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RESEARCH

The effects of beech masts and 1080 pest control on South Island robins (*Petroica australis*)

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Abstract: We assessed the effect of aerial 1080 control of possums (*Trichosurus vulpecula*), ship rats (*Rattus rattus*) and stoats (*Mustela erminea*) on the survival and nest success of South Island robins (*Petroica australis*) at Tennyson Inlet, Marlborough Sounds, from 2012–2017. Cereal baits containing 1080 were applied in 2013 when rat and stoat numbers were low, and again in 2014 after a beech mast when rat numbers were high. Survival rates of 134 banded adult South Island (SI) robins and 209 SI robin nests were monitored. Ship rats were the main predator of eggs and chicks, with stoats, possums and ruru (*Ninox novaeseelandiae*) also preying on nests. Rats were the only predator identified killing adult females on the nest. Nest success was negatively affected by rat abundance and increased when 1080 reduced rat abundance. Our study did not detect a measurable negative effect of aerial 1080 use on nest success or adult survival, although over the course of the study two nests failed and two adults disappeared while 1080 was present in the forest. The positive effect of aerial 1080 pest control was short-lived, with rat numbers increasing rapidly in subsequent years. To achieve long-term population benefits in small beech forest blocks, future pest control operations will need to achieve higher rat kills in beech mast years, and/or be undertaken at roughly three yearly intervals.

Keywords: 1080, adult survival, nest success, sodium fluoroacetate, South Island robin, *Petroica australis*

Introduction

Many New Zealand native birds are negatively affected by introduced mammalian predators (Holdaway 1989; Clout & Craig 1995; Brown et al. 1998; Innes et al. 2010; Robertson et al. 2012), in particular possums (*Trichosurus vulpecula*), ship rats (*Rattus rattus*) and stoats (*Mustela erminea*). Control of these mammals is the main tool used to conserve native forest-dwelling birds in New Zealand (Parliamentary Commissioner for the Environment 2011). Five species of southern beech (Nothofagacae) occur in about half of New Zealand's remaining native forests (Schauber et al. 2002); all are mast seeders, producing large crops of seed every 2–6 years (Wardle 1984). Rodent and stoat numbers increase dramatically following a beech mast (King 1983; King & Moller 1997). The rat and stoat plagues that occur after beech masts are the cause of dramatic declines and local extinctions amongst beech forest-dwelling birds (Elliott & Kemp 2016).

In recent years, pest control in beech forests has mostly occurred during the rodent and stoat plagues following a beech mast (Elliott & Kemp 2016). The most widely used tool for large-scale pest control in New Zealand is sodium fluoroacetate (1080) (Parliamentary Commissioner for the Environment 2011; Morgan et al. 2015), which is mostly applied by helicopter in the form of cereal baits; 1080-laced cereal baits kill rodents and possums. Cats and mustelids are killed through secondary poisoning when they eat dead and dying rodents (Meenken & Booth 1997; Eason et al. 2013); 1080 is therefore an effective multi-target poison (Murphy et al. 1999). In the past, 1080 was applied in carrot and cereal baits at sowing rates of up to 20 kg ha^{-1}. Small bait fragments (chaff) in carrot bait were eaten by some non-target species including North Island robins (*Petroica longipes*) which were killed (Powlesland et al. 1999; Westbrooke & Powlesland 2005; Veltman & Westbrooke 2011). Today however, lower sowing rates of 1–2 kg ha^{-1} are common (Warburton & Cullen 1995), and carrot bait is rarely used. These changes have reduced by-kill and the use of non-toxic pre-feed has increased kill rates of target species (Westbrooke et al. 2003; Nugent et al. 2011), but 1080 still kills some native wildlife (Morris et al 2016) and its use is often controversial (Green & Rohan 2012; Russell 2014). The impact of 1080 predator control on a range of forest birds has been assessed (Powlesland et al 2003; Greene et al 2013;Tinnemans et al 2018) including the relationship between South Island robin nest success and survival following 1080 operations (Schadewinkel et al. 2014; van Heezik et al. 2020). However, these previous studies monitoring SI robin nest success and survival were undertaken in exotic forests

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where 1080 was used at regular intervals to control possums and in nearby kānuka (*Kunzia ericoides*)-dominated forests.

In this study, we assess the impact of two 1080 pest control operations specifically undertaken to control predators in a beech forest. We compare the effect of a 1080 operation undertaken during a beech mast-induced stoat and rat plague with a 1080 operation undertaken when stoats and rats were relatively uncommon. Our study was undertaken in a patchily distributed SI robin population, predominantly confined to high altitudes where predator densities, particularly rat densities, were low. We aimed to determine whether SI robin nest success and adult survival improved when aerial 1080 operations were undertaken in association with a beech mast. Assessment of overall benefit (or otherwise) to SI robins and other forest birds from 1080 use was assessed in a concurrent study using bird counts. These have yet to be analysed.

Methods

Study area

The study was undertaken at Tennyson Inlet in the Marlborough Sounds, at the northern end of the South Island of New Zealand. The study area comprised two areas about 4.5 km apart within a continuous mature mixed beech-podocarp forest (Fig. 1). The treatment area (57 ha) was within a 4300-ha aerial 1080 treatment block on a peninsula, near Mt. Stanley, while the non-treatment area (121 ha) was centred around Opouri Saddle and included Lookout Peak. The areas were chosen because they had similar topography and vegetation, were at similar altitudes and had SI robins accessible on foot.

1080 pest control

Two aerial 1080 pest control operations covering almost the same extent were undertaken during our study (Fig. 1). The first took place on 2 November 2013 in the absence of a beech mast, with a non-toxic pre-feed 13 days earlier. The second was carried out on 23 November 2014 during a beech mast, 44 days after the pre-feed. In 2014, weather prevented aerial sowing of bait in 12.5 ha near the summit of Mt Stanley. Bait was sown by hand in this area on 8 December 2014. Both pest control operations aimed to suppress rats to below a 5% tracking rate.

