



## Radio collaring reveals long-distance movements of reinvading ship rats following landscape-scale control

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**Abstract:** Understanding rates of reinvasion is critical for determining what drives ship rat population recovery following large-scale control operations. We radio-tracked 23 adult ship rats on the edge of a forested area where rats had been suppressed by aerial compound 1080 in the Hollyford Valley, Fiordland. Eleven individuals died within two months of collaring and two individuals were never detected again, leaving us with data from 10 rats. Six individuals were recorded moving 70–174 m from their collaring sites over the nine month monitoring period, which is comparable to normal home range movements found by other studies. Four individuals were recorded moving 657–1516 m into the operational area (mean 1172 m). Sex was unrelated to whether individuals moved large distances or not. Our study confirms that ship rats may move large distances when at low density.

**Keywords:** 1080, dispersal, home range, immigration, *Rattus rattus*

### Introduction

Ship rats (*Rattus rattus*) are a major threat to New Zealand's native biodiversity (Towns et al. 2006; Innes et al. 2010). To protect rat-sensitive species at large spatial scales (> 10 000 ha), aerial control operations using the toxin sodium fluoroacetate (1080) are often used to suppress ship rat populations (Elliott & Kemp 2016). For example, in 2019 the New Zealand Department of Conservation (DOC) aerially applied poison to 691 000 ha of conservation lands across New Zealand to protect a range of native species (e.g. long-tailed bats *Chalinolobus tuberculatus*, North Island kōkako *Callaeas wilsoni*, whio *Hymenolaimus malacorhynchus*) from ship rats, brushtail possums (*Trichosurus vulpecula*), and stoats (*Mustela erminea*) (Environmental Protection Authority 2020). However, ship rat populations can recover rapidly (e.g. within 4–5 months) following these operations (Innes et al. 1995; O'Malley et al. 2022), which may jeopardise biodiversity outcomes.

The recovery of ship rat populations after control relies on two key processes (that can operate independently or cumulatively): reinvasion by individuals from outside the operational area and in situ breeding by immigrants and/or by residual survivors. Griffiths and Barron (2016) demonstrated, using inked footprint-tracking data, that reinvasion of rats from untreated edges was probably the key process driving the initial recovery of rat populations in operational areas within Tararua Forest Park. This may be particularly true in so-called mast years of substantial tree seeding, when an influx of food results in rats reaching high densities (Carpenter et al. 2022), which could place considerable pressure on the edges

