Response of a reintroduced bird population to a rat reinvasion and eradication

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Abstract: Many endemic species on islands are vulnerable to predation and local extinction by introduced rats (*Rattus* spp.). As a result, the reintroduction of species to predator-free sanctuaries is a successful conservation strategy, especially in New Zealand. Nevertheless, reintroduced populations, even those that reach high densities, are still vulnerable to predation in the event of a rat reinvasion, and may also be susceptible to non-target poisoning during a subsequent eradication operation. We quantify for the first time the changes in population size and survival rate of a well-established, reintroduced species (Stewart Island robins, *Petroica australis rakiura*) following the reinvasion and eradication of Norway rats (*Rattus norvegicus*) on Ulva Island, New Zealand, in 2011. The robin population declined by nearly one-third (31.5%; 432 to 296 adults) in the breeding season following the rat reinvasion and eradication. The survival rate of robins prior to the poison operation was only slightly lower than expected, which suggests the growing population of Norway rats may have had a relatively minor negative effect on robin survival. In contrast, the majority of the decline occurred immediately following the poison operation. This suggests the robins were susceptible to non-target poisoning from the brodifacoum poison bait, although the robin population would have likely declined even further if Norway rats had not been eradicated. Our results indicate the importance of developing permanent surveillance systems on island sanctuaries to detect and kill rats upon arrival in order to avoid the potentially high rates of non-target poisoning associated with post-invasion, large-scale eradication operations.

Keywords: brodifacoum; invasion; islands; New Zealand; poison operation; robin; survival; Ulva Island

Introduction

The decline and extinction of endemic species on islands can often be attributed to the introduction of invasive rats (*Rattus* spp.) (Towns et al. 2006). To prevent extinctions and restore native ecosystems, conservation managers initiated systematic attempts to eradicate rats from islands in the 1980s (Thomas & Taylor 2002). Since then, efforts to eradicate rats have become increasingly cost-efficient and effective, and as a result rats have been eradicated from nearly 300 islands worldwide (Howald et al. 2007).

Although the majority of eradications of rats from islands have been successful, reinvasions occasionally occur (Clout & Russell 2006, 2008). Endemic species that are reintroduced to islands after eradications are likely to be particularly susceptible to predation following a rat reinvasion, similar to cases where native species are exposed to rats for the first time (e.g. Thorsen et al. 2000; Towns 2009). For example, saddlebacks (*Philesturnus carunculatus*) have been reintroduced to numerous predator-free offshore islands in New Zealand but are extirpated from islands in the presence of rats (Lovegrove 1996). Birds reintroduced to rat-free islands could also lose their ability to recognise rats as predators within one generation (Jamieson & Ludwig 2012). Previous studies have not examined the effects of a rat reinvasion on survival and viability of reintroduced populations because rat reinvasions have not yet occurred on islands with reintroduced populations that are well established and monitored. However, the frequency of rat reinvasions onto islands has been increasing over time and will likely continue to occur in the future (Clout & Russell 2008).

Endemic species are also vulnerable to non-target poisoning during an attempt to eradicate or control rats.

Anticoagulant rodenticides (such as the second-generation toxin brodifacoum) are the most commonly used poison to eradicate introduced mammalian predators from offshore islands both in New Zealand (Innes & Barker 1999; Towns & Broome 2003) and worldwide (Stone et al. 1999; Howald et al. 2007). Although the use of brodifacoum is an efficient method of controlling rodents, it poses a risk to non-target species such as native birds through primary and secondary poisoning (Eason et al. 2002; Hoare & Hare 2006). Birds are the only group of animals known to have been fatally poisoned by brodifacoum in New Zealand (Hoare & Hare 2006), but many endemic species are typically absent from islands undergoing poison operations using brodifacoum in order to eradicate introduced mammalian predators for the first time (Holdaway 1989).