The non-toxic pre-feed consisted of 0.3% cinnamon-lured cereal pellets (16 mm, 6 gm RS5) at a 1kg ha^{-1} sowing rate. Toxic baits were also applied at a 1kg ha^{-1} sowing rate and were the same as the non-toxic baits except they were dyed green and laced with 0.15% 1080. Based on National Institute of Water of Atmospheric Research Ltd. observations, rainfall had exceeded 100 ml 35 days after both aerial 1080 applications by which time baits were deemed no longer toxic (Bowen et al 1995).

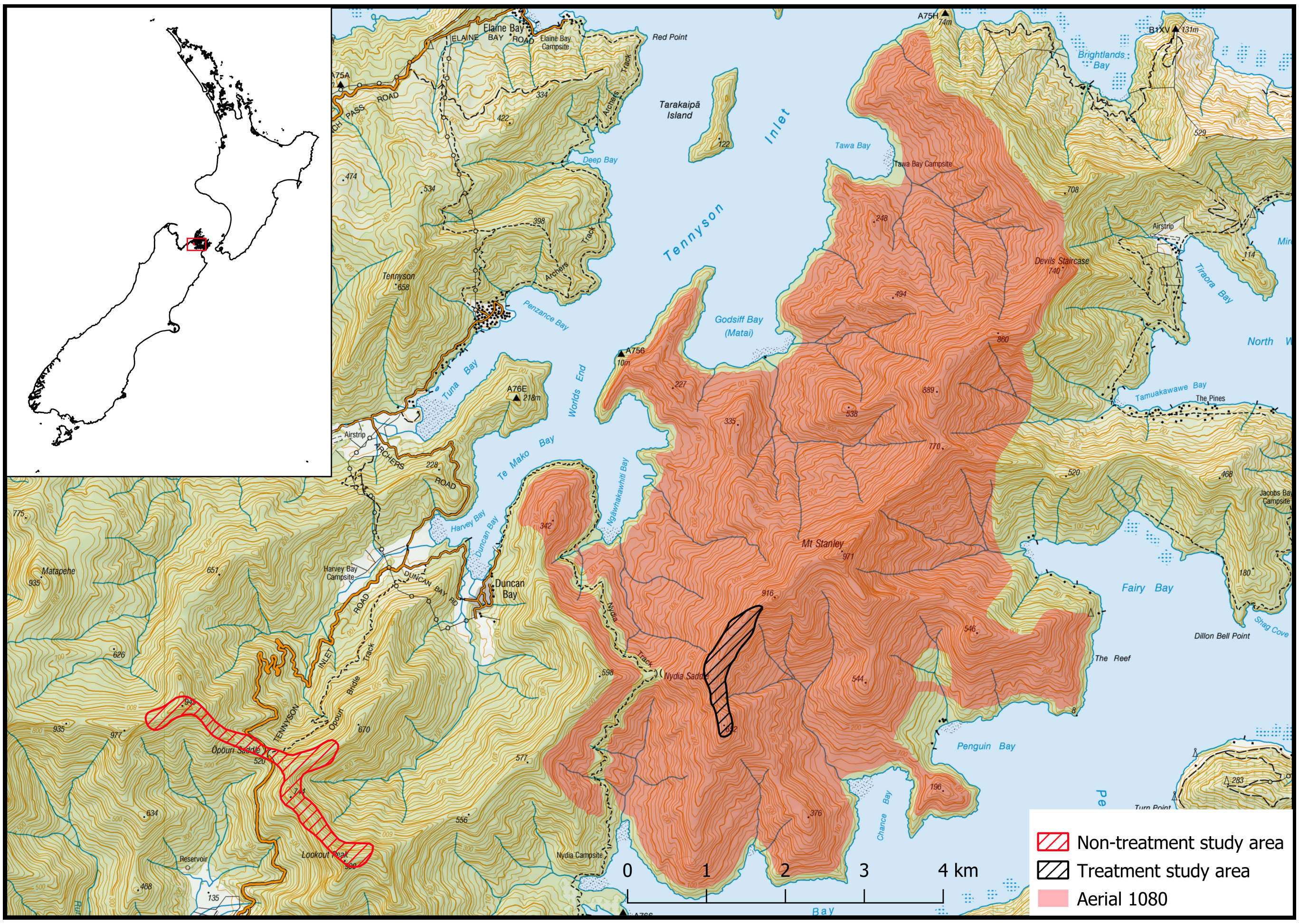

Figure 1. Study areas and 1080 treatment area.

Rat and stoat abundances

Rat abundance in the treatment and non-treatment areas were indexed using tracking tunnels, according to standard protocols (Gillies & Williams 2013) with surveys undertaken quarterly in February, May, August, and November. Stoats were surveyed using tracking tunnels biannually in February and August, initially using the standard 3-night surveys (Gillies & Williams 2013) baited with fresh rabbit meat, but after February 2015 stoat surveys were conducted using salted rabbit meat left out for 14 nights.

Kill rates of rats during 1080 operations were estimated using the methods of Elliott et al. (2018).

Possum abundance

We indexed possum abundance three times in the non-treatment block and five times in the treatment block using a 7-day wax tag protocol (National Possum Control Agencies 2008) and between 100 and 400 wax tags per block in each survey. We estimated possum abundance at each wax tag survey by fitting a generalised linear model using the method of Elliott et al. (2018) which assumed a common possum kill rate for all 1080 operations and a common population growth rate between 1080 operations. We assumed the population at the non-treatment site was stable and at carrying capacity.

