# Effect of reduced possum density on rodent and stoat abundance in podocarp-hardwood forests

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CONTENTS

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ABSTRACT

The periodic control of possums (*Trichosurus vulpecula*) in cycles of c. 3–7 years is the most commonly applied pest-management regime on large tracts of indigenous forest in New Zealand. The densities of rodents (rats *Rattus* spp. and mice *Mus musculus*) and stoats (*Mustela erminea*) are also often reduced when possum control is applied, but these species recover far more quickly than possums. As possums and rodents may compete for food, and stoats in turn rely heavily on rodents as a food source, a key question is whether periodic possum control results in higher medium-term rodent and stoat densities. To test this hypothesis, indices of possum, rodent, and stoat abundance were measured in treated (possum control) and untreated (no possum control) blocks in podocarp-hardwood forest, before and up to 3 years after one-hit possum control operations in each of two areas. Prior to possum control, indices of possum, rodent and stoat numbers were similar in treated and untreated blocks. Following possum control, possum abundance was significantly lower in at least part of both possum-controlled areas throughout the rest of the study. Ship rat (*Rattus rattus*) abundance was significantly higher in both treated blocks for at least one breeding season during the 3 years after possum control. Overall, mouse abundance did not differ between treated and untreated blocks, but fluctuations in mouse populations occurred 6 months to 1 year later in possum-control blocks than in untreated blocks. Stoat populations did not respond to possum control, and remained low in the treatment blocks throughout the study.

Keywords: possums, ship rats, mice, stoats, possum control, population densities


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# 1. Introduction

To investigate the medium-term (1–3 years) effects of reduced possum (*Trichosurus vulpecula*) density on rodent (ship rat *Rattus rattus*, and mouse *Mus musculus*) and stoat (*Mustela erminea*) populations in podocarp-hardwood forests, indices of possum, rodent and stoat abundance were measured before and for 3 years after single ('one-hit') possum control operations at two sites. The trials were undertaken between June 2001 and March 2005 in widely separated tawa (*Beilschmiedia tawa*)-dominated forests in the North Island, New Zealand.

# 2. Background

The periodic control of possums in cycles of 3–7 years, either for the control of bovine tuberculosis (Tb) or for conservation management, is the most common large-scale pest-management regime on conservation land in New Zealand (J. Parkes, Landcare Research, Lincoln, pers. comm.). Aerial use of 1080 (sodium monofluroacetate) poison baits in New Zealand forests typically kills 80%–95% of possums (Morgan & Hickling 2000), large proportions of ship rats (Murphy & Bradfield 1992; Innes et al. 1995; Miller & Miller 1995; Murphy et al. 1999; Powlesland et al. 2000) and variable proportions of stoats (Murphy & Bradfield 1992; Murphy et al. 1998, 1999). With intrinsic rates of increase of c. 0.3 (Clout & Barlow 1982; Hickling & Pekelharing 1989), possums can take 10 or more years to recover from successful large-scale control operations, while rats (Murphy & Bradfield 1992; Innes et al. 1995; Miller & Miller 1995; Powlesland et al. 2000) and stoats (Murphy et al. 1998, 1999) usually recover from any direct effects of poisoning within c. 6 months. Ground control of possums using traps and cyanide poison can achieve similar levels of possum control (Montague & Warburton 2000; Morgan & Hickling 2000), but it is believed that they do not directly affect rodent or stoat populations (this study; pers. obs.).

Possums frequently eat invertebrates (Cowan & Moeed 1987; Nugent et al. 2000) and exhibit strong dietary preferences for fruits and seeds (Nugent et al. 2000; Sweetapple 2003), sometimes suppressing fruit production (Cowan 1990a; Cowan & Waddington 1990). Since fruits, seeds and invertebrates also dominate the diet of ship rats (Best 1969; Daniel 1973), it is likely that there is some level of competition for these foods between sympatric possum and ship rat populations. If interspecific competition from possums reduces the food available to rats, one consequence of reduced possum density may well be an elevated carrying capacity for rats. This would be unimportant where both possums and rats are controlled on an annual cycle, but where possums alone are controlled, or possum and rat control is applied less frequently, the density of rats could exceed pre-control levels for substantial parts of the control cycle.

Mouse population densities frequently increase within c. 6 months of possum control operations (Clout et al. 1995a; Miller & Miller 1995; Innes et al. 1995; Murphy et al. 1999). The causes of these post-control elevations in mouse abundance are unclear, but their duration may be short (c. 6 months; Miller & Miller 1995).

Rodents are an important food of stoats in many New Zealand habitats (King et al. 2001); rats are a particularly important food in podocarp-hardwood forest (Murphy & Bradfield 1992; Murphy et al. 1998), and mice are more important in beech (*Nothofagus* spp.) forests (King 1983). The number of stoats born each spring is strongly related to food abundance (King 1990). Therefore, any sustained increase in rodent populations resulting from periodic possum control may result in an increase in stoat abundance. As both ship rats and stoats are significant predators of indigenous forest fauna (Atkinson 1973; Bell 1978; King 1984; Innes 1990, 2001; King et al. 2001), increased rodent and stoat densities following periodic possum control may offset some of the benefits of reduced herbivory and predation by possums.

This study aims to quantify the medium-term (1–3 years) response of ship rat, mouse and stoat populations to one-hit possum control operations in North Island podocarp-hardwood forest. In doing so, we test the hypothesis that one-hit possum control results in an elevated abundance of ship rats, mice and stoats, relative to areas without control.

# 3. Objectives

- To investigate the medium-term effect of reducing possum densities on rodent and stoat abundance in podocarp-hardwood forest.
- To determine the duration of any effect of reducing possum densities on rodent and stoat abundance.

# 4. Methods

## 4.1 STUDY DESIGN AND SITES

A replicated BACI (Before-After-Control-Intervention) design (Underwood 1993) was used, with one-hit possum control as the experimental treatment. Treatment and non-treatment (no possum control) blocks were established and monitored for 3 years (2001–2005) in each of two areas (Whirinaki River Catchment, southeastern Bay of Plenty, and Mokau River Catchment and Mt Messenger Forest in northern Taranaki).

### 4.1.1 Whirinaki

In the Whirinaki study area, a possum-control block was established in the upper Okahu Stream (38°39′S, 176°50′E; Fig. 1), c. 8 km east of Minginui, and a non-treatment block was located on the west bank of the Whirinaki River (38°42′S, 176°41′E), c. 14 km southwest of the treatment block. The non-treatment block was 0.5–4.0 km from other areas in which there were possum control programs. Forests on both blocks are rimu-matai-tawa (*Dacrydium cupressinum-Prumnopitys taxifolia-Beilschmiedia tawa*) associations (Nicholls 1969), although many toe slopes in the Okahu have been logged, reducing the podocarp component there. Both blocks are in steep hill country at altitudes of between 400 m a.s.l. and 750 m a.s.l.