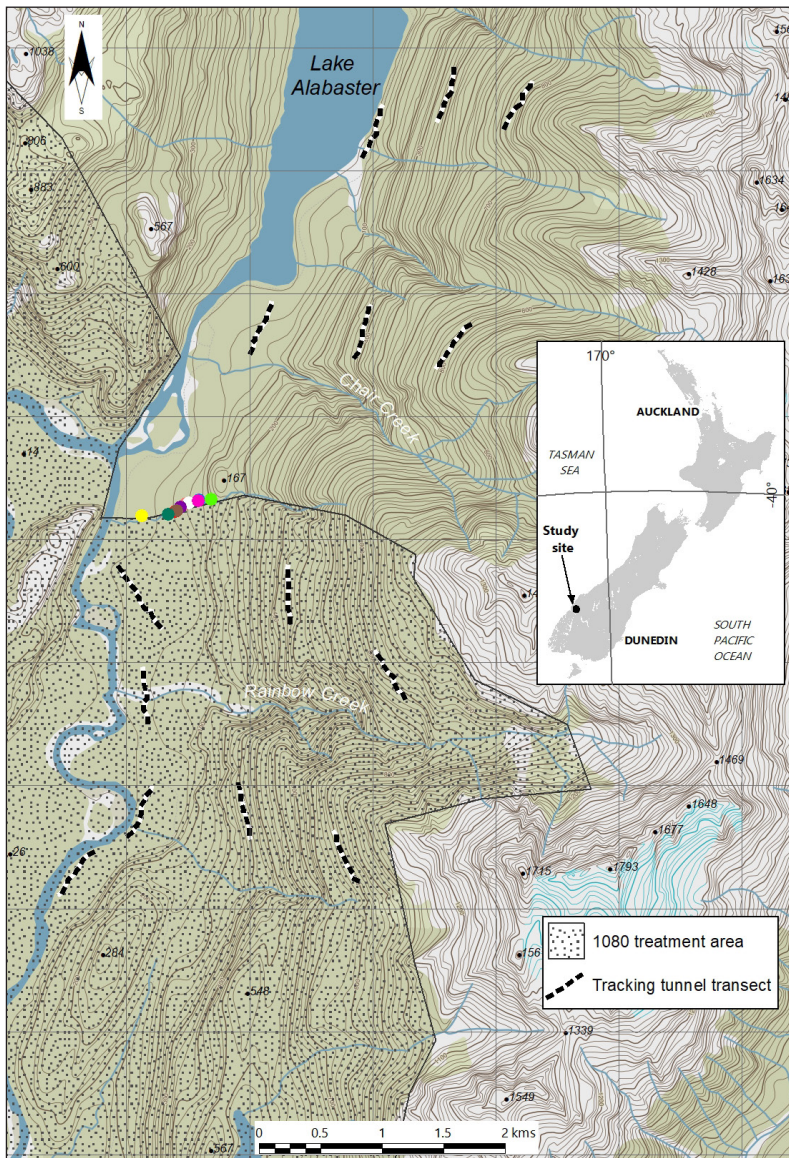
of operational areas. Griffiths and Barron (2016) suggested that the initial infilling of the edges of the treatment zone could have been due to “home range creep” rather than long-distance dispersal. However, to the best of our knowledge no studies have examined ship rat movement at the edge of large-scale control areas in continuous forest. Therefore, very little is known about how far individual rats migrate into operational areas, over what time frames, or whether reinvaders are more likely to be male (as has been found for reinvaders of Waikato forest fragments; King et al. 2011).

Here, we radio-collared individual ship rats on the edge of a 1080 operational zone in northern Fiordland to understand: (1) what proportion of individuals moved into the operational area; (2) how far individuals moved into the operational area, and over what time frame, and (3) whether there were differences in the sex of reinvaders compared with non-invaders.

### Methods

The study site is in the lower Hollyford Valley (44.5167° S, 168.1572° E), in northwest Fiordland, New Zealand (Fig. 1). The valley floor comprises lowland mixed beech-podocarp-kāmahi forest, which grades to upland silver beech (*Lophozonia menziesii*) forest around 500 m a.s.l. The treeline is at approximately 1100 m. Small creeks (c. 1–2 m across) dissect the study site, but are unlikely to inhibit ship rat movement.

In autumn 2019 the beech trees in the valley masted heavily (mean of 3935 silver beech seeds m<sup>-2</sup>), which led to the ship rat population reaching high densities (Carpenter et al. 2022;



**Figure 1.** Map showing the total study site, the aerial toxin (compound 1080) treatment area, and the placement of tracking tunnel lines, in the Hollyford Valley, South Island, New Zealand. The coloured dots show the sites where rats were collared, 11–12 days after the toxin treatment.

Carpenter et al. 2023). DOC carried out a 23 270 ha aerial 1080 operation over most of the Hollyford Valley on 1 and 2 November 2019, following a pre-feed operation on 16 October 2019. Toxic bait was sown at a rate of  $2 \text{ kg ha}^{-1}$ . The operation covered half of the study site, creating a treatment and non-treatment area (Fig. 1). Prior to the operation (October 2019), the mean percentage of inked tunnels with rat footprints was at 91.7% (SD = 9.8%) outside the intended operational area, and 88.8% (SD = 11.3) inside. Nine days after the operation, tracking rates were 96.7% (SD = 8.2) outside the treatment area, and 8.8% (SD = 8.3) within the operational area, indicating a significant knock-down of the rat population.

