

# Estimating the potential for reinvasion by mammalian pests through pest-exclusion fencing

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**Abstract.** Pest mammals are completely excluded from Maungatautari Ecological Island, New Zealand, by a 47-km Xcluder pest-proof fence; however, they are commonly sighted directly outside, along the fenceline. Permanent pest exclusion relies on maintaining fence integrity, and enhancing knowledge of pest activity and behaviour at fenced reserves. We describe summer and winter periods of activity and behaviour of mammalian pests directly adjacent to the pest-proof fence. We (1) tested for the effects of adjacent habitat type, breach type and season on the rate of mammalian pest sightings directly at the fence, (2) determined how quickly pest mammals may locate a fence breach, and how likely they are to exploit it, and (3) developed a predictive model to help assess the probability of a pest gaining entry to the sanctuary if repair to a fence breach is delayed. Observations inside the rolled fence hood provided firm evidence that rats travel and forage extensively in this artificial although highly acceptable aboveground habitat, much more than on the ground. We confirm and emphasise that mammalian pests are constantly testing the pest-proof fence. Pests are very common directly outside the fence, and within 24 h there is a very high likelihood that a fence breach will be located and exploited. The greatest threat of reinvasion comes (1) nocturnally, (2) from rodents and (3) in the summer; however, these results also confirm that there is constant risk from multiple pest species, regardless of time of day or season.

## Introduction

Pest-exclusion fences are now an established method of protecting areas of high conservation value, providing the fence design takes into account the physical abilities and behaviour of those pest animals it means to exclude (Clapperton and Day 2001). Exclusion fencing can be an especially cost-effective form of pest control for sanctuary areas that are large relative to perimeter length, and they can in theory achieve better conservation outcomes than would be gained by sustained control (Clapperton and Day 2001). The first successful example in New Zealand, the 8.6-km pest-proof barrier fence surrounding the 225-ha Karori Wildlife Sanctuary, was completed in 1999 (Karori Wildlife Sanctuary Trust 1999) and has stimulated a great demand for equivalent installations elsewhere.

Exclusion fences have had a long history in Australia and in the United Kingdom, where they usually target particular pest species such as dingoes (*Canis lupus dingo*), foxes (*Vulpes vulpes*), cats (*Felis catus*) and rabbits (*Oryctolagus cuniculus cuniculus*) (McKillop and Wilson 1987, 1999; McKillop and Silby 1988; McKillop *et al.* 1998). Results have been mixed, largely because of design faults, poor construction or insufficient maintenance (Day and MacGibbon 2002, 2007; Sanders *et al.* 2007). Unfortunately, few fence designs have been scientifically tested, fences designed to exclude only particular species (Avis and Roberts 1994) are not applicable

to the total exclusion requirements of sanctuaries and guidelines to provide advice to conservation managers are scarce (Long and Robley 2004).

The long-term effectiveness of a pest-proof fence depends on the use of high-quality materials and exacting construction techniques, combined with a comprehensive maintenance and monitoring program (Day and MacGibbon 2007). Damage to fence integrity is accepted as inevitable, because it is impossible to eliminate all chance events such as tree-fall, flood damage and gates being left open; however, once a sanctuary is pest-free, a good fence can minimise the chances of reinvasion, especially if managers are confident that they can reliably find and fix a potential breach before a pest finds and uses it.

Our objectives were to develop optimal breach-response procedures, and to find ways to quantify the risk of pest-mammal reinvasion by (1) describing baseline data on presence and activity periods of mammalian pests directly outside the fence, (2) testing for the effects of exterior habitat type, breach type and season on the number of mammalian pest sightings, (3) describing basic pest-mammal behaviour with respect to simulated fence breaches and (4) creating a simple model of the cumulative probability of at least one mammalian pest encountering a breach, according to the time of day and season the breach happens, and the speed of response by management.

## Materials and methods

### Study area

Mount Maungatautari (38°03'S, 175°33'W), an eroded andesitic volcanic cone, lies in the central Waikato, in the North Island of New Zealand (Clarkson 2002; Speedy *et al.* 2007). The mountain supports a dense mixed podocarp–broadleaf forest, covering ~3400 ha, and is completely surrounded by farmland (MacGibbon 2001). The majority of the original native fauna present on the mountain is now absent, and the remaining flora has been intensely browsed by introduced mammals for many years (McQueen 2004). The Maungatautari Ecological Island Trust was formed in the late 1990s, with the primary goal being to 'restore the diversity, vitality and resilience of the ecosystems of Maungatautari, as close as possible to the original condition, to re-create self-sustaining communities of indigenous plants and animals' (McQueen 2004).

In 2006, a 47-km Xcluder pest-proof exclusion fence (Xcluder™ Pest Proof Fencing Ltd, Rotorua, New Zealand) was completed, encircling a 3363-ha area. In total, 10 of 14 mammalian pest species known to exist within the enclosure were eradicated by aerial poison application ('Pestoff 20R' cereal pellets, containing 20 ppm brodifacoum, Animal Control Products Ltd, Wanganui, New Zealand) in 2006; by January 2008, the only pest mammals known to remain were house mice (*Mus musculus*, in isolated pockets), up to 10 goats (*Capra hircus*) and small numbers of rabbits and hares (*Lepus europaeus occidentalis*). These are being targeted in ongoing operations.

Preliminary tests of candidate fencing materials had found that the smallest hole through which a juvenile mouse could pass was 7.1 mm × 40 mm, so a mesh size of 6 mm × 25 mm was chosen to provide a safety margin (Day and MacGibbon 2002, 2007). The mesh was marine grade ('316') welded stainless steel, incorporating a 300-mm-wide, horizontal mesh 'skirt' (pinned to the ground and buried ~50 mm) to defeat digging animals. A folded Colorsteel (New Zealand Steel Ltd, Glenbrook, New Zealand) hood was attached to the top of the fence facing outside, rolled into a gutter at the outside edge for greater strength (Fig. 1) (Day and MacGibbon 2002, 2007).

Animals caught inside when the fence was closed could climb up to the top and jump out; animals climbing the fence from outside could reach the inside of the rolled hood and run along inside the gutter, but could not climb onto the top of the fence. An integrated remote alarm system installed along the top of the fence notified managers of potential breach events caused by e.g. a falling tree. Physical response to notification of a breach was usually rapid (within 90 min), except when weather and track conditions made a night response dangerous.