Nest success

Nests of banded SI robins were monitored during five breeding seasons (2012/13–2016/17). Nests were found by following banded birds. Only nests found with eggs or chicks were included in the analysis; nests found after they failed or fledged, were omitted. Where possible, nests were monitored using trail cameras which were checked at weekly intervals.

Nest failures were attributed to specific predators based on photographs, but no attempt was made to distinguish between ship and Norway rats (*Rattus norvegicus*). Nest failures were classified as "unidentified predator" if partial or no images were captured of the predator and chicks or eggs disappeared from the nest. Nests were classified as "abandoned" when they failed in the absence of a predator and in the absence of a change to the nest content. Nests were classified as a "human-caused failures" if the camera remained untriggered after a nest check and the nest contents remained unchanged.

Modelling factors affecting nest success

The relationship between nest success and a suite of explanatory variables was examined using methods described by Rotella et al. (2004) and Bolker (2014). In particular, daily nest survival rates were modelled using generalised linear models (glms) with binomial errors and a complementary log-log link function. This approach is almost identical to the nest survival model implemented in program Mark (Rotella et al. 2004), but allowed pair to be included as a random effect. Potential important explanatory variables included in the models were:

(1) rat abundance from tracking tunnel data,
(2) stoat abundance from tracking tunnel data,
(3) possum abundance from wax tags,
(4) timecode (one category for each breeding season except the 2013 and 2014 breeding seasons which divided in two before and after the 1080 operations),
(5) area (treatment or non-treatment),
(6) an interaction between timecode and area was included to examine whether the 1080 operations had any effect, and
(7) active1080 – a categorical variable indicating whether observations were within 35 days of a 1080 operation.

Three further nuisance variables were included in the models, not because they were of particular interest, but rather because they might improve model fit: (1) season (days from the beginning of the breeding season) and season^2, (2) age (nest age in days) and age^2, and (3) he random effect 'PairID' was included in all models, to account for multiple nest attempts by the same pair.

Two suites of glms with plausible combinations of explanatory variables were compared: (1) "pest abundance models" where indices of stoat, rat or possum abundance were the explanatory variables, and (2) pest control models where pest control treatment, area and time (before/after) were the explanatory variables. We fitted these models using the package lme4 (Bates et al. 2015) in R version 3.4.2 and compared them using QAICc (Burnham & Anderson 2002).

Adult survival mark-recapture analysis

SI robins were captured and individually metal and colour-banded. During the nesting season breeding adults were searched for every 7–10 days and non-breeding birds (such as single males) once a month. Systematic searches for all banded SI robin were only conducted at the start of each breeding season and pre/post 1080 treatment within the study area. Additional surveys of the study area were also conducted over the 2016 non-nesting season and at the end of the study in August 2017. Robins that disappeared were assumed to have died, a reasonable assumption given that we were monitoring territorial adults.

RMark (Laake 2013) was used to model the relationships between adult SI robin survival and sex, season, 1080 operations, rodent and stoat abundance. Monthly capture intervals were created for analysis. To explore the possibility that birds were killed by 1080, 35 days after the 1080 drops in which birds might be killed by ingesting 1080 were coded as "1080". A suite of models with plausible combinations of explanatory variables were compared using QAICc (Burnham & Anderson 2002).

Overdispersion in the data was examined using program Release within RMark which produces an estimate of c-hat. Competing models were compared using QAICc (Burnham & Anderson 2002) incorporating the value of c-hat provided by Release.

Results

Predator tracking rates and beech mast

Rat tracking rates were lower at higher altitudes (> 500 m) (average non-treatment tracking rate = 0.20) where we studied SI robins than they were at lower altitudes (< 500 m) (average non-treatment tracking rate = 0.47) where SI robins were absent. For this reason, our analysis of relationships between SI robins, rats and stoats uses tracking data only from the area in which we studied SI robins (> 500 m).

All four beech species flowered in Tennyson Inlet in spring 2013, resulting in heavy seeding in autumn and winter of 2014. After the seedfall rat numbers, then stoat numbers rose (Fig. 2). Rats were undetectable in the treatment block after the first 1080 operation, but their numbers rose quickly after the subsequent seedfall in both the treatment and non-treatment blocks and were again reduced in the treatment block by the