In New Zealand, robins (*Petroica* spp.) are one of the first bird species reintroduced to offshore islands following predator eradication (Armstrong 2000) and are susceptible to primary poisoning by brodifacoum (Taylor & Thomas 1993; Spurr & Powlesland 1997). Three previous studies have examined the effect of an aerial poison operation with brodifacoum on robin populations, but two of these studies were confounded by both non-detection due to possible emigration from the study area and low resighting rates (Walker & Elliott 1997; Empson & Miskelly 1999). The third study estimated the change in survival of an entire robin population at a low population density (Armstrong & Ewen 2000). Bird species in high-density populations may be more likely to feed on novel food items (Lefebvre & Bolhuis 2003), but the non-target effects of a rodenticide application on a high-density robin population have not been examined.

Ulva Island is located in Patterson Inlet, Stewart Island, New Zealand, and is an 'open sanctuary' managed by the

Department of Conservation. Norway rats were eradicated from Ulva Island in 1996, using bait stations containing brodifacoum. The successful eradication of rats was followed by the reintroduction of endemic bird species such as Stewart Island robins (*Petroica australis rakiura*). Robins disappeared over most of Stewart Island by the early 1900s, when ship rats (*Rattus rattus*) became widespread across the island (Harper 2009). Since the first eradication of rats in 1996, an average of one rat per year has been trapped on Ulva Island, mainly around the wharf (Russell et al. 2008). Ulva Island has essentially remained 'rat-free' for the last 14 years until late December 2010 when an established population of rats was discovered. Between December 2010 and March 2011, a total of 96 Norway rats were captured in the biosecurity trapping network set up along the coast to catch rats as they arrived (Fig. 1), and the population appeared to be increasing exponentially (Fig. 2). Trapping operations ceased in March when the rat population was declared to be unmanageable using the existing biosecurity trapping network. After holding a public submission and hearing process and subsequently obtaining approval from Environment Southland (2011), the Department of Conservation conducted an aerial application of brodifacoum on 18 August and 20 September 2011 (Fig. 1). Rats have not been detected as of February 2013, during the first 18 months after the application of poison.

The primary objective for this study was to determine the impact of a reinvasion of Norway rats and subsequent aerial application of brodifacoum on a reintroduced, high-density population of robins. Specifically, we aimed to determine (1) how the population size, number of breeding pairs and survival rate of robins changed in the breeding season following the rat reinvasion and eradication and (2) the effect of the rat reinvasion, as well as the poison operation, on the robin population. We also describe opportunistic observations of robins feeding on poison bait, and predict the robin population size during the 2012 season.

Methods

The robin population on Ulva Island has been intensively monitored each breeding season since release in 2000 as part of a long-term study on the effects of inbreeding in reintroduced populations (Jamieson 2011; Laws & Jamieson 2011). An annual survey of the population is conducted each breeding season using two monitoring techniques. Observers survey the entire island at the start of the breeding season by hand-clapping for 5 min at each point on a 100 × 100 m grid. Robins are trained to approach the sound of observers hand-clapping in order to receive a mealworm as positive reinforcement, and
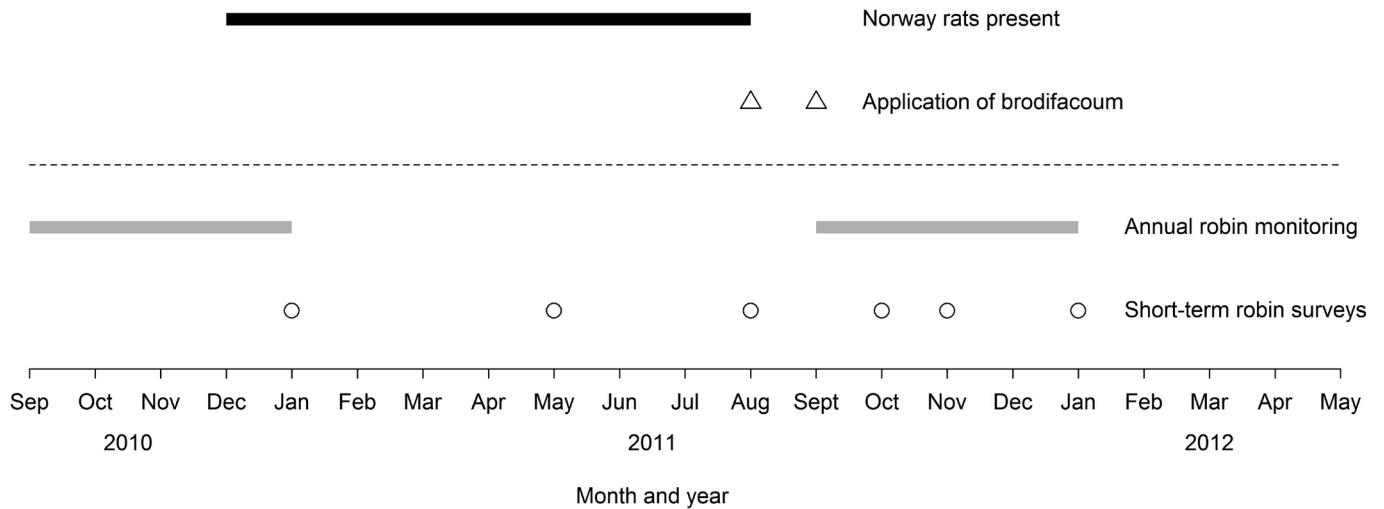