### Observation sites

Twenty observation sites were chosen along a 7-km section of the fenceline at which to simulate fence breaches. A 4-m-wide gravel service road runs directly along the outside of the entire 47-km fence, and the habitat on the opposite side of the road is mostly grazed pasture, interspersed with small (≤0.25 ha) pockets of indigenous mixed podocarp–broadleaf forest. The habitat across the service road from the fence was here classed



Fig. 1. Exterior view of the Xcluder 'Kiwi' pest-proof fence at Maungatautari, with gravel service road to the right.

as either 'pasture' (no trees present) or 'forest' (at least 20 trees present, >5 m in height). Along sections of the fence, opposite blocks of each of these habitats, 10 sites were selected, to test for the effects of adjacent habitat on pest sightings. Sites were separated by a minimum of 150 m, most by 200 m or more.

At each site, a 750 mm × 600 mm × 600 mm wire mesh cage was installed on the inside of the exclusion fence at ground level, each covered on five sides with 6 mm × 25 mm Xcluder stainless steel mesh (Fig. 2). The remaining 600 mm × 600 mm face was butted hard against and attached to the inside of the fence mesh, effectively sealing the sixth side of the cage. A hole measuring 250 mm × 250 mm was then cut in the fence mesh within the cage frame, at ground level. A temporary 600 mm × 600 mm mesh cover prevented pest entry, except when the hole was being filmed. The cages in effect formed an internal ballooning of the fence, and although animals could



Fig. 2. An observation cage as installed at the fence. The temporary mesh cover has been removed and the simulated 'flood-scour' breach is open.

exploit the hole, they were unable to go any further than the cage allowed, so the fence integrity was maintained.

A breach in the fence at ground level, called here a 'flood-scour' breach type, would not trigger the monitored alarm along the fence top, so might remain undiscovered for up to a week. A hole intended to simulate this sort of breach was opened by removing the temporary mesh face and disturbing the ground surface at the hole entrance. The hole was then filmed 24 h a day for 7 days, recording the mammalian pest species sighted, and the number and timing of sightings. On Day 7, the hole was resealed.

A 'tree-fall' breach type would trigger the alarm and be repaired within 24 h, so was filmed for only 1 day. By using the same ground-level holes as for flood-scour simulations, a 3-m-long branch was laid across the road perpendicular to the fence, with one end inside the opened hole, the other end on the far side of the road, and the ground surface was disturbed. In addition, to simulate a 'break' in the mesh (which would block animals moving along the mesh itself), a 500-mm-wide section of Colorsteel was attached to the mesh above the hole, up to the top of the fence. An obstacle was also placed inside the rolled fence hood gutter, to block animals from moving past the breach inside the hood. This arrangement was as close an imitation of a tree-fall event as was possible to simulate, while maintaining fence integrity.

Each breach type was filmed at each of the 20 sites, with an interval of at least 2 weeks between filmings. Two sessions of video filming of equal length (5 weeks each) were recorded to represent both summer and winter.

The hood gutter provided an extensive, easily travelled habitat for arboreal animals, and invertebrate activity within the hood was high. Stoats (*Mustela erminea*) have occasionally been sighted inside the hood (T. Day, pers. comm.), whereas ferrets (*Mustela furo*) and cats are less likely to reach it. At night, the fence hood is an attractive, virtually predator-free aboveground habitat for ship rats (*Rattus rattus*). A third set of observations was therefore designed to test the possibility that ship rats may be more active inside the hood than at the fence base.

#### *Recording schedule and equipment*

A single black and white CCD video camera (Jaycar QC3310, Innovative Technology, Taiwan) with manual zoom lens (Jaycar QC3394) was set up on the far side of the service road, facing the hole. Manual adjustment of the zoom lens produced a field of view sufficient to easily identify animals as small as mice, from a range of ~4 m (Fig. 6). Infrared spotlights (wavelength 850 nm) were attached to the camera housings for night illumination.

Summer filming (24 February to 26 March 2007) used six 12-V VCRs set to record in 24-h time-lapse mode (at ~3 frames per second), requiring daily battery and tape changes. Winter filming (3 August to 21 September 2007) used six high-capacity (internal 160-GB hard drive) digital video recorders (DVRs, Archos model 504, Archos S.A., Igny, France) recording 7 days of continuous real-time video footage (at 25 frames per second) and requiring only weekly battery changes. The DVRs were housed in weatherproof cases

differing only slightly in size from those housing the VCRs, and the same cameras and IR lighting were used for both. Therefore, we considered that the different external appearance of camera equipment between seasons was negligible and would not affect the study. We are also satisfied that the lower frame-rate of the summer VCRs, although only one eighth that of the DVRs used in the winter, was sufficient to capture images of all animals running across the field of view. Images captured over both seasons showed that hares were by far the quickest animals to run past the camera, even though they rarely moved at speed; very few such events were recorded in either season. For most sightings, animals moved slowly across the field of view and were visible for many seconds. We are thus satisfied that the summer VCRs captured images of all animals that passed in front of the cameras.

Up to six sites were filmed at any one time. At all times, both forest and pasture sites were filmed simultaneously. Sites were scheduled for filming in rotation, over 160 individual 24-h periods ('hole-nights', HN) in each season. No more than every second cage along the fenceline was used at any one time, meaning that cameras were always separated by at least 300 m.

A third block of filming (December 2007 to January 2008) used cameras focussed inside the fence hood gutter, each connected to a second DVR placed at the base of the fence 20 m along the fenceline. The aim here was to observe ship rat activity inside the hood, and compare the results with activity recorded simultaneously at the same sites but along the fence base. Four breach sites were filmed for a week each, two at a time.

#### *Data analysis*

Each sighting of a pest mammal was noted by species and time. No attempt was made to identify or count the number of individual animals recorded. A generalised linear mixed model (GLMM) was used to test for significance of season, habitat type and breach type on number of sightings per HN. GLMM was used rather than ANOVA because the count data were not normally distributed, and also because it could accommodate a nested blocking structure. The analyses were completed by using the generalised linear mixed model facility of GENSTAT (VSN International Ltd, Hemel Hempstead, UK), assuming a Poisson distribution for counts, with a blocking structure that recognised 'habitat' and 'site' as random factors.