Possum control was undertaken over c. 3000 ha in the Okahu Catchment between September and December 2001, using two ground-control techniques: leg-hold trapping and sodium cyanide paste. Neither of these control techniques is known to significantly reduce rodent or stoat abundance.

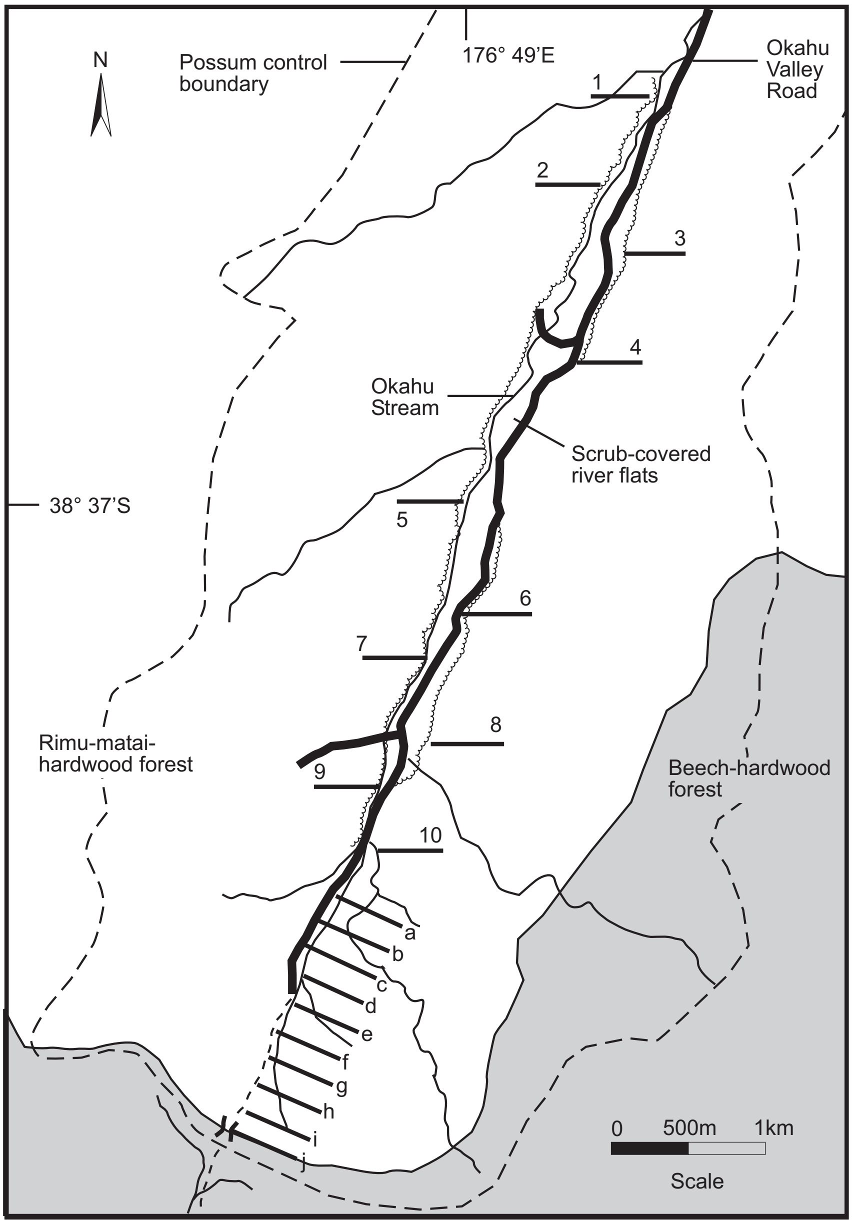



Figure 1. The Whirinaki possum (*Trichosurus vulpecula*)-control block at Okahu Stream, showing the location of the monitoring transects, possum-control boundary and major vegetation types. Transects 1–10 were monitored throughout the study, and transects a–j were measured once at the end of the study to measure pest abundance gradients near the possum-control boundary.

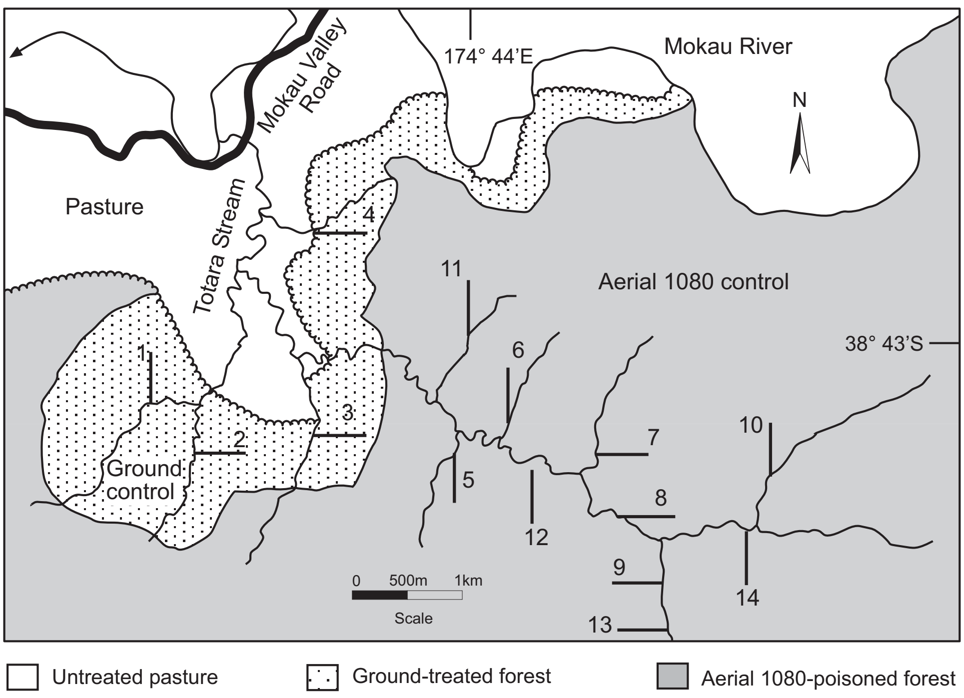
### 4.1.2 Mokau

The possum-control (treatment) block in the Mokau study area was located in the Totara Stream Catchment (38°43′S, 174°44′E), a tributary of the lower Mokau River (Fig. 2). The non-treatment block was located in Mt Messenger Forest (38°55′S, 174°37′E), c. 25 km to the southwest of the Totara Stream block, and at least 14 km from all possum-control areas. Both blocks are in steep hill country at between 20 m a.s.l. and 300 m a.s.l., and are forested with rimu-tawa associations (Nicholls 1979).