Rats were captured for radio collaring in live-capture traps c. 50 m outside of the boundary of the 1080 operation, between 5 and 100 m a.s.l., 11–12 days after the 1080 operation (13–15 November 2020). Live-capture traps contained food and shelter for rats. We first anaesthetised rats with isoflurane, then sedated them before collaring by injecting 0.01 ml Zoletil (made up at half label strength) into the muscle of the hind leg. We attached very high frequency (VHF) transmitters with mortality signals (Holohil RI-2D; 7.1 g) to 23 rats (12 females, 11 males). We only collared adult rats with a minimum body

weight of 140 g so that the weight of the transmitter was < 5% of the rat's weight. Rats were released once they had regained consciousness.

We radio-tracked the rats from a helicopter (fitted with a VHF receiver) every 2–3 months, recording their location and whether the signal was indicating mortality. When a signal was detected, the helicopter circled in on the signal until the location of the signal could be determined to between 20–30 m precision. We searched for rats approximately three kilometres into the 1080 area. Radio-tracking was done on 16 January 2020, 18 March 2020, 26 May 2020, and 17 August 2020. The VHF transmitters had an estimated battery life of 12 months, but this was significantly shortened if a mortality occurred (as this doubles the transmission pulse rate).

## Results

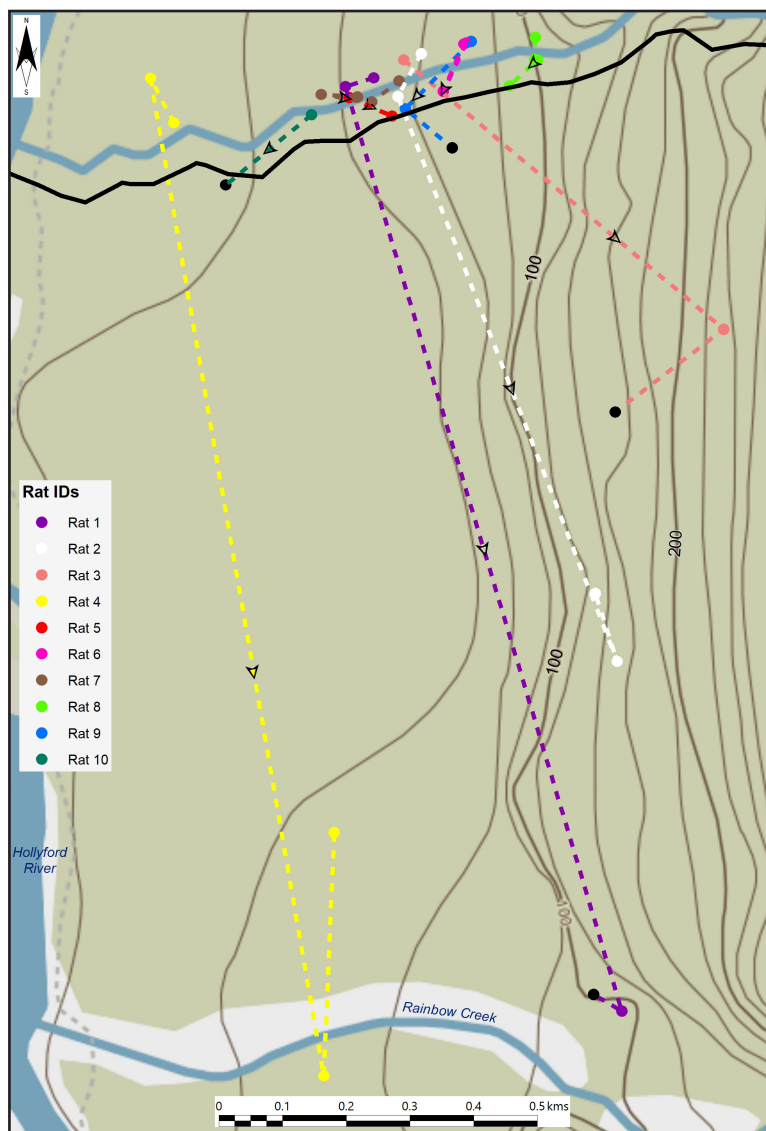
When the rats were radio-tracked in mid-January, two months following collaring, 10 were still alive (five females and five males), two could not be detected, and 11 (six females and five males) were on mortality signals. We do not further consider

the data from the 11 rats that died in the 2 months following collaring, as the data are unlikely to accurately represent the potential scale of their movements (none moved further than 136 m from their collaring site). Nor do we consider further the two rats we could not detect following collaring.