The 150-m minimum distance between sites (and minimum 300 m between any two sites filmed simultaneously) was considered far enough to assume independence for mice, ship rats and rabbits, which have average home-range lengths of <150 m (Gibb *et al.* 1978; Fitzgerald *et al.* 1981; Hooker and Innes 1995). For all other species, we could not assume independence between sites, so the GLMM analyses should be treated with caution. Non-independence in the data could have had the effect of overestimating the number of degrees of freedom (and significance) in the analyses for those species.

For analysis of breach type, data from the first 24 h of the flood-scour holes were compared with data from the tree-fall holes (for which only 24 h of data were recorded). Linear

regression and ANOVA were used to test for trends of increasing or decreasing visits per day, per species at the 7-day flood-scour holes.

A *sighting* is defined as any detection of an identified species on film. All records of sightings were subdivided into the following three categories of behaviour: (1) *encounter* (a pest passed near a breach but showed no interest in it), (2) *interest* (a pest showed interest in a breach but did not enter) and (3) *entry* (a pest entered a breach). Results for each category were compiled as a percentage of total sightings (all categories) for each species, to provide a summary of observed breach behaviour.

*Probability of a pest finding a breach*

A simple probability model was constructed to estimate the cumulative probability of at least one mammalian pest finding a fence breach within 24 h, according to the time of day and season the breach occurred. Each hour of the day for each season was deemed to consist of 60 1-min ‘trials’, each of which could be recorded as positive or negative for a pest sighting. For each hour, the data were then fitted in the following model:

$$P_e = 1 - (1 - P)^{60},$$

where *P* is the probability of a pest sighting per minute of a given hour, and *P<sub>e</sub>* denotes probability of pest sighting in any 1-h period. The cumulative probability of a pest being sighted over the following 24-h period was then calculated by multiplying *P<sub>e</sub>* with the 23 subsequent probability figures (e.g. for a breach occurring at hour A, *P<sub>e</sub>* within the first hour=*P<sub>e</sub>*1; *P<sub>e</sub>* within 2 h=*P<sub>e</sub>*1 × *P<sub>e</sub>*2; *P<sub>e</sub>* within 3 h=*P<sub>e</sub>*1 × *P<sub>e</sub>*2 × *P<sub>e</sub>*3, and so on). This series of calculations was completed 24 times, each starting in a different hour, so that the cumulative probability of a pest sighting was calculated over the first 24 h after breach, according to season and time of day the breach happened. The results were graphed to display cumulative probability curves.

**Results**

*Animals sighted*

During the summer, 788 sightings were captured on video, on 149 (95%) of 157 HN (Table 1). Most animals were identified

**Table 1. Summary of numbers for pest-mammal sightings, in total and per 100 hole-nights (HN)**

Three nights of summer footage were lost through battery failure

Species	Number of sightings		Sightings per 100 HN (± s.e.m.)	
	Summer	Winter	Summer (157 HN)	Winter (160 HN)
Mouse	201	30	128 ± 14.0	19 ± 5.4
Ship rat	83	42	51 ± 10.3	26 ± 6.4
Hedgehog	99	63	62 ± 8.2	39 ± 6.9
Possum	212	86	134 ± 13.2	54 ± 7.4
Rabbit	46	37	28 ± 5.9	23 ± 5.4
Hare	25	89	13 ± 3.4	55 ± 8.3
Cat	116	80	73 ± 7.5	50 ± 8.0
Ferret	5	0	3 ± 1.4	–
Stoat	1	1	0.6 ± 0.6	0.6 ± 0.6
Total	788	428	493 ± 65.1	267 ± 48.9

only to species, although pelage markings distinguished some cats as individuals, including at least seven different cats sighted in each season. Mean (± s.e.m.) sightings per 100 HN totalled 493 ± 65.1 across all species. In winter, sightings were fewer (total 428 on 141 (88%) of 160 HN) and distributed differently (Table 1). Mean winter sightings per 100 HN for all species totalled 267 ± 48.9.

*Significance of season, habitat and hole type*

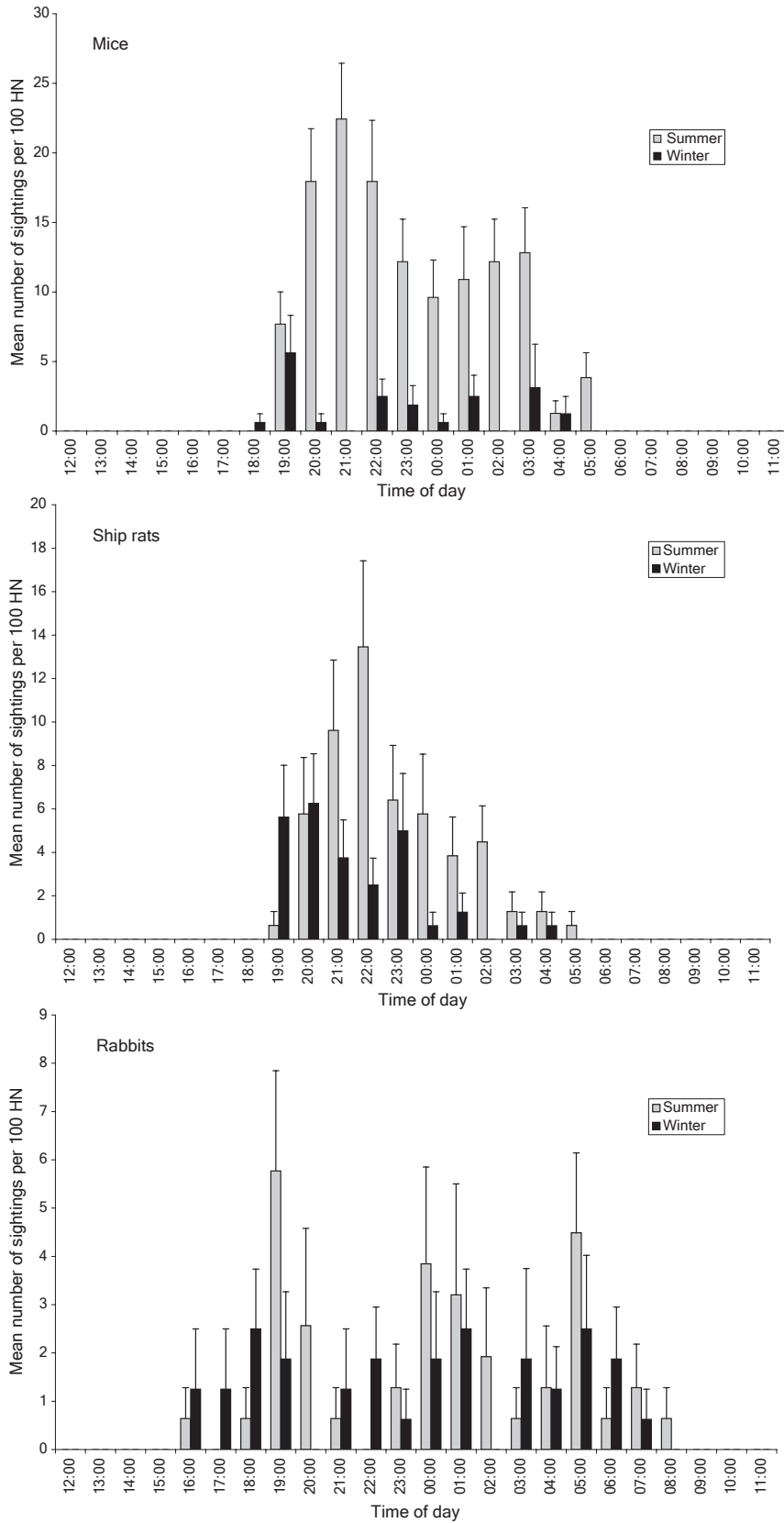
Significantly higher numbers of pest sightings were recorded in summer than in winter, overall (*P* < 0.001, Table 2) and for mice (*P* = 0.004), cats (*P* = 0.05), rabbits (*P* < 0.001) and brushtail possums (*Trichosurus vulpecula*) (*P* = 0.006), and almost so for ship rats (*P* = 0.06) and hares (*P* = 0.06). No seasonal difference was found for any other species.