Totara Stream was selected as an aerial-1080 poison operation site; it was part of a 15 600-ha possum control operation conducted in September 2002. However, only c. 90% of the study area was treated with an aerial application of 5 kg/ha of chopped carrot baits loaded with 1080. Toxic loading varied, ranging from 0.08% to 0.15% (M. Reynolds, Eco Effects, Otorohanga, pers. comm.). On the remainder of the site, some 250 ha of forest adjacent to grazed pasture in the lower Totara Stream (Fig. 2), possums were controlled by ground operators, using leg-hold traps, Feratox® cyanide baits and night shooting. In addition, 'PESTOFF®' brodifacoum baits were placed in bait stations, which were spaced at 100-m intervals along c. 3 km of forest margin in this ground-controlled area. The ground control achieved a poor possum kill and was repeated in April–May 2003 and in March–May 2004. We assume that the trapping, shooting and cyanide poisoning would have had little effect on rodents and stoats, but some rats (and possibly stoats by secondary poisoning) would have been killed by the brodifacoum baits. We do not know whether the repeated use of brodifacoum baits was intense enough to have had a significant impact on rodents or stoats within the ground-controlled area. All monitoring within the aerial-1080 block was undertaken at least 1 km from ground-controlled areas (Fig. 2).

There had been no systematic possum control operations in either area prior to our study (M. Reynolds, Eco. Effects, Otorohanga, pers. comm.). However, sporadic possum fur harvesting by commercial hunters has been undertaken in both areas (pers. obs.).

Figure 2. The Mokau possum (*Trichosurus vulpecula*)-control blocks at Totara Stream, showing the location of the monitoring transects and areas under different possum-control regimes.



## 4.2 SAMPLING DESIGN

Possum, rodent and stoat abundance was assessed repeatedly using ten permanently marked monitoring transects spread over c. 2000 ha within each study block. Transect origins were randomly located along major watercourses, and transect bearings were assigned as north, south, east or west, depending upon which gave the greatest altitudinal range over the 450-m length of the transect. Transect locations were rejected if they fell within 500 m of another transect. Pest abundance was assessed c. 6 months prior to the possum control operation, and annually or twice annually after control: rodent and stoat abundance was monitored in spring (November–December) and autumn (February–April) annually until March 2004 (Whirinaki) or March 2005 (Mokau) inclusive, with the exception that no spring measurement was conducted at Whirinaki in 2003. Post-control possum abundance was monitored annually in autumn. In the possum-control block at Mokau, four transects were placed in the area that subsequently received ground control, while the remaining six were in the aerial-1080 control area. This effectively split the Mokau possum-control area into two sparsely sampled blocks. Due to the small sample sizes and repeated possum control efforts in the ground-control block, the four transects there were abandoned after the November 2004 assessment and were re-established in the aerial-1080 block (transects 11–14 in Fig. 2).

Due to unplanned possum control in part of the non-treatment block at Whirinaki, four of the ten initial transects needed to be replaced with four new transects in other parts of the remaining untreated area.

In the Whirinaki treatment block, an additional ten transects were established and measured once only in autumn 2004. The first of these was located along the boundary of the possum-control area, in a low saddle at the head of the Okahu Stream; the remainder were established within the control area, parallel to and at 200-m intervals from the first transect (Fig. 1). This cross-sectional trial aimed to investigate the relationship between possum and ship rat abundance along a putative possum-abundance gradient resulting from 2.5 years of possum invasion across the possum-control boundary.

## 4.3 MONITORING PEST ABUNDANCE

### 4.3.1 Possum abundance

Possum abundance was assessed using leg-hold traps (Victor No. 1 hard jaw) set on 200 × 200 mm boards (Scott Boards), which were mounted horizontally on trees 500 mm above the ground to avoid the capture of kiwi (*Apteryx australis*). Ten traps were set for three fine nights at 20-m intervals along the middle 200 m of each transect. Traps were lured with a mixture of flour, icing sugar and cinnamon oil, which was smeared onto the tree trunk 30 cm above the trap. Captured possums were marked (stock marker paint) and released if uninjured, or euthanased. Traps were run in tandem with the tracking tunnels.

### 4.3.2 Rodents and stoats

Rodent and stoat abundance was assessed by recording tracking rates in ten tunnels located at 50-m intervals along each transect. Tunnels measured 600 mm long, with a square profile (80 × 80 mm). They were constructed from coreflute™ plastic (Mulford Plastics NZ) stapled to a plywood base (Whirinaki), or were constructed entirely of plastic (Mokau). Ink (liquid paraffin and carbon soot mix) was applied to the middle third of a 550-mm-long plastic tray, and a pea-sized 'blob' of peanut butter was placed in the centre of the inked portion. The tray was inserted into the tunnel, and paper was placed at both ends. Footprints on the papers were identified (Ratz 1997) after 1 night, to assess rodent abundance. Peanut butter was then removed from all tunnels and c. 10 g of lagomorph (rabbit *Oryctolagus cuniculus*, or hare *Lepus europaeus*) meat was placed in every second tunnel and left for a further 3 nights, to assess stoat abundance. Tunnels were established 1–2 days before the first assessment night at the start of the study, but relocated transects were established 4 and 7 months prior to their first measurement at Mokau and Whirinaki respectively. Tunnels were run concurrently in treatment and non-treatment blocks. A few tunnels (≤ 5% in all blocks during each assessment) were tipped over or had their papers removed by possums. In these cases, total tunnels available was adjusted down by 0.5 for each disturbed tunnel. When the papers were destroyed or lost by possums, the number of tunnels was adjusted down by 1.0.

### 4.3.3 Data analysis

After the first night of each survey, separate tracking rates (percentage of tunnels tracked by target animals) were calculated for rats and mice on each transect. Stoat tracking rate was calculated only for the meat-baited tunnels (five per transect) after they had been baited for 3 nights. For each transect, possum trap-catch rate was calculated as the number of possums caught over three fine nights, expressed as the percentage of total trap-nights. Half a trap-night was deducted for each sprung trap that failed to catch a possum, but sprung traps containing possum fur were treated as possum captures.

Pest abundance data from all three treated areas (ground control at Mokau and Minginui, and aerial-1080 control at Mokau) were analysed separately, because each method produced different post-control rodent population trajectories. Data were analysed with a mixed-effects model using the REML procedure in the statistical package GenStat. Transects within treatments in each area were included as random terms in the model. Treatment (possum control or not) and time were included as fixed effects, with time treated as a discrete variable. The hypothesis that possum control resulted in elevated populations of rats, mice and stoats relative to untreated areas was tested by the time × treatment interaction term.