Of our 10 remaining rats, four (three females, one male) moved significant distances (average maximum distance from collaring site: 1172 m) into the treatment area in the 6 months following the operation (Table 1; Fig. 2). The male moved into the operational area sometime in the two months after the

**Table 1.** Summarised information from the 10 rats that survived at least two months after collaring that were monitored for nine months following a compound 1080 operation in November 2019 in the Hollyford Valley, Fiordland.

Individual	Sex	Weight (g)	Maximum distance moved from collaring site (m)	Signal status on:		
				March 2020	May 2020	August 2020
Rat 1	F	140	1516	Alive	Dead	
Rat 2	F	170	1000	Alive	Alive	Not heard
Rat 3	M	160	657	Not heard	Dead	
Rat 4	F	158	1515	Alive	Alive	Not heard
Rat 5	F	140	73	Heard but could not locate	Not heard	Not heard
Rat 6	M	195	81	Alive	Not heard	Not heard
Rat 7	M	170	70	Alive	Alive	Dead
Rat 8	M	162	87	Alive	Alive	Not heard
Rat 9	M	218	170	Dead		
Rat 10	F	143	174	Not heard	Dead	



**Figure 2.** Map showing waypoints of the 10 ship rats that survived the first two months post-radio-collaring. Black dots represent mortality signals from transmitters. The black line represents the aerial toxin treatment area boundary; all terrain to the south of the line was treated with compound 1080. Rainbow Creek was unlikely to act as a substantial barrier to movement as it is a small river, and treefalls across it would likely have facilitated movement.



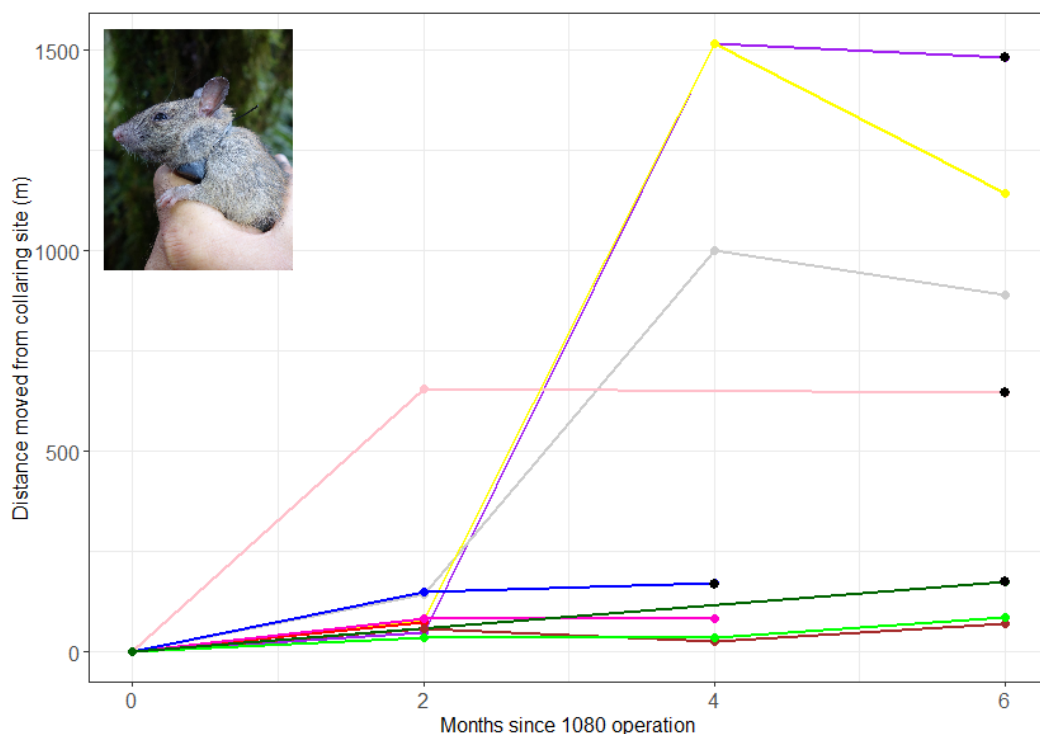
operation, but the females did not move until sometime between January and March (2–4 months after the operation; Fig. 3). The remaining six rats moved maximum distances of between 70 and 174 m (average distance: 109 m) from their collaring sites (Fig. 2), which is typical of home range movements in unmanaged mainland ship rat populations in North Island podocarp-broadleaved forests (Innes & Russell 2021). Sex did not predict whether rats were more or less likely to emigrate (Fishers exact test statistic: 0.52), where emigration is defined as moving > 200 m from the collaring location. None of the rats made large changes in their elevation; the largest change was made by Rat 3, which was collared at 60 m a.s.l. and then moved to 240 m a.s.l. (Fig. 2). All individuals had either died or could not be detected (probably due to transmitter battery failure) by August 2020, nine months after collaring.