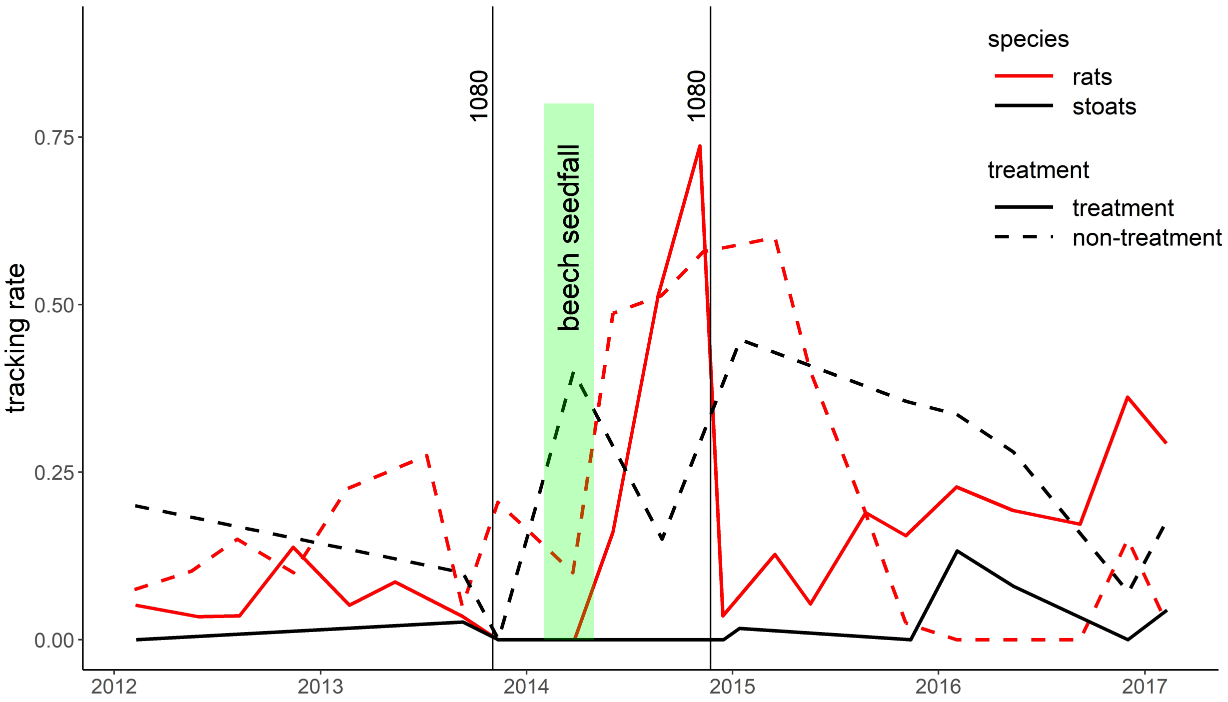

Figure 2. Stoat and rat tracking rates in the treatment and non-treatment blocks at Tennyson Inlet and the timing of 1080 operations and beech seedfall.

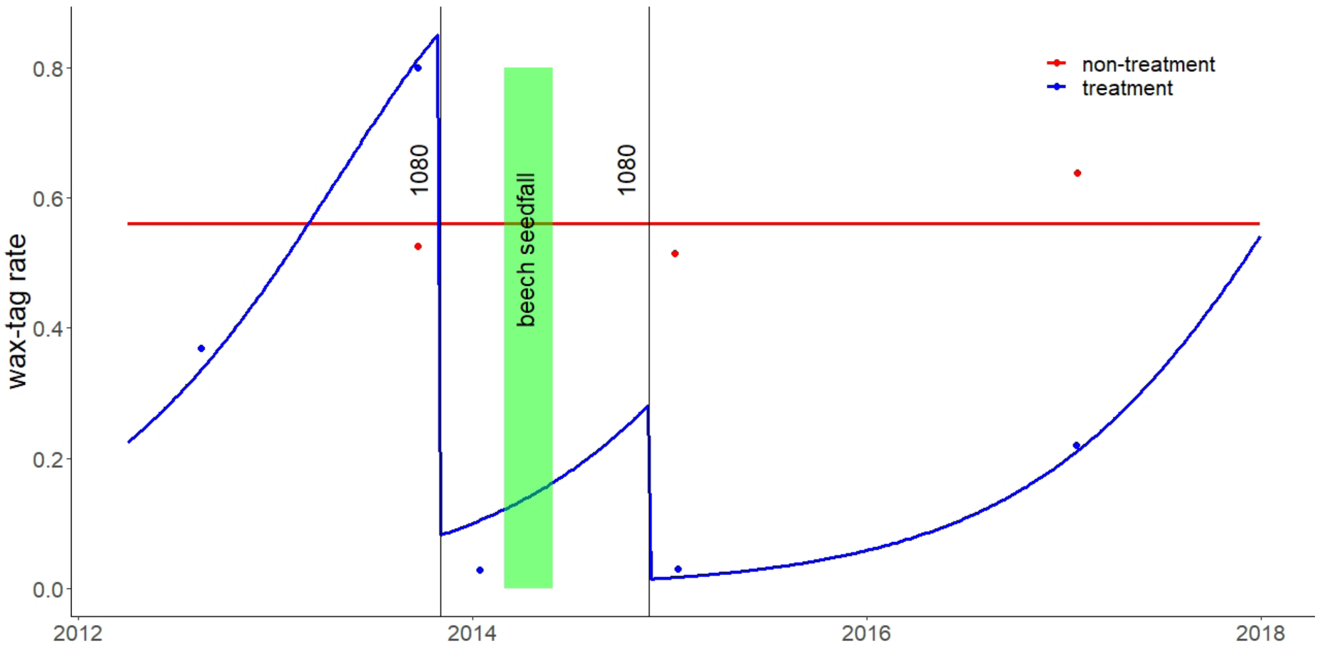

Figure 3. Waxtag possum bite mark indices for the two study blocks between 2012 and 2018 and the timing of 1080 operations and beech seedfall. Blue and red points are actual wax-tag rates, while red and blue lines are fitted rates.

second 1080 operation (a kill rate of 98%). The two 1080 operations appeared to almost completely suppress stoats in the treatment block for the subsequent two years of the study.

Although rat numbers declined immediately after the second 1080 operation in the treatment area, over the next two years they gradually rose to numbers higher than they had been before the 1080 operation. In contrast, rat numbers in the non-treatment area initially rose following the beech seedfall and then declined about a year later. This was presumably a natural population crash following beech-mast-induced plagues.

Based on possum wax-tag indices, possums density appeared to grow at a rate of 359% per annum in the treatment area and the average kill rate in the two 1080 operations was 96% (Fig. 3). The high growth rate indicates a combination of immigration and reproduction rather than solely reproduction. Possum numbers were approximately stable in the non-treatment area and presumably at carrying capacity. Some ground-based possum control had occurred in the treatment area in the years before our study started.

Nest success

We found a total of 218 SI robin nests and were able to monitor and determine the outcome at 209 of them (Table 1). Sixty-nine per cent of all nests failed, and possums, rats and stoats were responsible for at least half of these failures. Since possums, rats and stoats are likely to have been responsible for at least some of the failed nests for which we could not identify a cause or a predator, these predators are likely to have caused the failure of more than half of all nests monitored. There was considerable annual variation in the proportion of nests preyed upon by stoats and rats and this is likely to reflect their abundance which is turn reflects time since beech masts and predator control efforts. The effects of these factors are explored in the modelling nest success section.