All rodent and stoat tracking data were also compared between treatment blocks within areas using Kruskal-Wallis tests, with Bonferroni adjustments to *P*-values to compensate for the increased likelihood of type-I errors when undertaking multiple comparisons. Possum abundance data were compared between treatment blocks within areas using unpaired *t*-tests, again with Bonferroni adjustments.

The relationships between rat and possum abundance and the distance from the control boundary, as assessed by the trials conducted at Whirinaki in March 2004, were investigated using Pearson correlation coefficients.

# 5. Results

Pre-control indices of possum, rat, mouse and stoat possum abundance were similar in the treatment and non-treatment blocks at both Whirinaki and Mokau, although rodent and stoat abundance indices were all very low (Figs 3 & 4; Appendix 1).

## 5.1 POSSUM ABUNDANCE

Trends in possum abundance during the study differed significantly between all three possum-controlled areas and their respective untreated areas (Whirinaki: $\chi^2 = 30.9$, df = 3, $P < 0.001$; Mokau ground control: $\chi^2 = 7.4$, df = 2, $P = 0.25$; Mokau 1080 control: $\chi^2 = 45.8$, df = 3, $P < 0.001$). Possum abundance was similar in treated and untreated blocks prior to control (25%–33% trap-catch), but was significantly lower in treated blocks following control for the rest of the study (Figs 3A & 4A). Possum control was most effective in the Mokau 1080 block, where residual trap-catch rates (RTCs) immediately after control were 3.3%, rising to 7.7% 2 years later (Fig. 4A). More modest levels of possum control were achieved in the ground-control blocks: RTCs during the 2-year post-control period were 6.0%–13.7% in the Whirinaki ground-control block and 10.0%–11.8% in the Mokau ground-control block (Figs 3A & 4A).

## 5.2 RAT ABUNDANCE

Indices of rat abundance were low in all areas prior to possum control, but were 2–6 times higher in the non-treatment blocks than in their respective treatment blocks (Figs 3B & 4B). Post-possum-control patterns of rat abundance differed between the 1080 treatment and non-treatment (Mt Messenger) blocks at Mokau ($\chi^2 = 126.4$, df = 6, $P < 0.001$). While rat tracking rates remained stable throughout the post-control period in the non-treatment block at Mt Messenger (24%–42%), in the 1080 block no rats were tracked 2 months after possum control, then tracking rates steadily increased to very high levels (85%–88%) over the next 2 years (Fig. 4B). As a result, rat tracking was significantly lower in the 1080 block than in the non-treatment block in November 2002 and March 2003, but significantly higher in November 2004 and March 2005, peaking at 3.2-fold higher (Fig. 4B).

In contrast to the 1080 block, there was no evidence of an immediate post-control decline in rat abundance in either of the ground-control blocks, and rat abundance increased more modestly, peaking at 1.7–1.9 times the level recorded in the non-treatment blocks 18 months after possum control, before declining to means similar to their respective non-treatment blocks (Figs 3B & 4B). This pattern of rat abundance was significantly different from that observed in the non-treatment block at Whirinaki (treatment × time interaction: $\chi^2 = 27.0$, df = 5, $P < 0.001$), but was not different from that found in the sparsely sampled ground-control block at Mokau (treatment × time interaction: $\chi^2 = 6.7$, df = 5, $P = 0.24$).