## Discussion

Understanding rates of reinvasion into control areas is critical for gaining an understanding of what drives ship rat population recovery following large-scale control operations. Our study provides the first assessment of distances moved by adult ship rats at the edge of a treatment area in the nine months following a 1080 operation. Just under half of our surviving radio-collared individuals moved substantial distances (650 m – 1.5 km) into the treatment zone. Griffiths and Barron (2016) suggested that home range creep may be the mechanism behind higher tracking rates towards 1080 zone edges, since ship rats have been shown to rapidly expand their ranges into areas vacated by removed neighbours (Innes & Skipworth 1983). Ship rats moving into a 1080-controlled area may not

encounter neighbours, so they may move large distances. The six individuals that remained in the general vicinity of their collaring sites moved a maximum distance of 109 m on average, well within usual home range limits. Mean home range lengths for ship rats from four North Island studies were 103–171 m for females, and 159–500 m for males (Dowding & Murphy 1994; Hooker & Innes 1995; Perry et al. 2009; Fitzgerald et al. 2017), and the sole study in South Island beech forest found home range lengths of 400 m and 700 m for two males (Pryde et al. 2005). However, because our tracking was carried out in the daytime, when ship rats are not usually active, the locations we recorded represented denning sites only. Actual movements by both non-invaders and reinvaders may have been greater than the distances we recorded.

Although natal dispersal in rodents generally (Krebs et al. 2007) and in Norway rats (*R. norvegicus*) has been regarded as male-biased (Calhoun 1962), subsequent studies have found that some females also move large distances (Heiberg et al. 2012). Nathan et al. (2020) recorded natal dispersal distances in ship rats, but the sample size was too small to determine differences in males ( $n = 2$ ) versus females ( $n = 1$ ). We know of no other natal dispersal studies of ship rats, but we found that among the adult ship rats we studied, females were just as likely to make large movements into the operational area as males. In fact, the three longest distance movements into the area were all by females. However, our results are not indicative of the total rat population, as we could collar only adults due to minimum weight requirements. King et al. (2011) found that reinvasion of Waikato forest fragments following ship rat removal was primarily by juvenile males, and it is possible we would have observed more ship rats moving into the operational area if we could have monitored natal dispersal



**Figure 3.** Distances moved by the 10 radio-collared ship rats in the six months following a compound 1080 operation in the Hollyford Valley, Fiordland. Each line represents one individual, following the colour legend in Fig. 2 (with the exception of Rat 2, which is grey rather than white). Black points represent mortality signals. Photo credit: Max Harvey.

by juveniles. It is also possible that the two individuals we could not detect following collaring moved extremely large distances into the operational area, beyond the area we were surveying by helicopter.