Female deaths on the nest

Eight brooding or incubating female SI robins from 138 well-monitored nests were attacked by predators and six of them died. At seven nests, cameras identified rats as the predator and all eight predations happened at night. Four predation events occurred in the non-treatment area, and four in the treatment area. Three of these events occurred when rat numbers were high before the 2014 1080 operation and one in 2016 when rat numbers had recovered.

Nest failures during the active 1080 period

Two nests were abandoned within 35 days of a 1080 application. One failed within 24 h of the 1080 operation when the eggs were close to, or just hatched, but both adults were subsequently found alive. The other failed during incubation, about four days after the 1080 operation, when the female disappeared.

Modelling nest success

The best model of daily nest survival included terms for rats, possums, and a quadratic term for season (Table 2), indicating that nest survival decreased with possum and rat abundance and with time through the season (Fig. 4). The relationship between rat abundance and nest success is stronger than the

Table 1. Outcome of 209 SI robin nests in non-treatment and treatment areas at Tennyson Inlet.

	Non-treatment						Treatment						
	2012	**2013**	**2014**	**2015**	**2016**	**Sub-total**	**2012**	**2013**	**2014**	**2015**	**2016**	**Sub-total**	**Total**
Failures													
Morepork	0	0	0	1	0	1	0	0	1	0	0	1	**2**
Possum	0	3	3	3	0	9	3	0	0	0	0	3	**12**
Rat	3	5	7	0	4	19	0	1	10	4	11	26	**45**
Stoat	1	1	0	6	5	13	1	0	1	0	1	4	**16**
Unknown predator	2	2	4	2	2	12	3	0	4	3	3	13	**24**
Unknown cause	1	0	6	3	4	14	1	1	7	5	3	17	**31**
Abandoned	1	3	2	0	1	7	0	5	0	1	0	6	**13**
Successes	4	4	3	5	8	24	3	10	12	13	3	41	**73**
Total	12	18	25	20	24	99	11	17	35	26	21	110	**209**

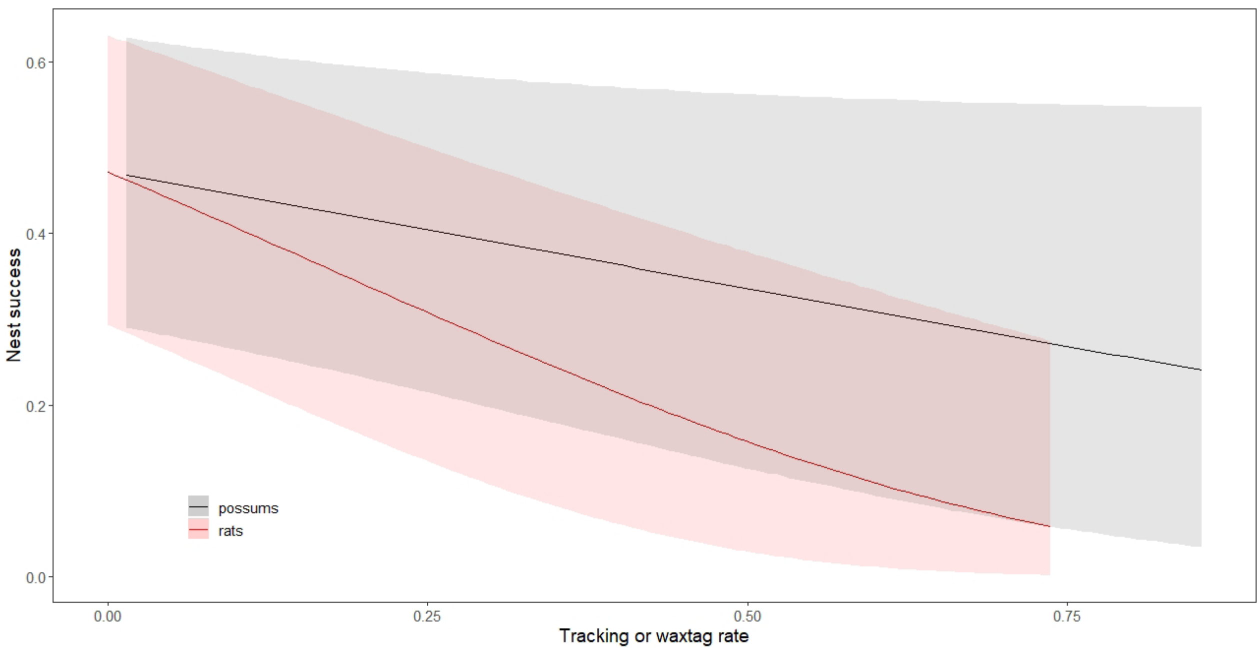

Figure 4. Modelled relationships between nest success and possum and rat abundance. Shaded areas indicate 95% confidence intervals.

Table 2. Sixteen plausible models of the relationship between SI robin nest success and some explanatory variables. All models also include a random effect for pair. Age^2 and season^2 indicate quadratic terms for age and season.