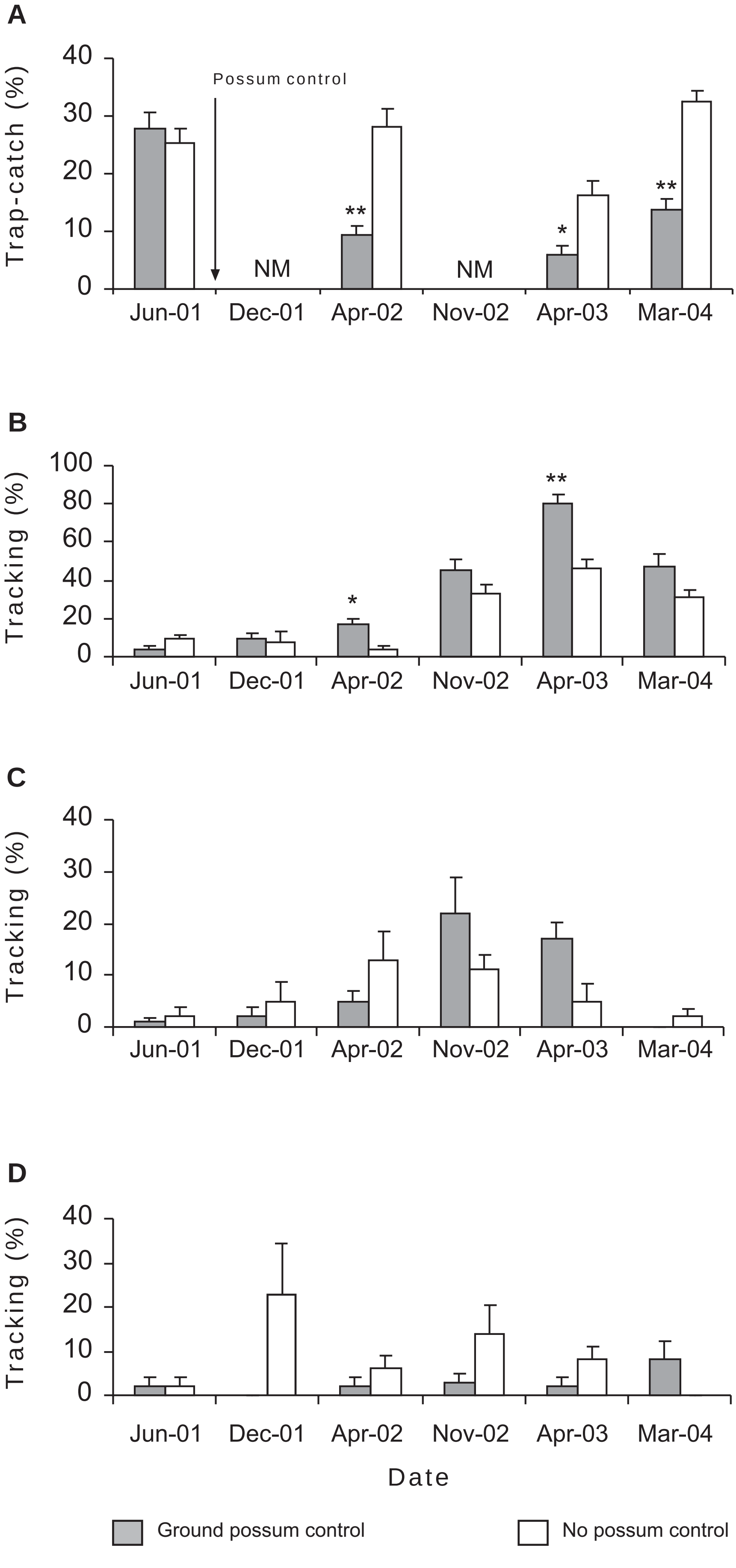
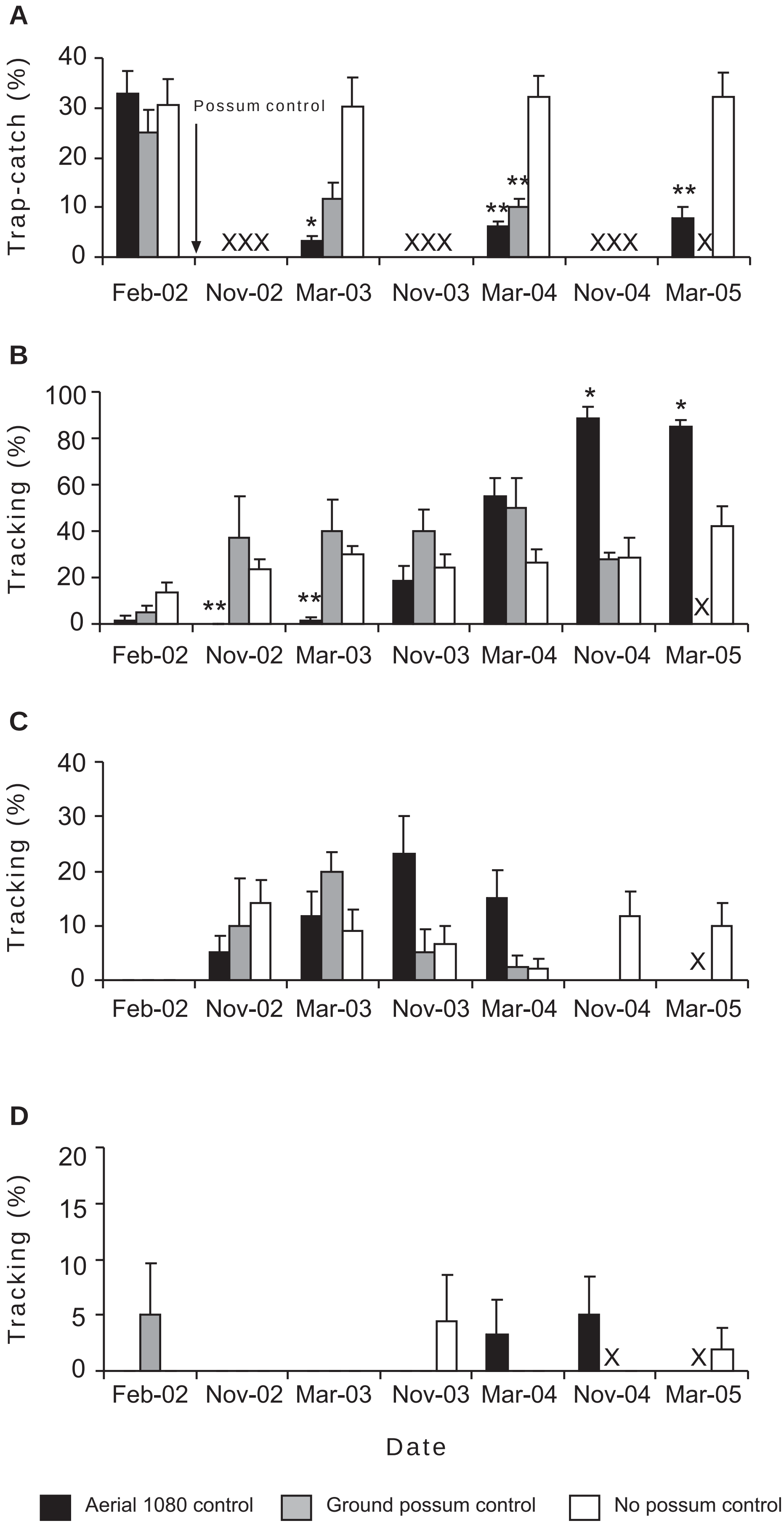



Figure 3. Mean indices (+ SEM) of A. Possum (*Trichosurus vulpecula*), B. Rat (*Rattus rattus*), C. Mouse (*Mus musculus*) and D. Stoat (*Mustela erminea*) abundance in the possum-control and non-treatment blocks at Whirinaki between June 2001 and March 2004. 'NM' denotes that possum abundance was not measured on these dates. Significant differences between possum-control and non-treatment blocks at the 5% (*) and 1% (**) levels are indicated (Kruskal-Wallis non-parametric tests with Bonferroni adjustments for multiple comparisons). Note that the *y*-axis parameter and scale varies between graphs.

Figure 4. Mean indices (+ SEM) of A. Possum (*Trichosurus vulpecula*), B. Rat (*Rattus rattus*), C. Mouse (*Mus musculus*) and D. Stoat (*Mustela erminea*) abundance in the aerial-1080, ground-control and non-treatment blocks at Mokau between February 2002 and March 2005. 'X' denotes that animal abundance was not measured on these dates. Significant differences between possum-control and the non-treatment blocks at the 5% (*) and 1% (**) levels are indicated (Kruskal-Wallis non-parametric tests with Bonferroni adjustments for multiple comparisons). Note that the *y*-axis parameter and scale varies between graphs.



## 5.3 MOUSE ABUNDANCE

Mouse numbers were also low in all blocks during pre-control assessments (no mouse tracks were recorded in the three Mokau blocks). At Whirinaki, tracking rates increased in both the treatment and non-treatment areas, peaking in 2002 (paired *t*-tests: $t \geq 2.4$, df = 9, $P \leq 0.041$); rates then declined to low levels again by March 2004 (Fig. 3C). The peak in mouse abundance occurred 6 months later in the possum-control block; although this peak was 1.7-fold higher, it was not significantly different from peak mouse abundance in the non-treatment block (Kruskal-Wallis test: $\chi^2 = 0.79$, df = 1, $P = 0.390$). Tracking-rate patterns were significantly different between the Whirinaki blocks overall (treatment × time interaction: $\chi^2 = 15.6$, df = 5, $P = 0.008$), reflecting a lack of synchronisation between the pulses in mouse abundance.