Figure 1. Timeline of robin monitoring before, during and after a Norway rat (*Rattus norvegicus*) reinvasion and eradication on Ulva Island from 2010 to 2012.
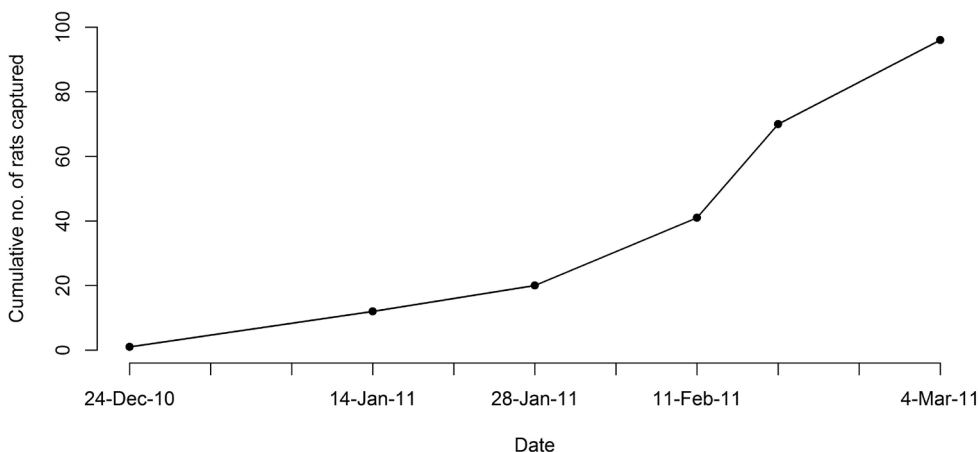

Figure 2. Cumulative number of Norway rats (*Rattus norvegicus*) captured on Ulva Island between 24 December 2010 and 4 March 2011 in the biosecurity trapping network set up along the coast.

observers record the identity of all uniquely colour-banded robins observed at and between each grid-point. Observers also record the unique colour-band combination of all robins observed while nest monitoring over the entire island during the breeding season (September–January). Data collected from both the survey at the start of the breeding season and surveys conducted during nest monitoring are combined, and each robin is scored as either present or absent each breeding season. Robin mortality typically occurs over the winter (IGJ unpubl. data), and therefore if a robin was observed at least once it was assumed to have survived for the entire breeding season. The annual survey has been conducted during each breeding season since release, including the 2010 and 2011 breeding seasons, which allowed us to compare population estimates during the breeding seasons immediately before and after the rat reinvasion and eradication (Fig. 1).

In addition to the annual survey, we conducted two short-term surveys immediately before, and two immediately after, the poison application to determine whether survival rates differed when rats were present (before) versus when rats were absent but poison was present (after). The short-term surveys were conducted using the same protocol as the initial annual survey, but the entire island was covered twice per survey.