Model		npar	AICc	ΔAICc	weight
Pest abundance models					
1	possum+rat+season^2	6	1022.903	0.000	0.251
2	age^2+possum+rat+season^2	8	1023.288	0.386	0.207
3	possum+rat	4	1023.767	0.864	0.163
4	1080+possum+rat+season^2	7	1023.962	1.059	0.148
5	rat+season^2	5	1024.107	1.204	0.138
6	possum+rat+season^2+stoat	7	1024.906	2.003	0.092
7	.	2	1037.642	14.740	0.000
8	possum+season^2	5	1037.945	15.042	0.000
Pest control models					
9	area*timecode+age^2+season^2	19	1028.859	0.000	0.405
10	area*timecode+season^2	17	1029.837	0.977	0.248
11	area*timecode+age^2	17	1030.594	1.734	0.170
12	1080+area*timecode+age^2+season^2	20	1030.861	2.002	0.149
13	age^2+season^2+timecode	12	1036.270	7.410	0.010
14	area+timecode+age^2+season^2	13	1037.183	8.323	0.006
7	.	2	1037.642	8.783	0.005
15	age^2+season^2	6	1038.165	9.305	0.004
16	age^2+season^2+area	7	1038.624	9.764	0.003

relationship between possum abundance and nest success, and the confidence intervals around the possum relationship are large (Fig. 4). Comparison of models with and without an active 1080 period term (models 1 and 4 in Table 2) and a stoat term (models 1 and 6 in Table 2) provide no support for an immediate post operation 1080 effect, nor an effect of stoat abundance. Similarly, there was no support for including a term for age. Amongst the suite of pest control models there is strong support for including an interaction term between area and timecode (models 9 and 14 in Table 2), indicating that pest control had a large effect on nest success. There was less support for including quadratic terms for age and season. Models with rat and possum abundance were better than models explicitly modelling the effect of 1080 treatment on our treatment and control areas (models 1 and 9 in Table 2).

Close examination of the best pest control models, indicated that in both 2013 and 2014, nest success in the treatment area increased after 1080. This is presumably because of the dramatic decline in rat abundance, while in the non-treatment area, nest success decreased as rat numbers rose (Fig. 5). In 2015 and 2016 nest success decreased in the treatment area with increasing rat abundance, while in the non-treatment area nest success increased as rat numbers decreased.

This analysis suggests that rat, possibly possum, but not stoat abundance, had an impact on robin nest success, and that 1080 treatments had a substantial impact on nest success by reducing rat abundance.

Adult survival

During the study 134 banded robins were monitored, 67 in each of the non-treatment and treatment areas. Males made up the majority of banded adults, with 80 males and 54 females (1.5:1 ratio). Both 1080 operations had a maximum active-1080-period of 35 days until 100 ml of rain had fallen. After the 2013 1080 operation two SI robins disappeared, a male and a female (already described in the nest failures during the active 1080 period section). No robins disappeared after the 2014 1080 operation.

The best model of adult survival had a weak relationship between rats and survival (Table 3 and Fig. 6). Models including sex, season, active 1080 period, possums and stoats as well as a term for rats were within two QAICc units of the best model but had one additional parameter and higher QAICc scores and are thus not well supported by the data (Burnham & Anderson 2002). The null model was also within two QAIC units of the most parsimonious model indicating that even the best model was not well supported. Including interaction terms between rats and sex did not improve model fit and we conclude that any relationship between rat abundance and survival was the same for male and female robins.

Discussion

Pest control

In the absence of a beech mast in 2013, rats were in low abundance and the 1080 operation reduced them to undetectable levels. There was a beech mast before the 2014 1080 operation, and rat tracking rates rose steeply to reach 94% before the operation which reduced rat tracking rates to 12% three weeks after the operation. This reduction in rat abundance represents about a 98% kill rate, but the residual rat abundance was still higher than desired. Tennyson Inlet was one of seven 1080 operations that failed to reduce rats to below 5% tracking rate during the 2014 beech mast (Elliott & Kemp 2016), but it also had one of the highest rat tracking rates before the 1080 operation.

Following the 2014 1080 operation, rats increased steadily over the next two years, reaching abundances higher than before the two 1080 operations. Rats are known to recover quickly after pest control in small treatment blocks (Innes & Skipworth 1983) and although the Mount Stanley treatment