Habitat was not a significant predictor of the distribution of pest sightings overall (*P* = 0.95) or for any species except rabbits, which were significantly (*P* < 0.001) more often sighted at pasture sites than at forest sites.

Hole type did not significantly predict sightings in general (*P* = 0.87), or for any individual species, although the higher number of rat sightings at tree-fall holes was close to significant (*P* = 0.06).

**Table 2. Results of GLMM analysis for effects of season, habitat type and hole type on sightings**

Species	Significance of season			Significance of habitat type			Significance of hole type		
	Wald	d.f.	<i>P</i>	Wald	d.f.	<i>P</i>	Wald	d.f.	<i>P</i>
Mouse	8.14	1	0.004	0.00	1	0.94	0.71	1	0.40
Ship rat	3.54	1	0.06	0.02	1	0.88	1.04	1	0.06
Hedgehog	0.62	1	0.43	0.00	1	0.98	1.18	1	0.28
Possum	7.70	1	0.006	0.08	1	0.78	0.02	1	0.90
Rabbit	15.28	1	<0.001	19.69	1	<0.001	0.62	1	0.43
Hare	3.52	1	0.06	0.09	1	0.77	2.25	1	0.13
Cat	3.72	1	0.05	0.75	1	0.39	0.47	1	0.49
Ferret	–	–	–	–	–	–	–	–	–
Stoat	–	–	–	–	–	–	–	–	–
Total	16.54	1	<0.001	0.00	1	0.95	0.03	1	0.87



**Fig. 3.** Mean ( $\pm$  s.e.m.) number of sightings per hour of the day, per species, by season. Summer sightings are corrected to New Zealand Standard Time.