Two short-term surveys were conducted before the poison application: (1) from 21 to 28 May 2011 (3 months before poisoning) and (2) from 9 to 21 August 2011 (less than 1 month before poisoning) (Fig. 1). Because the last three days of the August survey (19–21 August) were conducted after the first poison application on 18 August, we conducted an additional survey of robins that were observed the day prior to the poison operation. All 25 robins (15 adults, 10 juveniles) observed the day before the poison operation (17 August) were alive on the last day of the August survey (21 August). Furthermore, brodifacoum accumulates and is stored in the liver (Huckle et al. 1988) and thus mortality in other insectivorous bird species is delayed by at least 7 days after the aerial application of poison bait (Robertson & Colbourne 2001). Therefore we assumed that surveys conducted in August accurately described birds that were alive before the poison operation. Two short-term surveys were also conducted after the application of poison: (1) from 9 to 26 October (2 months after poisoning) and (2) from 19 to 30 November (3 months after poisoning) (Fig. 1).

Data analysis

To estimate apparent survival (Φ) between breeding seasons, we used Program MARK (White & Burnham 1999). Robins were initially released on Ulva Island on three separate occasions: September 2000, August 2001 and November 2001 (Jamieson 2011). To avoid including birds that died due to translocation-related causes, we did not include adult survival data from the 2000 and 2001 seasons in the analysis.

We were primarily interested in differences in survival between breeding seasons and therefore included time and cohort as factors in our analysis, and examined adult and juvenile survival separately. Candidate models included each factor and their interaction. We initially evaluated the global model for goodness-of-fit using the median c-hat ($\hat{c}$) procedure, which indicated evidence of overdispersion ($\hat{c} = 1.72$). We therefore adjusted the variance accordingly and report QAICc values for each candidate model (Burnham & Anderson 2002). The median $\hat{c}$ procedure produces slightly positive biased estimates of $\hat{c}$ and is therefore a conservative estimate. Lebreton et al. (1992) suggested that models with $\hat{c} < 3$ are appropriate for the data.

We then used the annual survival rates calculated with Program MARK to determine the expected survival rate during the 2011 season if the rat reinvasion and eradication had not occurred. The adult survival rate was relatively constant in the nine seasons prior to the 2011 season, and therefore the expected adult survival rate during the 2011 season was determined as the mean survival rate of the previous nine seasons. Juvenile survival of robins on Ulva Island is strongly correlated with the number of breeding pairs (Laws & Jamieson 2011), and has declined since the 2008 season (see below). Therefore, we used Microsoft Excel to generate a regression equation of juvenile survival rate on the total number of breeding pairs during the past three seasons, in order to determine the expected juvenile survival rate during the 2011 season.

We also conducted an additional analysis on our short-term surveys to determine which interval immediately before and after the application of brodifacoum stood out as a period of low survival. We therefore included time, age class and the period during which the poison operation occurred compared with all other survey periods, in our set of candidate models. Candidate models also included interactions between factors. Our dataset consisted of six encounter occasions corresponding to an initial capture occasion at the end of the 2010 breeding season (i.e. all marked birds known to be alive at the end of January 2011), followed by four surveys conducted before and after the poison operation, and a final occasion at the end of the 2011 breeding season (i.e. the end of January 2012; Fig. 1). We again found evidence of overdispersion ($\hat{c} = 2.56$), and therefore we adjusted the variance accordingly (Burnham & Anderson 2002).

Results

Annual population size and survival rates

The total number of banded robins on Ulva Island decreased from 432 during the 2010 season to 296 during the 2011 season, a decline of 31.5% (Fig. 3). As a result, the robin population during the 2011 season was at a similar size to that of the 2009 season, when the population was growing exponentially (Fig. 3). The total number of breeding pairs declined to a lesser extent, from 158 to 131 (17.1%), possibly because of the lower proportion of non-breeders in the 2011 season (11.5%) compared with 2010 (26.9%).

The best-fitting model from the annual monitoring dataset suggested that survival was time dependent for both adults and juveniles (Table 1). Both adult and juvenile survival rates decreased after the rat reinvasion and poison operation (between the 2010 and 2011 seasons), and were lower than our expected values if the rat reinvasion and eradication had not occurred (Fig. 4). Prior to the 2011 season, adult survival has been relatively constant over the previous nine seasons (mean = 90% ± 1% SE). However, adult survival decreased from 95.2% in the 2010 season to 49.8% in the 2011 season (Fig. 4). Based on the previous three seasons, we expected juvenile survival in 2011 to be 55.1%, but in fact it was nearly half this rate (32.7%) (Fig. 4). The best-fitting model also suggested that the resighting rate was constant (94.3% ± 1% SE).