At Mokau, patterns of mouse abundance showed some similarities with those observed at Whirinaki. In all blocks, post-control tracking increased from the low pre-control levels (paired *t*-tests: $t \geq 4.9$, df = 3–9, $P \leq 0.016$), peaking first in the non-treatment block, followed by the ground-control block 6 months later, and then the 1080 block 6 months later still, before declining to low levels again. During the last year of monitoring, mouse abundance then increased again in the non-treatment block, while remaining very low in both possum-control blocks (Fig. 4C). Peak mouse abundance was not significantly different between the three blocks (Kruskal-Wallis tests: $\chi^2 \leq 1.05$, df = 1, $P \geq 0.306$). Overall, the pattern of mouse abundance in the non-treatment block at Mokau was significantly different from that in the 1080 block ($\chi^2 = 30.9$, df = 6, $P < 0.001$) but not in the ground-control block ($\chi^2 = 7.8$, df = 5, $P = 0.165$), again reflecting the different timing of peaks in mouse abundance in the 1080 and non-treatment blocks.

## 5.4 STOAT ABUNDANCE

Very few stoat tracks were recorded during the study at Mokau, and in the possum-control block at Whirinaki the number of tunnels with tracks never exceeded 5% (Figs 3D & 4D). In the non-treatment block at Whirinaki, stoat tracking peaked at 22% in December 2001, while remaining very low in the ground-control block ($\chi^2 = 22.0$, df = 5, $P < 0.001$); this was a time when rodent abundance was very low (Fig. 3). Stoat tracking rates appeared to be unrelated to rodent tracking rates (Figs 3 & 4).

## 5.5 POSSUM AND RAT ABUNDANCE GRADIENTS AT WHIRINAKI

In autumn 2004, there was no evidence of a gradient in possum density inside the possum-control boundary at Whirinaki. Possum RTCs for the ten transects surveyed ranged from 3.3% to 23.3% trap-catch and were not correlated with distance from the control boundary ($r = 0.13$, $P = 0.70$, $n = 10$; Fig. 5). Rat abundance was also unrelated to distance from the possum-control boundary ($r = 0.22$, $P = 0.51$, $n = 10$; Fig. 5). There was no significant correlation between possum and rat abundance ($r = 0.25$, $P = 0.46$).

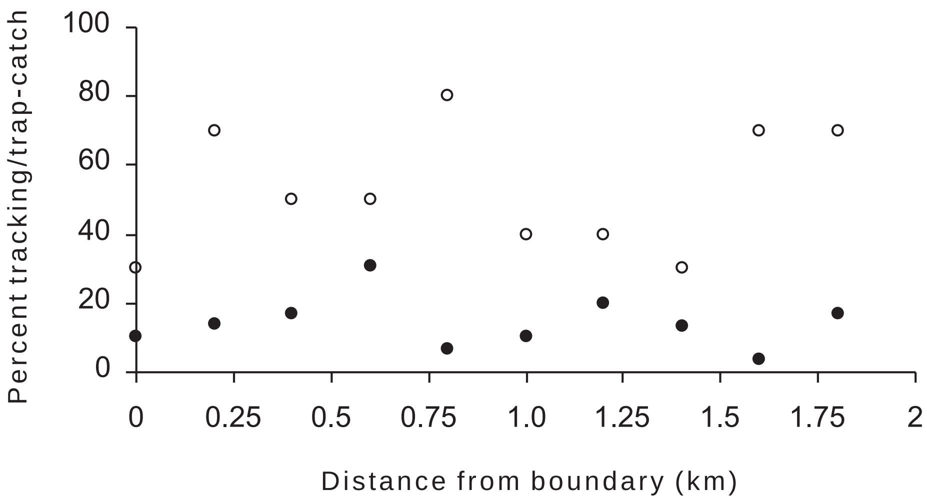



Figure 5. Possum (*Trichosurus vulpecula*) (●) and ship rat (*Rattus rattus*) (○) abundance indices on transects at increasing distances from the possum-control boundary, in the possum-control block at Whirinaki in March 2004.

# 6. Discussion

Interpretation of the study results has been hampered by study design constraints and by unanticipated outcomes of the possum control operations. Firstly, resources permitted only one pre-control assessment of pest abundance at both Whirinaki and Mokau. Coupled with the very low rodent and stoat abundance indices recorded at that time, this means that we cannot be confident about the pest carrying capacities of treatment and non-treatment blocks prior to possum control, which affects our ability to interpret the relative abundance of post-control rodent and stoat populations. In the absence of robust pre-control abundance data, we can only cautiously assume that the selected treatment and non-treatment blocks have similar pest carrying capacities in the absence of possum control, as suggested by the limited pre-control data. Secondly, the unanticipated application of ground possum control in part of the Mokau treatment area split that site into two treatments, each of which received a low sampling intensity. Further, the modest reduction in possum abundance achieved by this ground control, and its subsequent annual reapplication, including the use of brodifacoum baits, which may have affected rodent and stoat populations, means that little can be concluded about the effect of ground possum control on rodent and stoat populations at this site. Therefore, results from the ground-control block at Mokau will not be discussed further. Finally, the level of possum control achieved at Whirinaki was also poor, achieving an RTC of 9.3%, which is well above standard management targets of 2%–5% RTC. Furthermore, these RTC estimates understate 'true' RTC values as they were obtained using raised sets, which typically catch c. 30%–40% fewer possums than the ground-set traps on which standard management targets are based (unpubl. data; Nugent et al. 2001). A poor possum kill may have limited the potential of the rat population to respond to reduced possum abundance.

## 6.1 RATS

Although both ship and Norway rats (*Rattus norvegicus*) were potentially present in the study areas, their footprints cannot be easily separated. However, since ship rats dominate rat populations in New Zealand forests (Innes 1990), most, if not all, the rat tracks we recorded are likely to have been from this species.

Assuming that pre-control rat abundances were comparable between the two blocks at Whirinaki, our data indicate a modest post-control increase in rat abundance in the possum-control block, where tracking rates peaked at a level 1.7 times higher than found in the non-treatment block. This apparent relative increase in rat abundance appears to be short-lived, having ended by March 2004, although further monitoring would have been required to confirm this. Since rat abundance in both blocks at Whirinaki followed the same general pattern throughout the study, and the pre-control data were severely limited (see above), it is possible that the differences in tracking rates simply reflect intrinsic differences between the blocks, independent of possum abundance.

Data from Mokau provide more robust evidence that possum control affected rat abundance, because the patterns of abundance differed markedly between the 1080 treatment and non-treatment blocks. In the non-treatment block, rat tracking rates remained low to moderate (14%–42%) throughout the study. In contrast, in the 1080 block, rat tracking rates were very low (≤ 2%) for the first year (three assessments), then increased to very high levels over the following 18 months, peaking at a level 3.2 times higher than found in the non-treatment block 2 years after possum control; the rate then remained very high over the last 6 months of the study. As at Whirinaki, further monitoring is needed at Mokau to determine the duration of apparently elevated rat abundance in the possum-control block.