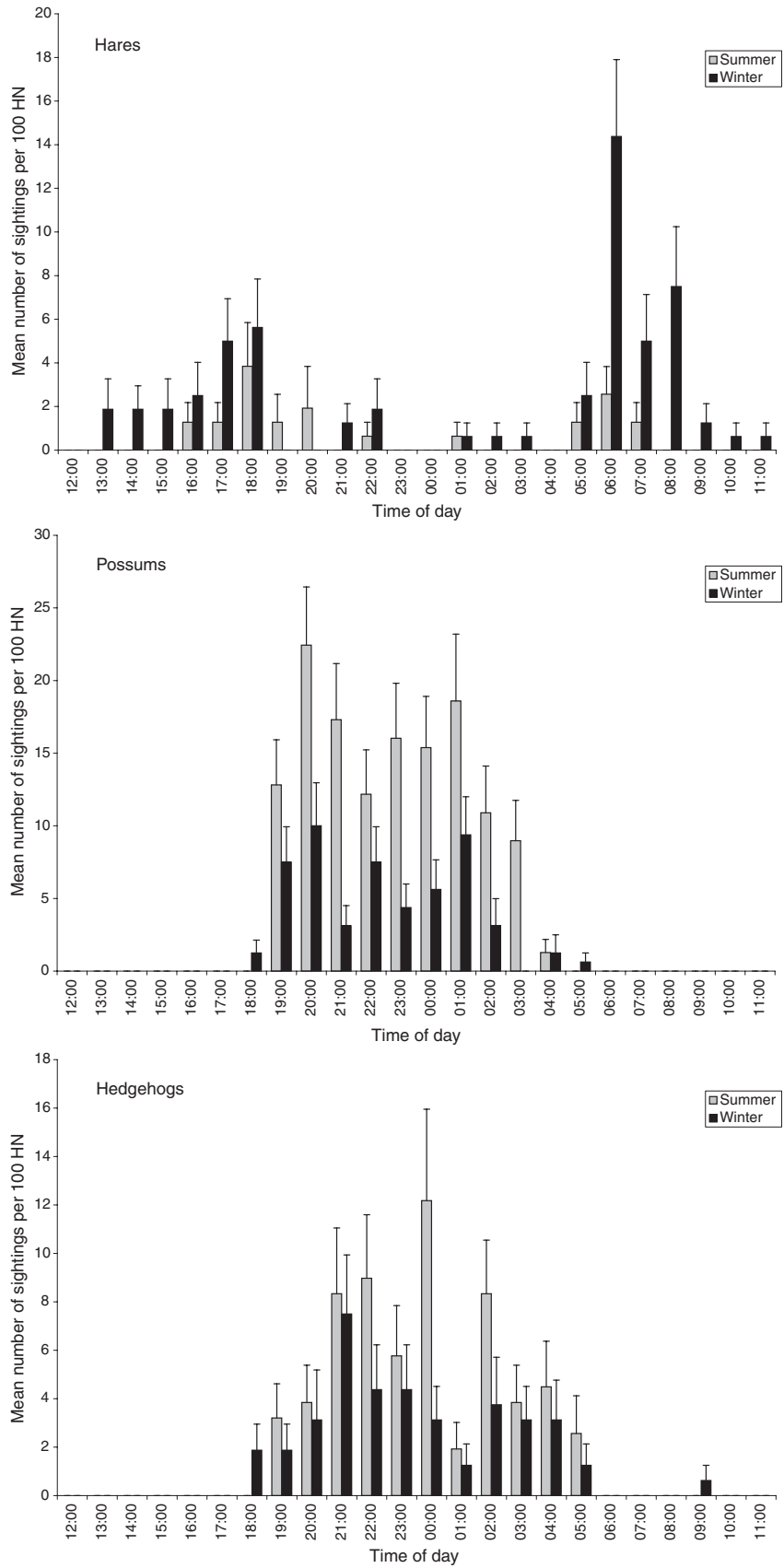


Fig. 3. (continued)

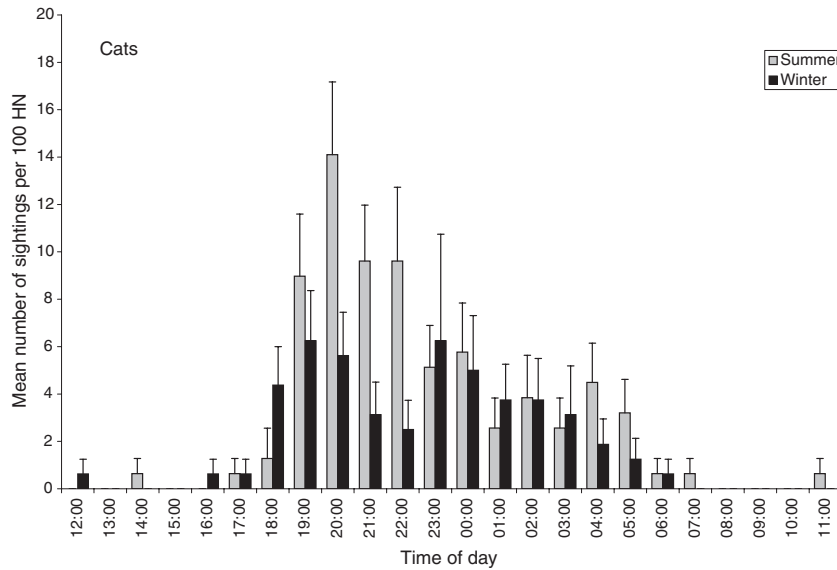


Fig. 3. (continued)

Timing of pest sightings

Altogether, 95.4% of all sightings were nocturnal in the summer, compared with 86.2% in the winter. The activities of mice, ship rats, possums and hedgehogs (*Erinaceus europaeus occidentalis*) were 100% nocturnal, regardless of season (Fig. 3); cat sightings were 92.2% nocturnal in the summer, and 93.8% nocturnal in the winter. Especially in summer, sightings began, for many species, almost immediately after the end of civil twilight (Fig. 3).

The first 24 h, all breach types

In summer, pest mammals were sighted at 39 of 40 holes of both breach types (97.5%) within the first 24 h of being opened. In winter, this figure was 37 of 40 (92.5%). The mean number ( $\pm$  s.e.m.) of sightings per hole in the first 24 h was  $5.4 \pm 0.5$  in summer, and  $2.6 \pm 0.4$  in winter. The mean number of species recorded per hole in the first 24 h (representing an absolute minimum mean number of individual animals sighted) was  $2.8 \pm 0.2$  in summer and  $1.4 \pm 0.1$  in winter.

Seven-day breaches (flood-scour type only)

In the summer, total mean ( $\pm$  s.e.m.) cumulative sightings per week-long hole increased from  $5.05 \pm 0.6$  after Day 1, to  $33.6 \pm 2.4$  after Day 7 (Fig. 4). Mean cumulative winter sightings increased from  $2.6 \pm 0.6$  after Day 1, to  $18.9 \pm 2.0$  after Day 7. There was no trend of increasing or decreasing number of sightings per day (per species, over a 7-day period) ( $t = -0.94$ ,  $P = 0.35$ ), in either season. Mean ( $\pm$  s.e.m.) cumulative number of species sighted per hole by Day 7 was  $5.7 \pm 0.25$  in the summer, and  $4.9 \pm 0.2$  in the winter.

Cumulative probabilities

We constructed a model to estimate the cumulative probability of at least one mammalian pest finding a breach, according to time of day and season (Fig. 5). In summer, the cumulative