Survival immediately before and after the poison operation

We also used Program MARK to determine when the population declined relative to the poison operation. The top four models with low QAICc weightings (ΔQAICc < 2) were a good fit to
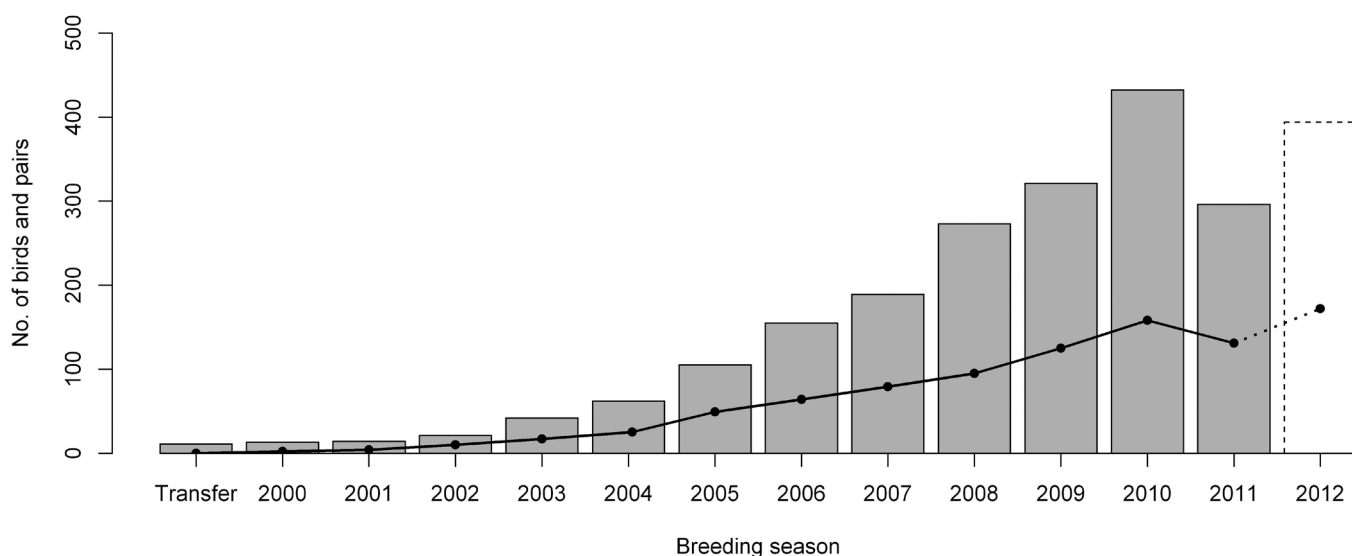
Figure 3. Annual number of adults and breeding pairs of Stewart Island robins (*Petroica australis rakiura*) recorded on Ulva Island at the end of each breeding season (31 January). The number of adults is indicated with bars, and the number of breeding pairs is indicated with small circles. We estimated the number of adults during the 2012 season based on the mean adult survival rate over the past nine seasons and the juvenile survival rate predicted from the regressed survival rate over the last three years (see Methods). The number of breeding pairs was projected based on the ratio of paired to unpaired adults during the 2009 season.
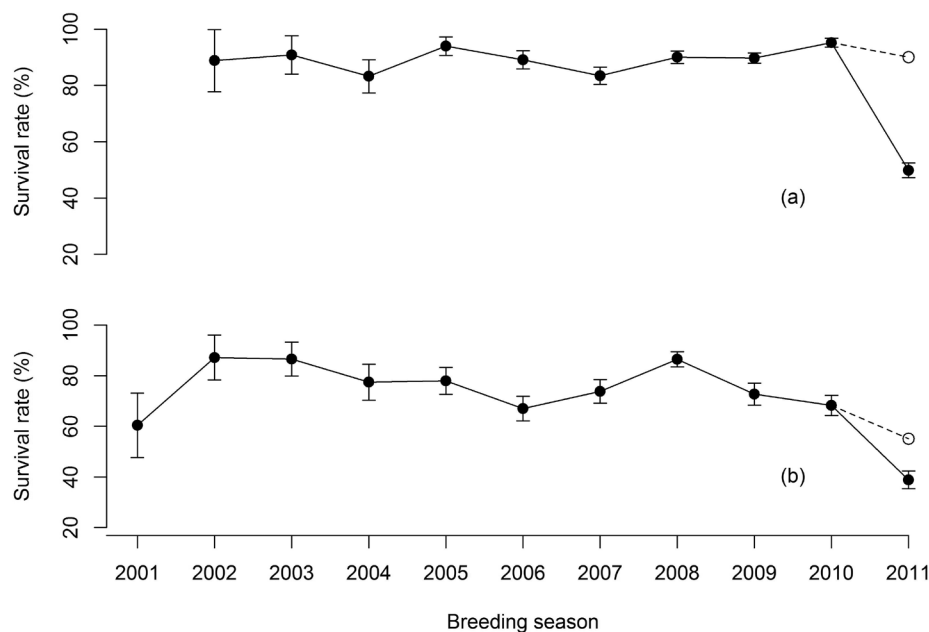