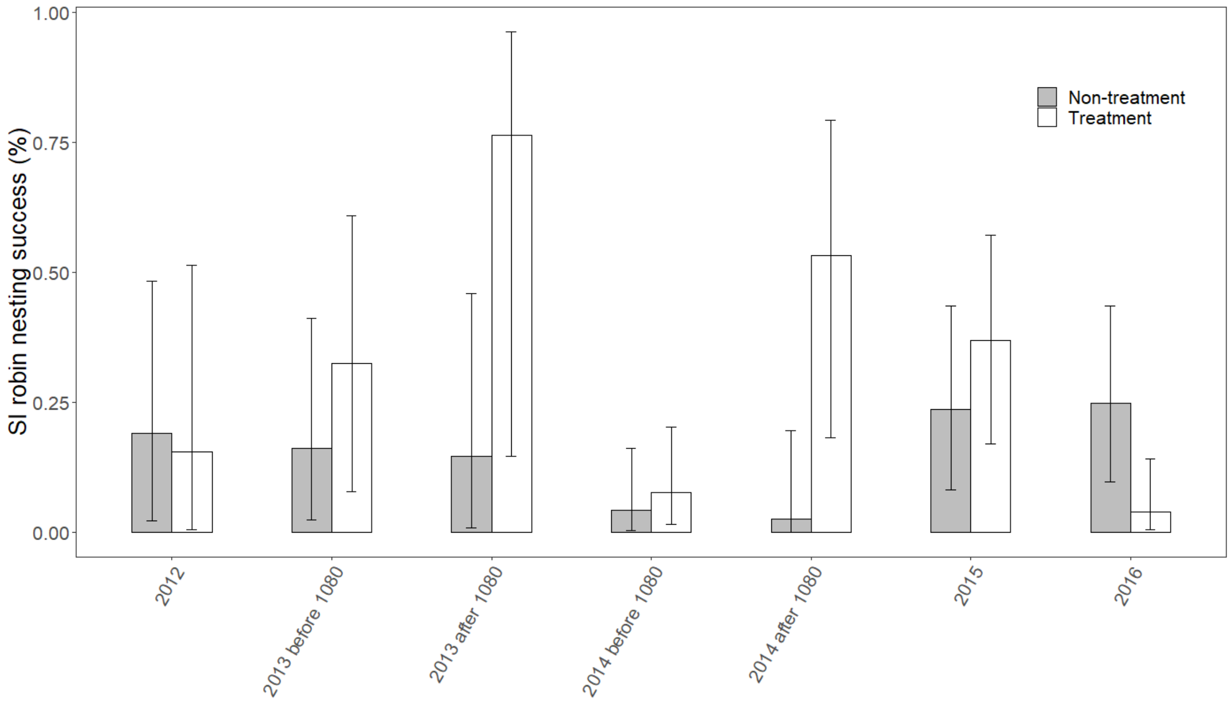

Figure 5. South Island robin nest success in treatment and non-treatment areas in relation to 1080 operations. Error bars are 95% confidence intervals.

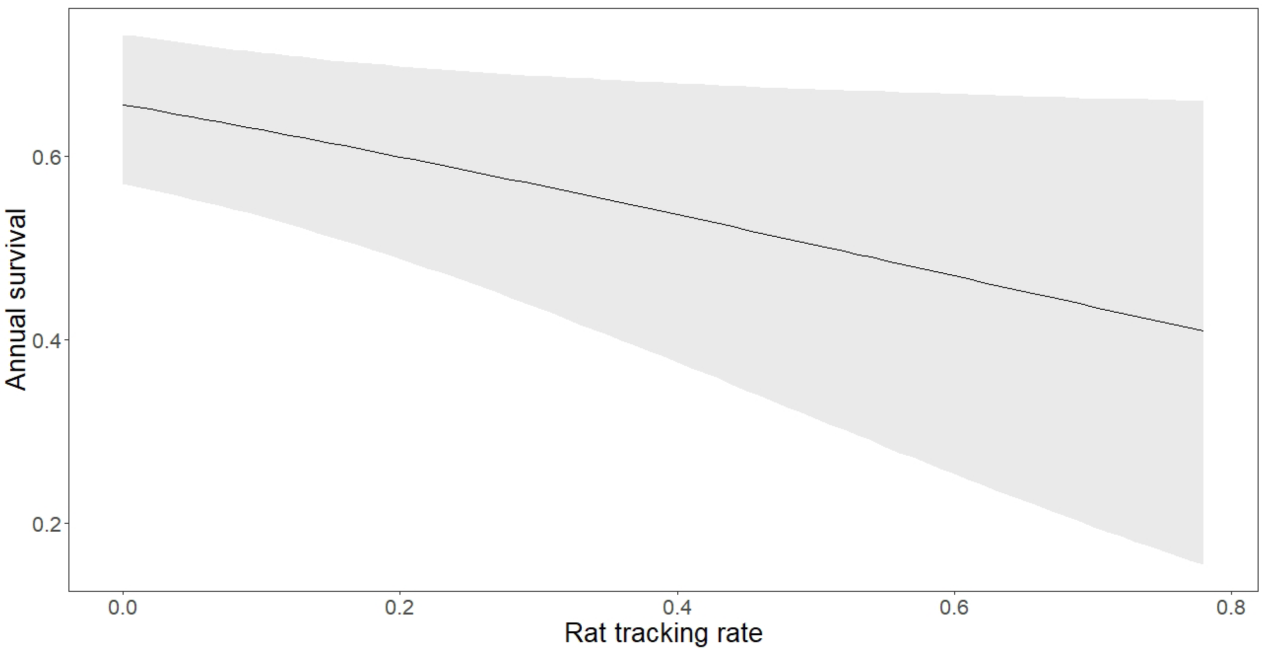

Figure 6. Modelled relationship between adult robin survival and rat tracking rate. Shaded areas are 95% confidence intervals.

block is on a peninsula, much of the peninsula was untreated such that no part of the treatment area was more than 2 km from untreated land. Furthermore, surviving rats are likely to have had access to a good food supply after the 1080 operation and are likely to have continued breeding. McQueen and Lawrence (2008) found that rat diets contained beech seeds well after the time of germination and speculated that rats cached seeds securing a food supply into the summer months. While the proximity of uncontrolled rat populations and the availability of food within our treatment area can explain why rats were able to rapidly increase in abundance following the 1080 operation, they do not explain why the rat population rose to higher levels than before the beech mast and 1080 operations. This phenomenon has been observed before and has been explained by a reduction in competition from possums for high energy foods such as fruit and seeds (Sweetapple et al 2006; Sweetapple & Nugent 2007). A modelling exercise by Tompkins and Veltman (2006) predicted that the elimination of possums would have little impact on rat abundance in beech forests, but they speculated that in podocarp-hardwood forests

Table 3. Plausible models exploring the relationship between adult SI robin survival and a suite of possible explanatory variables. All models included recapture probabilities specified by time + sex. QAICc was estimated using a c-hat value of 1.351.

Model	npar	QAICc	ΔQAICc	weight
rat	39	1484.39	0.00	0.17
rat + possum	40	1485.25	0.86	0.11
.	38	1485.28	0.89	0.11
rat + active	40	1485.34	0.95	0.11
rat + Sex	40	1485.42	1.02	0.10
rat + season	40	1485.77	1.38	0.09
since1080	39	1485.94	1.55	0.08
area + since1080	40	1486.35	1.96	0.07
rat + stoat	40	1486.55	2.16	0.06
area	39	1487.23	2.83	0.04
rat * Sex	41	1487.53	3.14	0.04
area * since1080	41	1488.46	4.07	0.02

it might have considerable impact. Our study area included both higher altitude beech forests and low altitude podocarp-beech forests and our results seem therefore consistent with Tompkins and Veltman's (2006) prediction.