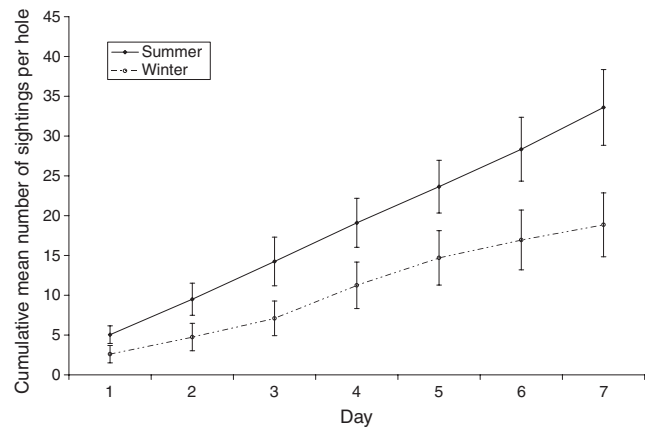
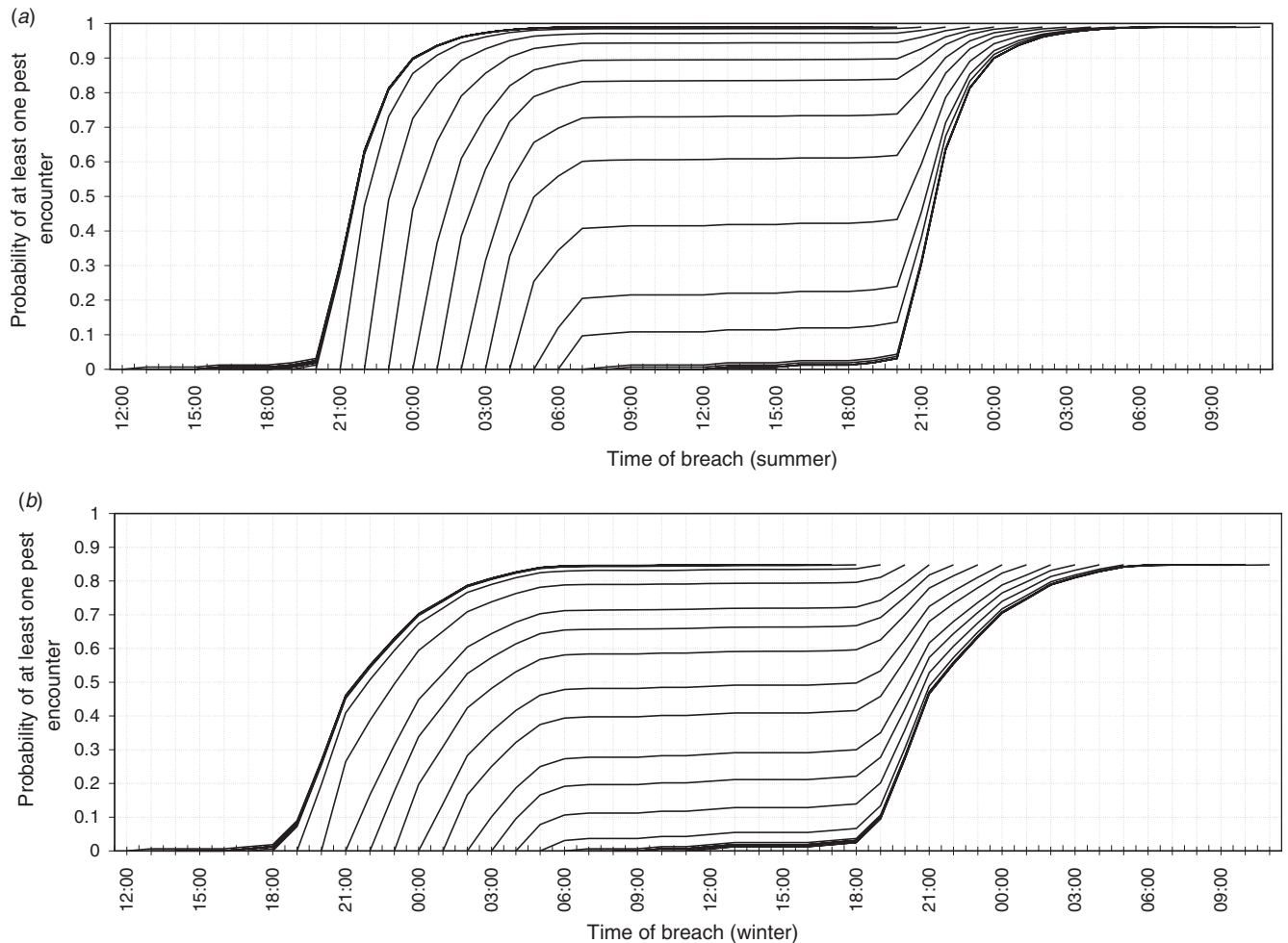


Fig. 4. Mean ( $\pm$ s.e.m.) cumulative number of sightings at ‘flood-scour’ breaches, over a 7-day period.

probability of at least one pest finding a breach increased much faster at night than by day (Fig. 5a). For example, if a breach should happen at 1800 hours in the summer, there was a 30% probability that a pest would find it within 3 h. This rose to 90% by midnight, and 99% by 0600 hours if the breach had not been repaired. In contrast, if the fence was breached at 0600 hours, the probability that it would be found within 3 h was 1%; this increased to only 12% by 1800 hours, and to 99% by 0600 hours the following day. Predictions for winter breaches were similar to those of summer, except with a lower probability level (Fig. 5b). As in summer, the probability of a pest finding a breach increased at a much faster rate per hour at night than during the day.

Pest behaviour

Rodents collectively comprised only 36% of the 788 total pest sightings in summer (Table 3), whereas 78% of all 302 breach



**Fig. 5.** Graphs displaying cumulative probability curves for summer (a) and winter (b). Each curve represents the cumulative probability of at least one pest mammal being sighted immediately adjacent to a fence breach during the 24 h following breach, according to the time of day a breach happens. Times are to New Zealand Standard Time.

entries in summer were by rodents. Mice entered summer breaches more often than any other species, with ship rats entering the next most often. Possums and hedgehogs were observed entering summer breaches less often than rodents. Cats entered breaches rarely, and in both summer and in winter, at least seven individual cats were recorded, and some of these were sighted at multiple sites in a single night. Most were regularly seen along particular stretches of fenceline up to ~2 km in length. Mustelids were rarely seen, although always at least showed interest in a breach, and actually entered during five of six summer sightings.

Numbers of rodent sightings dropped to only 17% of the 428 winter sightings, and fewer of those recorded were interested in either type of breach (Table 3), although rodents were still responsible for 59% of all breach entries. Entries by all other species were few. Only one mustelid was sighted in the winter (a stoat), which also entered a breach.

#### *Behaviour towards the fence*

A selection of still images taken from video clips (Fig. 6) illustrates the differences in reactions of pest species towards

the fence. Mice were almost always sighted moving at a steady pace, and always directly at the base of the fence; they were very rarely seen climbing on the fence mesh. In contrast, ship rats were regularly seen on the fence mesh (30% of sightings in summer, 40% in winter), moving up, down or even along the fence. When on the ground, ship rats most often moved directly along the fence base, although they also used the nearest wheel rut to the fence on the roadway. Hedgehogs usually moved along the fence base, and also used both wheel ruts. All other species were most often seen moving along the wheel ruts, in particular the rut nearest the fence; only very rarely were any animals seen entering the field of view from behind the camera.