Figure 4. Annual apparent survival rates of (a) adult and (b) juvenile Stewart Island robins (*Petroica australis rakiura*) on Ulva Island, based on the best-fitting models and model averaging (see Table 1). The expected survival rates in the 2011 breeding season if the reinvasion and eradication had not occurred are indicated with an open circle and dashes.

Table 1. Model selection to determine annual survival (Φ) and recapture (p) probabilities of Stewart Island robins (*Petroica australis rakiura*) on Ulva Island from the 2001 to 2011 breeding seasons. Model factors for annual survival are listed for adults before the forward slash and juveniles after. The top five of 16 models are listed, and ranked by ascending ΔQAICc.

Rank	Model description	QAICc	ΔQAICc	QAIC weight	K	QDeviance
1	$\Phi_{time/time}p_{constant}$	3013.90	0	0.66	22	245.58
2	$\Phi_{constant/time}p_{time}$	3016.33	2.44	0.20	23	245.98
3	$\Phi_{time/time}p_{time}$	3107.65	3.75	0.10	31	230.95
4	$\Phi_{constant/constant}p_{time}$	3109.93	6.03	0.03	13	269.87
5	$\Phi_{time/constant}p_{time}$	3112.00	8.11	0.01	22	253.69

the data, therefore we used model averaging to estimate apparent survival (Burnham & Anderson 2002). These models suggested that apparent survival varied over time, varied between the period during which the poison operation occurred and all other survey periods (i.e. indicated by the factor 'poison'), and between age classes as an interaction with 'poison' and time (Table 2). Model averaging indicated a high initial monthly survival rate for both adults and juveniles before the poison operation, followed by a period of low monthly survival immediately after the poison operation, then another period of relatively high monthly survival between October and January 2012 (Fig. 5). These results indicate that most of the mortality recorded in Figs 3 and 4 occurred immediately after the poison operation. In support of this conclusion, we opportunistically observed five robins pecking at the poison bait during the first three days after the application of brodifacoum (19–21 August); none of these robins were observed in subsequent surveys.

To determine the effect of the presence of rats on juvenile and adult survival, we first calculated the survival rate between January and August 2011 (prior to the poison operation) based on the minimum number of birds known to be alive in August plus any remaining birds subsequently observed throughout the remainder of the breeding season. Adult and juvenile survival rates were 84.3% and 53.8%, respectively, compared with the expected annual adult survival rate of 90.0% (Fig. 4) and juvenile survival rate of 55.1% (see above). These results suggest that the presence of rats may have had a negative effect on both adult and juvenile overwinter survival, but

was relatively minor compared with the large decrease in the minimum number alive immediately after the poison operation: 44.5% for adults (from 364 to 202 individuals) and 38.9% for juveniles (from 113 to 69 individuals) (see also Fig. 4).