The apparently contradictory pattern of initially fewer rats post-control in the 1080 block than in the untreated block, followed by more rats at a later time, can probably be explained by the knowledge that aerial-1080 possum control operations usually also kill most resident rats (Murphy & Bradfield 1992; Innes et al. 1995; Miller & Miller 1995; Murphy et al. 1999). Rat populations usually recover to pre-control levels within c. 6 months of possum control (Innes et al. 1995). Although rat tracking rates in the 1080 block were the same 6 months after possum control as they were prior to control, they were significantly lower than in the other two blocks, suggesting that the rat population in the control block had not fully recovered, and did not do so until about a year after the poison operation (Fig. 4B). It is possible that the recovery time was longer due to the very large scale of the 1080 poison operation (15 600 ha); this may have resulted in the effect of immigration from outside the control area being lower than is usually observed for smaller-scale poison operations.

The differences in tracking rates observed between treatments may underestimate the real differences in rat density, particularly when tracking rates were high (e.g. 88% in the 1080 block in November 2004), because percent indices of animal abundance usually exhibit a curvilinear relationship with absolute density, becoming saturated at high index levels. However, this can be corrected for by Poisson transformation of the data (Caughley 1977). Poisson transformation of our data suggests a 2.5- and 6-fold difference in rat density between blocks at Whirinaki in April 2003 and at Mokau in November 2004 respectively.

If possum control results in increased rat abundance, we would expect to find a negative relationship between possum density and rat density. When we measured possum and rat density in relation to distance from a non-treatment possum population at Whirinaki 2.5 years after possum control, there was no evidence of such a relationship. However, there was also no evidence of the expected immigration-induced gradient in possum density, meaning that the experiment did not provide the expected test of the hypothesis. The absence of a gradient in possum density is puzzling, but may reflect low possum carrying capacity in the non-treatment area immediately adjacent to where the experiment was conducted. Forest type changed abruptly at the control boundary, from podocarp-tawa inside the controlled area to red beech-silver beech-tawari (*Nothofagus fusca-N. menziesii-Ixerbia brexioides*) in the non-treatment area (Fig. 1). Beech forests generally support low possum densities (Efford 2000), and a field inspection of the beech forest south of the treatment block (Fig. 1) at the end of the trial revealed little possum sign in what was a cold and damp, south-facing site.

Despite implementation difficulties (low pre-control rat abundance, poor possum kill achieved at ground-controlled sites, and short duration of post-control monitoring), this study indicates that ship rat populations, at least sometimes, increase following possum control in podocarp-hardwood forests. The study provides little insight into the mechanisms that drive this phenomenon, but we speculate that it is likely to be related to post-control increases in the availability of quality foods for rats. This may occur directly, through reduced competition from possums for favoured foods, or indirectly, through improvements in forest condition and productivity resulting from possum control (Cowan 1990a; Cowan & Waddington 1990; Brockie 1992; Norton 2000; Veltman 2000). Possums have been recorded eating mice (Cowan 1990b) and scavenging ship rat carcasses (Brown et al. 1993), but rodents have never been reported in published quantitative studies of possum diet (Nugent et al. 2000), so it seems unlikely that predation by possums would occur frequently enough to reduce rat densities. Likewise, it is unlikely that competition for nest space and shelter is of importance in mature podocarp-hardwood forest, in which fallen and hollow trees and other cavities are abundant. As ship rats eat little foliage of woody species (Best 1969; Daniel 1973), we suspect that competition, if present, is likely to be for high-energy and/or high-nutrient foods, such as fruit, seeds or invertebrates, rather than for foliage.

Few previous studies have recorded ship rat abundance following possum control in podocarp-hardwood forest beyond their initial short-term recovery after poison operations, and those that have had mixed results. Rat abundance at Waihaha, Central North Island, was five-fold higher for up to 6 years after possum control than during the 4 years prior to possum control (Sweetapple et al. 2002a; unpubl. data). In contrast, in another study at Whirinaki, rat numbers in a possum-controlled area did not exceed those in a nearby non-treatment area during 2 years of post-control monitoring (Powlesland et al. 2003). However, that study did not provide a robust test of the medium-term effect of possum control on rats, because intensive commercial possum hunting in the non-treatment block reduced post-control possum abundance there to levels similar to those found in the possum-control block.

Studies in other forest types have also returned mixed results. Ship rat abundance did not exceed pre-control levels within 1 year of possum control in pohutukawa (*Metrosideros excelsa*)-dominated seral hardwood forest (Miller & Miller 1995), but Clout (1980) recorded a sharp increase in ship rat activity following possum trapping in a *Pinus radiata* plantation.

## 6.2 MICE

It has previously been found that mouse abundance indices increased following pest control operations that reduced possum abundance (Clout et al. 1995a; Innes et al. 1995; Miller & Miller 1995; Murphy et al. 1999). In these studies, mouse abundance indices increased dramatically within 2–6 months of pest control (at the same time as rat numbers were increasing), but only following operations that first reduced rat abundance to very low levels. In our study, however, the mouse population response to possum control was different. Indices of mouse abundance in the 1080- and Whirinaki ground-control blocks were, at some stage after possum control, higher in relative terms than in the associated non-treatment blocks; however, this was due to differences in the timing of fluctuations in mouse numbers rather than a general population increase. Peaks in mouse tracking were recorded 6 and 12 months after they occurred in non-treatment blocks at Whirinaki and Okahu respectively. We are unable to account for these patterns.

The Mokau 1080 block provides some evidence that very abundant rat populations suppress mouse numbers or detectability. No mice were tracked there during the last two assessments, when rat tracking exceeded 80% and mouse tracking in the non-treatment block was 10%–12%. No evidence of this phenomenon was observed at Whirinaki.

The significance of our results, or those of previous studies, is difficult to determine, as the interpretation of mouse abundance indices is problematic: mouse tracking rates may not always accurately reflect mouse density (Brown et al. 1996; Ruscoe et al. 2001), because behavioural interactions between rats and mice may result in lower detection rates for mice when rats are present in high numbers (Brown et al. 1996; Sweetapple & Nugent 2005).

## 6.3 STOATS

We expected stoat numbers to be positively correlated with rodent abundance because stoats are flexible and opportunistic in their diet, and have a high potential productivity (King 1990), which is closely related to food supply during the season of embryo implantation, gestation and lactation (spring to early summer; King et al. 2001). They can therefore respond rapidly, both functionally and numerically, to changes in food supply (King 1983; Murphy & Bradfield 1992). In New Zealand, this is best documented in beech forests, where stoat populations increase dramatically following beech-mast-induced mouse population eruptions (King 1983; Fitzgerald et al. 1996). Because rats are an important food for stoats in podocarp-hardwood forests (Murphy & Bradfield 1992; King et. al. 1996; Murphy et al. 1998), rat abundance might also drive stoat densities here. However, the lack of any evidence of a relationship between stoat and rodent abundance in this study argues against this. Similarly, stoat abundance was consistently low (equivalent to non-mast years in beech forest) in podocarp forest in Pureora Forest Park over a 4-year period, despite an abundance of rats (King et al. 1996), even though stoats do sometimes attain high densities there (e.g. Murphy et al. 1999); however, the lack of an obvious relationship between rodent and stoat abundance in this study may be due at least in part to the low detectability of stoats when stoat foods are abundant (King & White 2005).