When rodents entered a breach, most remained inside the cage for at least 60 s; in this time they quickly inspected every internal surface, both wire mesh and wooden frame. Corners received particular attention, and often the animal would remain out of sight of the camera for some time as it investigated the ceiling of the cage. Possums often moved directly to the rear of the cage on entry, standing on their hind legs as they explored the back face of the cage. Although some possums remained within the cage for more than 30 s, most departed within 20 s. Cats entered only when



**Table 3. Summary of mammalian pest behaviour in relation to simulated breaches, in summer and winter**

Season	Species	Entered breach	Did not enter breach		Total sightings in summer
			Interested	Not interested	
Summer	Mouse	174	4	23	201
	Ship rat	62	6	15	83
	Hedgehog	19	21	59	99
	Possum	22	65	125	212
	Rabbit	13	6	27	46
	Hare	2	4	19	25
	Cat	5	26	85	116
	Ferret	4	1	–	5
	Stoat	1	–	–	1
	Total	302	133	353	788
Winter	Mouse	11	4	15	30
	Ship rat	18	3	21	42
	Hedgehog	4	6	53	63
	Possum	7	25	54	86
	Rabbit	2	2	33	37
	Hare	1	10	78	89
	Cat	5	6	69	80
	Ferret	–	–	–	–
	Stoat	1	–	–	1
	Total	49	56	323	428

prey was sighted within, and were twice seen catching a mouse inside a cage.

#### *Hood observations*

Altogether, 187 ship rat sightings were recorded within the fence hood during 20 nights ( $9.35 \pm 1.5$  per night, mean  $\pm$  s.e.m.). Of these, only one was of a rat running down the fence mesh to ground level within the field of view of the ground camera, and none resulted in breach entry. Rats often stopped directly above the simulated breach, and spent a few seconds looking down towards the ground (Fig. 6). Invertebrate activity was very high within the hood, and on at least 10 occasions rats were seen to capture and eat invertebrates. No other mammalian species were observed inside the hood at any time.

#### **Discussion**

These results emphasise the constant threat that mammalian pests pose to a pest-proof sanctuary fence. We found that pests of many different species were very common directly outside the fence, and were very likely to find and exploit a fence breach within 24 h. Not unexpectedly, the greatest threat of reinvasion came (1) at night, (2) from rodents and (3) in the summer, although there was a constant risk of invasion regardless of time of day or season.

#### *Pest species*

Our results confirm that all of the species sighted are capable of locating a fence breach and willing to enter it. Managers should therefore assume the worst-case invasion-risk scenario, namely that when pest mammals find and enter a breach, they will stay within the reserve.

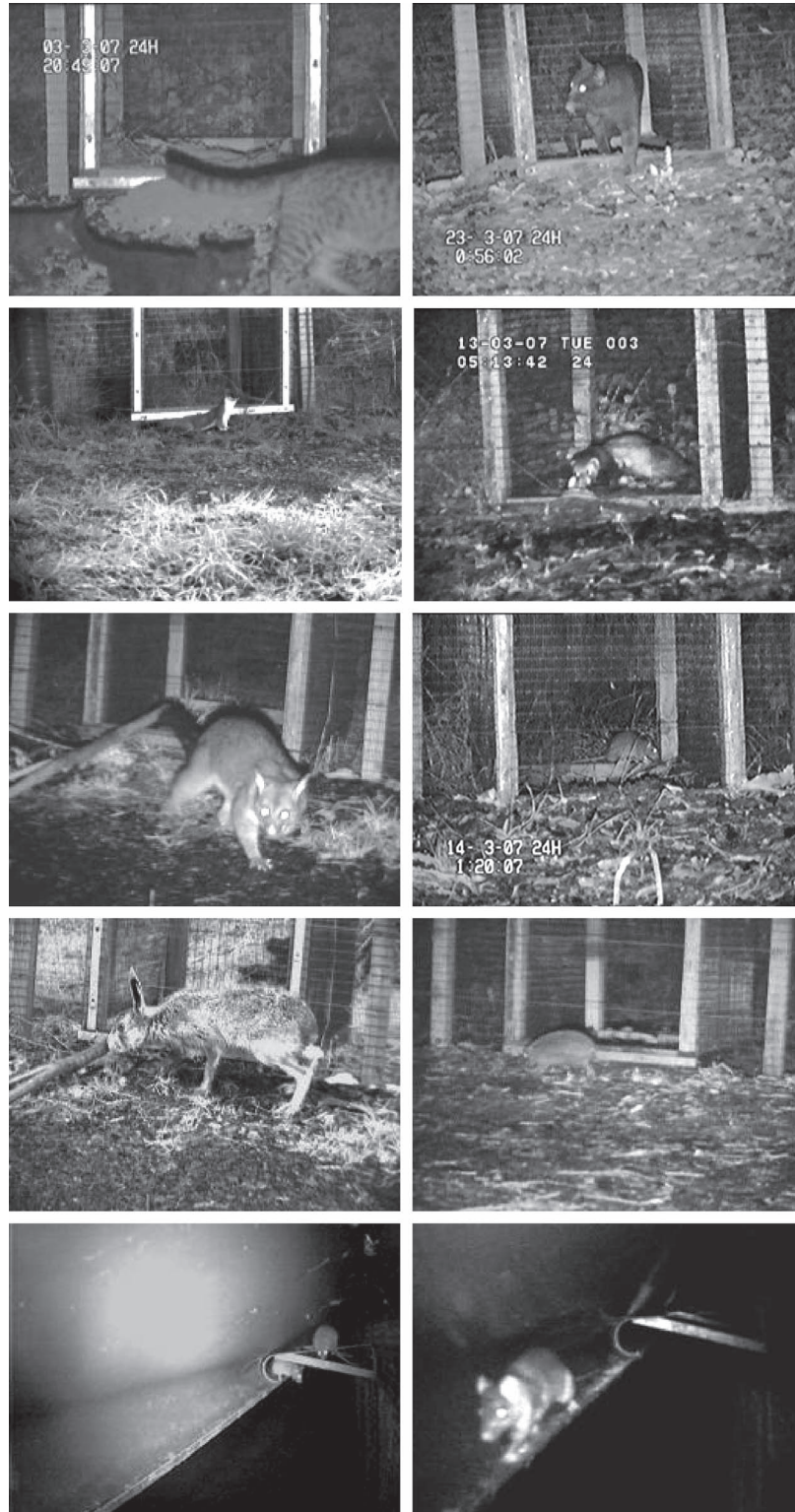
The greatest threat posed to the reserve by mice and rats lay in their willingness to enter breaches. Once free of mammalian predators, a sudden, massive increase in a founding (or remnant) mouse or rat population is inevitable, which in turn could sustain any invading predators, such as mustelids (King 2002; King and Murphy 2005) and cats (Fitzgerald and Karl 1979).