The robin population is already showing signs of recovering, with 220 offspring that successfully fledged during the 2011 breeding season. Based on previously estimated overwinter survival rates, we predict the population will recover in the 2012 season to 89% of what it was in the 2010 season, just before rats had established (Fig. 3).

Discussion

The results from our annual monitoring on Ulva Island indicate that the reintroduced Stewart Island robin population declined by nearly one-third after a reinvasion and eradication of Norway rats. Results from our short-term surveys suggest the presence of Norway rats that reinvaded Ulva Island had a relatively small negative effect on robins, as their survival rate in the presence of rats was only slightly lower than that expected in the absence of rats over the non-breeding season. A study on Ulva Island before the rat reinvasion indicated that adult robins are less likely to recognise a model Norway rat than those on the mainland of Stewart Island (Jamieson & Ludwig 2012). This suggests that we might have expected robin survival leading up to the poison operation to have been lower than our observed rates. However, several factors may have reduced the likelihood of predation on robins by Norway

Table 2. Model selection to determine survival (Φ) and recapture (p) probabilities of Stewart Island robins (*Petroica australis rakiura*) on Ulva Island between 31 January 2011 and 31 January 2012. The top five of 18 models are listed, and ranked by ascending ΔQAICc.

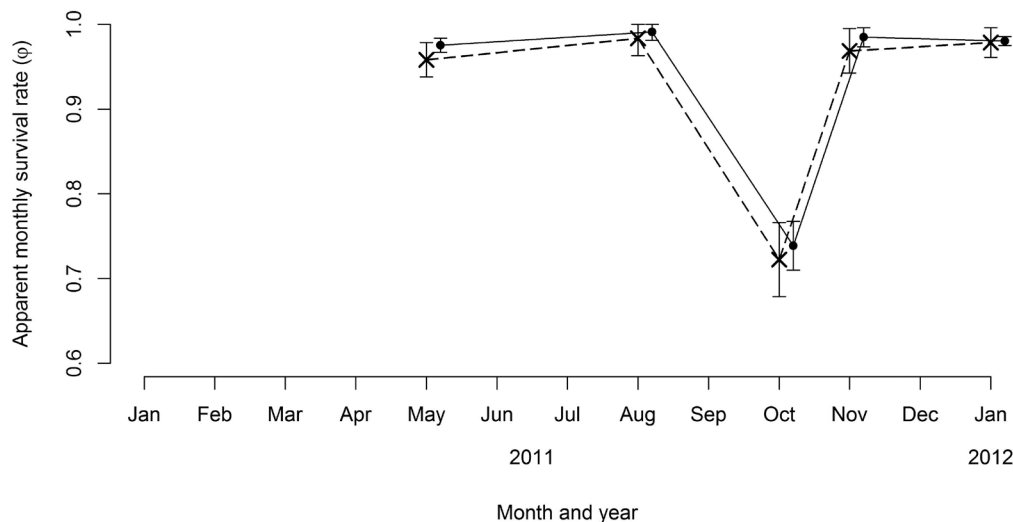| Rank	Model description	QAICc	ΔQAICc	QAIC weight	K	QDeviance
1	$\Phi_{time}p_{age*time}$	1096.64	0	0.32	14	96.04
2	$\Phi_{poison*age}p_{age*time}$	1096.71	0.07	0.31	14	96.11
3	$\Phi_{age*time}p_{age*time}$	1097.35	0.71	0.22	18	88.61
4	$\Phi_{poison}p_{age*time}$	1098.05	1.41	0.16	12	101.51
5	$\Phi_{age*time}p_{time}$	1125.14	28.50	0	14	124.54

Figure 5. Monthly apparent survival estimates based on model averaging for juvenile and adult Stewart Island robins (*Petroica australis rakiura*) before and after a brodifacoum poison operation on Ulva Island in 2011. Data points are shifted to prevent overlap of error bars. Survival rate is indicated with a straight line for adults and a dashed line for juveniles. The poison operation was conducted following the survey in August 2011 (Fig. 1).

rats: (1) the rat population had not reached carrying capacity, (2) rats were not present during the robins' nesting period, when predation by rats can be significant (Powlesland et al. 1999), and (3) Norway rats are predominantly terrestrial and rarely climb higher than 2 m (Foster et al. 2011). Therefore, robins roosting in trees at night would be less vulnerable to predation by Norway rats than if arboreal ship rats (*Rattus rattus*) were present (Hooker & Innes 1995).