At Whirinaki, there was some evidence that stoats may have been more abundant in the non-treatment block than in the possum-control block (Fig. 3D). However, even if stoats were more numerous in the non-treatment block, they may not have affected rodent abundance, since previous New Zealand studies have failed to detect a suppressive effect of stoats on rodents (Blackwell et al. 2003; Ruscoe et al. 2003).

In conclusion, results of this study to date do not support the hypothesis that one-off possum control operations in podocarp-hardwood forests result in mid-term (1–3 year) increases in mouse or stoat abundance relative to non-treatment areas. However, there is evidence to support this hypothesis with respect to ship rats. In the ground-controlled area at Whirinaki, results, though equivocal, strongly suggest that rat abundance is elevated following possum control. In the aerial-1080 block at Mokau, there was a strong positive response by ship rats to possum control once the rat population had recovered from the immediate effects of the poison operation. Further investigation is required to determine the universality and duration of this effect on ship rats.

## 6.4 ECOLOGICAL IMPLICATIONS

Ship rats are important predators of birds, invertebrates and seeds (Atkinson 1973; Bell 1978; Innes 1990, 2001), and the breeding success and survival of several forest bird species has been linked to ship rat abundance (Clout et al. 1995b; Innes et al 1999; Powlesland et al. 1999, 2000). The consequences of any increase in rat abundance resulting from possum control could potentially undermine the reported benefits arising from that control (Norton 2000; Veltman 2000; Nugent et al. 2002; Sweetapple et al. 2002b). There is, therefore, strong justification to further investigate the medium-term response of ship rat populations to possum control, and the ecological and pest-management consequences of any resulting increase in rat populations.

# 7. Recommendations

Possum control has been reapplied to the ground-control block at Whirinaki, but monitoring of pest abundance should continue in the 1080 block at Mokau, to determine the duration of the numerical response of rodents to the one-hit possum control operation there. The extension of monitoring beyond autumn 2005 would be useful.

Medium-term monitoring of rodent and stoat abundance following one-hit possum control should also be extended to forest types other than podocarp-tawa forest, to determine the universality of post-control elevation in rodent densities. This should include mixed beech forests that hold moderate possum numbers, because possums eat substantial quantities of beech seed during beech mast seeding (Sweetapple 2003) and could, therefore, moderate rodent and stoat eruptions that follow such mast events. A useful precursor to any future studies would be to canvas Department of Conservation conservancies for existing datasets of rodent and stoat abundances before and after possum population reductions.

Conservation managers need to be aware that while intermittent possum control can benefit forest ecosystems through reduced herbivory and short-term reductions in rodent and stoat populations, there may also be negative, as yet unquantified, consequences due to the post-control enhancement of ship rat populations in the medium term.

Research is needed to determine the ecological consequences of increased rat abundance following possum control, where this occurs. This will require better understanding of the impacts of unmanaged rodent, stoat and possum populations in podocarp-hardwood forests, and the net change in those impacts following periodic possum control with and without simultaneous rodent control, and for control cycles of varying lengths.

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# Appendix 1

## POSSUM, RAT, MOUSE AND STOAT ABUNDANCES

Mean percent trap-catch rates for possums (*Trichosurus vulpecula*) and mean percentage of tracking tunnels with rat (*Rattus rattus*), mouse (*Mus musculus*) or stoat (*Mustela erminea*) prints in the five study blocks from June 2001 to March 2005.

| AREA | DATE | POSSUMS | RATS | MICE | STOATS |
|---|---|---|---|---|---|
| **Whirinaki (Bay of Plenty)** | | | | | |
| Okahu Stream (treatment) | June 2001 | 27.7 | 4.0 | 1.0 | 3.0 |
| | Dec 2001 | | 9.0 | 2.0 | 0.0 |
| | Apr 2002 | 9.3 | 17.0 | 5.0 | 4.0 |
| | Nov 2002 | | 45.0 | 22.0 | 2.0 |
| | Apr 2003 | 6.0 | 80.0 | 17.0 | 2.0 |
| | Mar 2004 | 13.7 | 47.4 | 0.0 | 5.0 |
| Whirinaki Forest (non-treatment) | June 2001 | 25.3 | 9.0 | 2.0 | 1.0 |
| | Dec 2001 | | 8.0 | 5.0 | 22.0 |
| | Apr 2002 | 28.1 | 4.0 | 13.0 | 9.0 |
| | Nov 2002 | | 33.0 | 11.0 | 10.0 |
| | Apr 2003 | 16.1 | 46.0 | 5.0 | 7.0 |
| | Mar 2004 | 32.6 | 31.1 | 2.2 | 1.1 |
| **Mokau (Taranaki)** | | | | | |
| Totara Stream (aerial 1080) | Feb 2002 | 32.9 | 1.8 | 0.0 | 0.0 |
| | Nov 2002 | | 0.0 | 5.0 | 0.0 |
| | Mar 2003 | 3.3 | 1.7 | 11.7 | 0.0 |
| | Nov 2003 | | 18.3 | 23.3 | 0.0 |
| | Mar 2004 | 6.1 | 55.0 | 15.0 | 1.7 |
| | Nov 2004 | | 88.3 | 0.0 | 5.0 |
| | Mar 2005 | 7.7 | 85.0 | 0.0 | 0.0 |
| Totara Stream (ground control) | Feb 2002 | 25.2 | 5.3 | 0.0 | 2.6 |
| | Nov 2002 | | 37.5 | 10.0 | 0.0 |
| | Mar 2003 | 11.8 | 40.0 | 20.0 | 0.0 |
| | Nov 2003 | | 40.0 | 5.0 | 0.0 |
| | Mar 2004 | 10.0 | 50.0 | 2.5 | 0.0 |
| | Nov 2004 | | 28.0 | 0.0 | 0.0 |
| Mt Messenger (non-treatment) | Feb 2002 | 30.5 | 13.5 | 0.0 | 0.0 |
| | Nov 2002 | | 23.8 | 14.0 | 0.0 |
| | Mar 2003 | 30.2 | 30.0 | 9.0 | 0.0 |
| | Nov 2003 | | 24.4 | 6.7 | 2.2 |
| | Mar 2004 | 32.2 | 26.3 | 2.0 | 0.0 |
| | Nov 2004 | | 28.8 | 11.8 | 0.0 |
| | Mar 2005 | 32.5 | 42.0 | 10.0 | 2.0 |