Ship rats are widespread on the New Zealand mainland (Innes 2005), so we expected that ship rats would also be the species most often seen on video. This was not the case, which seemed odd until we implemented a separate set of observation devices inside the Colorsteel fence hood. Then we saw that ship rats were using the fence in other ways, most often within the fence hood gutter rather than along the ground. A tree fall that left a breach in the top of the fence could decant several rats at a time direct into the reserve, from nests in the tree canopy or from inside the hood gutter, with disastrous consequences (Innes and Barker 1999; Innes *et al.* 1994, 1999, 2004).

The environment within the enclosure appears ideal for an invading ship rat, with a plentiful food supply and no competitors for food resources or territories. However, when Speedy *et al.* (2007) experimentally (and sequentially) released six individual radio-collared male ship rats into a pest-free, 65-ha southern subsection of the main enclosure, four climbed back out within a week. This was possible because the Xcluder fence is designed to prevent entry, but not exit, of animals from the reserve. Self-exporting behaviour was unexpected, although may be confined to solo invaders. We assume that the absence of conspecifics, and the scent of their original home range just through the wire, enticed them to leave. Rats arriving through a breach in a breeding group might not be so obliging, so the potential for rats to enter in groups is especially significant.

The minimum home-range area of a domestic cat living on a property 1.2 km from the boundary of Trounson Kauri Park in Northland, New Zealand, was found to be 11.7 ha, with a home range length of 906 m (Gillies 2007). Many farmhouses lie within ~500 m of the fenceline at Maungatautari. The close proximity of farmhouses and farm buildings, the high number of sightings of cats and the high number of individual cats seen, all suggest that some were farm or even domestic cats, which routinely travelled to and inspected the Maungatautari fenceline; any pest control carried out on external predators would need to account for this. Linear habitat features such as roads, waterways, fences and field edges tend to concentrate the movements of potential prey, so cats (Fitzgerald and Karl 1986) and mustelids (Alterio *et al.* 1998; King *et al.* 1996; Murphy and Dowding 1994) are known to follow them. Cats often showed interest in a breach, especially if given a chance to follow prey through a hole in the mesh, and it is highly likely that a fence breach will be encountered by a cat within 24 h, particularly between dusk and dawn.

Although mustelids were far less abundant than other species at the fenceline, they were probably a significant threat. Those that we sighted always located holes, and showed little hesitation in entering, so the chances of breach encounter and exploitation by mustelids are probably higher than we estimated, both at night (ferrets) and by day (stoats and weasels). Mustelids have the potential to cause major ecological damage within the reserve in a short space of time, and must be prevented from entering if at all possible. Once inside, they would be hard to get out, because



**Fig. 6.** A selection of still images taken from the video footage. Top row: cat with two kittens (L) and cat having caught a mouse (R); 2nd row: stoat (L) and ferret (R); 3rd row: possum (L) and ship rat (R); 4th row: hare (L) and hedgehog (R); bottom row: ship rats inside the fence hood, looking at the ground (L), and ship rat running the gutter.

individual stoats, particularly pregnant females, are notoriously difficult to detect and catch, and learn to be extremely wary of traps and tracking tunnels (Crouchley 1984).

Populations of hedgehogs and possums increase more slowly than those of rodents. Incursions by either are not to be ignored, although they would be less urgent as threats to a reserve than are those of rodents. Hedgehogs eat mostly invertebrates, and also lizards, frogs and the eggs of ground-nesting birds (Jones and Sanders 2005). Similarly, possums are known to prey on bird eggs and chicks (Brown *et al.* 1993, 1998), compete for food resources with species such as kokako (*Callaeas cinerea wilsoni*) (Leathwick *et al.* 1983) and significantly affect vegetation through browsing (Cunningham 1979).

#### Seasonal and habitat effects

Sightings of rodents in general (and especially mice) and possums significantly declined from summer to winter, a common seasonal pattern in environments not dominated by mast-seeding events (Badan 1979; Daniel 1978; Brockie *et al.* 1981; Murphy 1989; Innes *et al.* 2001; Harper 2002). By contrast, hedgehog sightings did not significantly drop in the winter. The severity of the winter influences the proportion of a hedgehog population that will take the risk of entering hibernation (Jones and Sanders 2005), so the relatively mild central Waikato winter of 2007 permitted many to avoid it. The increase in the number of hare sightings in September corresponds with the intense breeding behaviour common among hares at this time (Norbury and Flux 2005).

The habitat opposite the fenceline did not significantly influence the presence of any pest species except rabbits. Even though some species may den in certain habitats (e.g. ship rats and possums in forest fragments), the service road (and even the fence itself) provides a convenient, unbroken pathway along which pests range widely.

#### Breach types

No species was sighted significantly more often at either breach type, and a fence breach was as likely to be found by a pest mammal whether a branch had fallen across the road or not. Although not statistically significant, ship rats were sighted more often at tree-fall breaches in the summer, which implies that rats moving along the fence inside the hood would find and enter such a breach very quickly.

#### Probability models

The probability model suggests a 99% probability of at least one pest mammal finding a breach within 24 h in the summer, and an 85% probability in the winter. Predictably, nocturnal pest sightings were far more frequent than diurnal sightings. A breach during the hours of darkness, especially in the first half of the night, is of greatest concern to reserve managers, because cumulative probabilities increase massively after dusk, but more slowly in daylight. This is of huge concern in the event of a fence breach, and emphasises again the vital importance of a quick response, particularly to night-time breaches. However, there is always a risk of pest encounter regardless of time of day, and this risk is always increasing with time.

## Conclusions

Although alarming, these data are conservative, because we recorded only the pests that were present directly at the base of the fence, or inside the fence hood, during only two seasons of a single year. Nevertheless, these data strongly emphasise the need for a quick response to a fence breach at all times of day; where that need is met, the risk of pest invasion can be managed effectively. During the first 3 years since the establishment of the 47 km of Xcluder fence around Maungatautari, there have been 12 significant risk events (one vehicle gate open, one water gate jammed open, 10 tree falls) (T. Day, unpubl. data; P. de Monchy, pers. comm.). On three occasions, there was a significant delay (6–24 h) before staff could repair the breach, followed by three recorded invasions: two events each resulting in rat detection, one in mouse detection. The invaders were trapped, and tracking tunnels confirmed they had been removed. In contrast, rapid response to the other nine breaches prevented any animal invasions (Day and MacGibbon 2007). MEIT now aims to physically respond to any alarm notifications of breaches within 90 min (P. de Monchy, pers. comm.).

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