In contrast, the robins experienced a sharp decline in their survival rates immediately after the application of poison, and robins were observed eating the poison bait. Taken together, the results of our study suggest primary or secondary poisoning, or both, from the brodifacoum bait was the major cause of decline in the robin population. In addition to our study, there have been several reports of robins directly consuming poison cereal bait (Taylor & Thomas 1993; Spurr & Powlesland 1997). Previous studies have examined the potential to use colour, repellents and combinations of visual and olfactory cues with repellents to deter robins and other birds from feeding on cereal bait (Hartley et al. 1999; Day et al. 2003; Clapperton et al. 2012). Our observations suggest that further research is still required to deter birds such as robins from consuming poison bait. In addition, a small proportion of robin nestlings on Ulva Island suffered from secondary poisoning via consuming toxic invertebrates (unpubl. data). Secondary poisoning of wild birds through ingesting toxic invertebrates has only been observed in one other case, involving adult New Zealand dotterels (*Charadrius obscurus aquilonius*) (Dowding et al. 2006).

Based on the minimum number of birds alive, both adults (55.5% post-poison survival rate) and juveniles (61.1% post-poison survival rate) appear to be susceptible to non-target poisoning. Three previous studies quantified the change in survival rate of banded robins following an aerial poison operation with brodifacoum, but did not examine juvenile and adult survival separately (Walker & Elliott 1997; Empson & Miskelly 1999; Armstrong & Ewen 2000). The post-poison survival rate in these studies was found to range between 58.7% and 90.0% (Table 3), indicating that the rate of loss of robins on Ulva was one of the highest recorded.

It is unclear why mortality due to non-target poisoning on Ulva Island was relatively high, but it may have been exacerbated by the high density of robins at the time of the poison operation, as birds in high-density populations may be more likely to eat novel food items (Lefebvre & Bolhuis 2003). At the time of the poison operation, juvenile survival was declining, which suggests the robin population was reaching carrying capacity (Armstrong et al. 2005). There is also a negative association between post-poison survival and the number of applications of poison and/or density of poison sowed during an attempt to eradicate rats (Table 3).

Although robin survival on Ulva Island was negatively affected by the poison operation and to a lesser extent by the presence of Norway rats, this does not mean that the robin population would have been viable in the long term if the eradication had not gone ahead. Adult robins can persist in the presence of rats, but nesting success is significantly reduced, which reduces recruitment and ultimately population viability (Etheridge & Powlesland 2001). In addition, the sex ratio tends to be biased against female robins in the presence of rats (because females incubate the eggs and brood the nestlings) (Powlesland et al. 1999), which also reduces population viability. Although not as arboreal as ship rats, Norway rats do prey on birds that occasionally nest close to the ground such as robins (Morris & Gilroy 2008). Therefore, the robin population is likely to have declined if Norway rats had not been eradicated.

Ultimately, our results are a reminder of the importance of preventing rats from reinvading island sanctuaries and establishing to the point where a poison eradication operation becomes necessary. Our results also emphasise the need for developing permanent surveillance systems to detect and kill rats upon arrival (Russell et al. 2008), especially on islands that are at a high risk of a rat reinvasion.

Acknowledgments

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Table 3. Survival rate of robins (*Petroica australis*) following an aerial application of brodifacoum. Adult and juvenile survival rates are combined for robins (*Petroica a. rakiura*) on Ulva Island.

Island	Year	Survival rate (%)	No. alive pre-poison	No. of poison applications	Brodifacoum concentration (ppm)	Total density of sowing (kg ha^{-1})	Reference
Nukuwaiata	1993	70.0	20	1	20	11	Walker & Elliott (1997)
Tiritiri Matangi	1993	87.5–90.0	40	1	20	10	Armstrong & Ewen (2000)
Kapiti	1996	58.7	92	2	20	14.1	Empson & Miskelly (1999)
Ulva	2011	56.8	473	2	20	14	This study

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