methods designed to index the relative abundance of species, as many of these rely on devices set for 1 or 3 nights only. This conclusion is in agreement with the recommendations of Byrom et al. (2002) who estimated that 10 nights of trapping were needed for an 80% catch rate of female ferrets. The very short time (3 nights) predicted for a 90% POD of cats using three CTT or HT, and possums using 12 WaxTags®, is likely to be an underestimate because of the aforementioned issue with POD_{survey} estimates of 1.

Other factors affecting detectability

Season, habitat and environmental variables can influence detection probability (MacKenzie et al. 2002; O'Connell et al. 2006). Factors that may be most relevant to this study include (1) seasonal behaviours, such as breeding, juvenile dispersal and hibernation that alter activity rates and home range size, and may affect device encounter rates (Moors & Lavers 1981; Molsher 2001; Moss & Sanders 2001). The timing of this study, in spring and early summer, was chosen to coincide with the bird breeding season and not to maximise predator detectability. For example, in one study the highest catch rates of cats and ferrets were in autumn, and of hedgehogs in summer, whereas the stoat catch rate was constant (Lal 2008). (2) Inclement weather may reduce detection rates if animals are less active then (Harper 2007). (3) Fluctuations in the availability of natural food sources may also affect detectability, with fewer animals attracted to baited devices when naturally-occurring food is abundant (Molsher 2001; Short et al. 2002). There can be both functional and numerical responses by predator populations to changes in prey availability (Norbury et al. 1998b; Barlow & Norbury 2001). (4) Species at low density, either naturally or following intensive predator control, are less likely to be detected because individuals are less likely to interact with a device within the survey period (Russell et al. 2005; Watkins et al. 2010). In addition, individuals that have evaded predator control may be wary of artificial objects (King et al. 2009).

Other detection techniques

Spotlighting (NPCA 2009a) was not a feasible detection technique as a number of our study sites had dense vegetation alongside vehicle tracks. But other techniques that should be considered include using trail cameras (e.g. Foresman & Pearson 1998; Hansen 2010; Bengsen et al. 2011; Meek et al. 2012) and specially trained predator dogs (Long et al. 2007; Gsell et al. 2010; Cheyne 2011), which have been successfully used in other habitats. The open riverbed environment may be unsuitable for the prolonged use of cameras although they have been deployed on nests of riverbed birds (Keedwell & Sanders 2002; Sanders & Maloney 2002; McClellan 2009; Steffens et al. 2012). Cameras have the additional advantage of enabling identification of individual cats from markings and therefore they have the potential to provide estimates of abundance (Bengsen et al. 2011). Using dogs to detect cats and mustelids was trialled on 17 Rangitata islands (at six sites)

in 2008 and 2009. Cats were detected on seven islands with just one morning sweep each; subsequent monitoring with our techniques took an average of 9 nights per site to achieve a similar result (GP, unpubl. data). However, the dogs were less efficient at detecting mustelids compared with our combined techniques. Although the riverbed's arid environment limits the efficacy of dogs during the day (S. Theobald, DOC, pers. comm.), the positive results and potential cost-effectiveness of our trial justify further investigation of this technique. In future, it may be possible to detect mammalian predators with environmental DNA metabarcoding, a PCR-based method whereby multiple taxa can be identified from DNA extracted from an environmental sample (Taberlet et al. 2012). Successful applications of this technique include detection of invasive aquatic species (Dejean et al. 2012), but Andersen et al. (2012) highlight some issues to be addressed when identifying vertebrate species from soil samples.

Recommendations

In New Zealand, there are standardised monitoring protocols for possums (WaxTags® or leg-hold traps: NPCA 2010, 2011), rats and mustelids (tracking tunnels: Gillies & Williams 2007), which are intended primarily for indexing species' abundance rather than detecting species' presence. The protocols are most commonly used in forest and agricultural habitats. Where monitoring has been undertaken in other ecosystems, the norm has been to follow or slightly modify the existing standardised methods (e.g. Leseberg et al. 2005; Morgan et al. 2009) without knowing how well these detect the suite of species present. Our findings emphasise the merit of using more than one technique when detecting a species (Russell et al. 2008). Also for species and habitats where monitoring protocols are not already established, we recommend investigating the efficiency of different detection techniques before a monitoring programme is started. The number of detection devices and the length of the monitoring period needed for a high probability of detection will depend on the density of the species and the level of confidence in detection required. For our more efficient techniques, simple simulations showed that in most cases monitoring devices could be placed at lower densities than we used in our study without significantly affecting detection rates.

Alternatively, retaining our survey line composition, probability of detection (POD) analysis using POD_{night} indicated how detection rates could be improved by increasing the number of nights of monitoring. Based on our findings, we recommend that when undertaking a monitoring programme where determination of a species' presence is important, devices be left open for at least 10 nights and regularly rebaited where appropriate. Although our findings relate to the Rangitata River, we have no reason to believe that these conclusions would not apply to (1) other river systems, (2) other times of year, or (3) open habitats with different predator guilds. The time to detect a species may vary for reasons already discussed, although we would expect the relative efficiencies of the detection techniques to remain unaltered.

In short, when detection of a full range of mammalian predator species is desired, we recommend the use of large cat tracking tunnels (CTT), placed 400–800 m apart, and opened for at least 10 'good tracking' nights. We would especially recommend using CTT when detection of cats or hedgehogs is required. Because their size and weight limits portability, CTT should be used in conjunction with standard-sized tracking tunnels for detecting species with small home ranges and with wax tags for detecting possums. However, care is needed when placing CTT in open environments as they are susceptible to the effects of wind. We recommend also that further research be carried out to develop standardised monitoring protocols for introduced mammalian predators in New Zealand's non-forested habitats, including investigating the use of trail cameras and predator dogs.

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