We found that most of the individuals that moved long distances did not do so until 2–4 months following the treatment. Similarly, ship rats took three months to reinvade 1 ha forest blocks that had undergone ship rat removal (Hansen et al. 2020). One explanation for the lag in ship rat movement relates to ship rat population dynamics in response to the mast event that had occurred earlier in 2019. Carpenter et al. (2022) found that ship rats were at extremely high densities following the seedfall in the untreated part of the study site, and these high densities were maintained until January 2020, when populations declined rapidly, potentially due to food resources running out and an increase in stoat predation. The timing of this decline corresponds to when some individuals started moving large distances into the operational area, perhaps because they were pushed out of their territories by dominant individuals as resources declined. Feng and Himsforth (2014, p. 158) stated that for urban Norway rats and ship rats, “Long distance dispersals are more uncommon [than short] and tend to occur as a result of extreme resource limitation, high intraspecific competition, and/or extreme environmental change”.

More generally, our findings demonstrate that ship rats can move large distances in areas where rat density is low. Although ship rat home range lengths are typically in the range of 100–300 m (Innes & Russell 2021), rats may make far greater movements in large areas with very few rats. For example, Nathan et al. (2020) found that a biomarked ship rat mother moved over 1500 m, and her offspring moved up to 675 m, from the release site in a post-1080 zone to which they had been translocated. Radio-collared adult male ship rats experimentally placed in Maungatautari sanctuary also made large movements of up to 1100 m, perhaps to search for mates (Innes et al. 2011). Accounting for these large movements will be important for Predator Free New Zealand initiatives (Russell et al. 2015), in particular the “remove and protect” model, which aims to locally eliminate key species from blocks of land with defensible boundaries, i.e. natural barriers (Bell et al. 2019; Nichols et al. 2021). Our findings support efforts by conservation managers to minimise edge to treatment ratios of operational areas by increasing their size, and using natural (e.g. high mountains, large rivers) and constructed (e.g. pest fences or virtual fences; Day & MacGibbon 2007; Bell et al. 2019) barriers to dispersal where possible.

Rats had high (50%) mortality in the first two months following collaring. There are several potential explanations for this. First, the collaring field trip in November coincided with a period of cold, wet weather, which may have affected their ability to recover from the anaesthesia. We estimate that around four individuals may have died shortly after collaring from hypothermia based on the short distance between their collaring site and where they were recovered. Second, some collared rats may have undergone secondary 1080 poisoning by consuming other poisoned animals, as we collared individuals less than two weeks after the bait was sown. Some individuals may also have been preyed on by stoats, as stoat numbers were increasing around this time in response to the elevated rodent numbers (Carpenter et al. 2022). We found one individual 136 m from its collaring site that appeared to have been preyed upon, and collaring may have exacerbated the risk of predation. However, it is worth noting that following this initial period of high mortality, collared ship rats on the edge of the 1080

zone had similar survival to uncollared individuals elsewhere (Carpenter et al. 2022). We recommend that in future radio-collaring studies, rats be collared only in fine weather, and that heat pads be used to keep animals warm until they recover from anaesthesia.

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## Additional Information and Declarations

**Conflicts of interest:** The authors declare no conflicts of interest.

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**Ethics:** All fieldwork was carried out under a global concession permit (CA-31615-OTH) with the New Zealand Department of Conservation. All animal manipulations were approved by the Manaaki Whenua – Landcare Research Animal Ethics Committee (AEC approval number 19/04/03).

**Data availability:** The data used in this paper can be accessed by contacting the corresponding author.

**Author contributions:** JKC, JI, JG, and AM conceived the idea and designed the study. JKC carried out data collection, analysis, and wrote the manuscript, with editorial contributions from JI, JG, and AM.

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