The increase in stoat abundance that occurred in the non-treatment area in response to the beech mast and rodent increase (Fig. 2) was completely suppressed in the treatment block by the two 1080 operations, and stoat numbers recovered to similar, but not higher levels after the two 1080 operations.

SI robin nest success and survival

Rats were the main identifiable cause of nest failure in our study, followed by stoats, possums and ruru. Rats were also the only identifiable predator of nesting adults. Rat numbers fluctuated more in response to beech mast and 1080 operations than other predators, and rat abundance was the best explainer of patterns of nest success and adult survival.

Our models showed that nest success and adult survival were both negatively affected by increasing rat numbers. We also found a weak negative relationship between nest success and possum abundance. Additionally, the models showed that both aerial 1080 operations were associated with increases in nest success. Although two nest failures and two adult deaths may have been caused by 1080, our models provided no evidence of a short-term negative impact of 1080.

The observed positive improvements in nest success associated with 1080 in our study were short-lived. Within a year of the second 1080 operation the relationship between treatment and non-treatment nest success had returned to its pre-treatment state. After two years, nest success had become considerably worse in the treatment block, almost certainly because rat numbers had risen to higher levels in the treatment block than they had in the non-treatment block. Rat numbers continued to rise for another year after the end of our study (Fig. 2) so it is likely that SI robin nest success would have been worse in the treatment area than the non-treatment area in both the second and third year after the 1080 drop.

Although stoats were the second most important predator of SI robin nests in our study, we were unable to detect any effect of stoats on nest success in our models. This is probably because compared to other causes of nest failure, nest predation by stoats was rare, and because the abundance of stoats and rats were highly correlated, any impact of stoats on nest success was obscured by the greater impact of rats.

Possums preyed on a similar number of SI robin nests to stoats, but our models nonetheless suggest a weak relationship between nest success and possum abundance (Fig. 4).

Armstrong et al. (2006) and Parlato and Armstrong (2012) found that adult male and female North Island robin survival was similar when predators were rare but was lower in females when predators were common. They attributed this difference to predation of nesting females. We detected no difference between male and female survival and our study was carried out at > 500 m a.s.l. where rats were most often uncommon and any difference in survival between males and females was likely to be small and undetectable with our small sample size. Contrary to this reasoning, Powlesland (1983) found an interaction between seasonality and sex, with similar survival rates between the sexes during the summer, but higher mortality amongst males in the winter.

Net effect of 1080 on SI robins

Although a small number of robins may have been killed and a small number of nests may have failed because of 1080, any such effects were small and probably trivial. The effect of changes in nest success caused by changes in rat abundance associated with 1080 treatments are, in contrast, large.

Over the period of our study, robins were slightly better off in our treatment area due to an increase in breeding success associated with 1080 use in 2014. This increased breeding success was greater than the decrease in nest success associated with increasing rat abundance over the two years following the 1080 drop. However, rat numbers increased in our treatment area for another year after our study ceased. If nest success continued to be negatively affected by high rat numbers, after 4 years robins would probably have been worse off in the treatment than the non-treatment area. If 1080 operations had been undertaken at 3-year intervals, then there probably would have been a small net benefit to robins in our treated area

The potential benefit to robins of 1080 operations such as those at Tennyson Inlet might be improved if kill rates of target species are improved and opportunities for recolonisation reduced. Controlling rat numbers by poisoning and or trapping along coastal buffers and tracks as well as on neighbouring land may be vital to the success of vulnerable species in small 1080 treatment areas.

The recovery of rats in our treatment block to higher levels after the 2014 1080 operation than in our non-treatment block is of considerable consequence in the assessment of the usefulness of 1080 operations for SI robins. Had rats recovered only to the same population abundance as without treatment, then a single 1080 operation would be of unequivocal benefit to SI robins and a series of operations would be beneficial regardless of treatment frequency. Our results suggest however, that at sites like ours, 1080 treatments might only provide long-term benefit if they are repeated at no more than 3 yearly intervals, or if rats are suppressed to very low abundances or immigration reduced by controlling rats on adjoining land, in our case over the whole peninsula.

Our results have similarities and differences to studies carried out near Dunedin (Schadewinkel et al. 2014; van Heezik et al. 2020). At both Dunedin and Tennyson Inlet, rat and possum numbers were reduced by 1080, and in both locations rat numbers recovered to higher levels than before treatment. At both sites the effects of direct mortality from 1080 were small or non-existent. At Tennyson Inlet, however, there was a detectable increase in SI robin nest success following 1080 and a subsequent decline in nest success the following year, while no such change was observed near Dunedin. The most likely explanation for this difference is that rat abundance was low at the Dunedin sites, and robin nest success was high even in the absence of pest control (Van Heezik et al. 2020), so that pest control made little or no difference.

Aerially applied 1080 is likely to be of benefit to small forest birds like SI robins where predators, particularly rats are abundant, but not at places where rats are uncommon. At lowland sites, or sites adjoining lowlands, aerial 1080 may suppress rat abundance for only a short time and they may subsequently rise to even higher abundances. At such sites 1080 will only be of benefit to birds such as SI robins when it is carried out frequently, unless very high kill rates are achieved and reinvasion is prevented. At higher altitude sites, aerial 1080 might be of more benefit to birds such as SI robins, regardless of its frequency or effectiveness, because at these sites, rats recover much more slowly after 1080 use. There is therefore a clear need for further research, especially long-term (10 plus years) monitoring of the abundance of small forest birds at a range of sites where 1080 is repeatedly used at a range of different frequencies.

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Author Contributions

MB & GE conceptualised, designed the methodology, and ran the investigation. MB wrote the original manuscript; DA and GE reviewed and edited the work. HR, TR, CV, AM, and KM were all involved in the investigation

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