Estimating impacts of poison operations using mark-recapture analysis: hihi *(Notiomystis cincta)*on Mokoia Island

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Abstract: Hihi *(Notiomystis cincta)* were reintroduced to Mokoia Island, Lake Rotorua, New Zealand, in September 1994, and two years later there was an aerial drop of brodifacoum cereal pellets aimed to eradicate mice *(Mus musculus)*. Using Program MARK, we analyzed data from resighting surveys to assess whether hihi had lower than normal survival in the 6-week interval following the drop. The resighting data were collected on a regular basis over a 3-year period, from 1994-97, allowing us to control for yearly and seasonal variation in resighting and survival probabilities. We initially established that the Cormack-Jolly-Seber model had a good fit to the data and could therefore be used as the global model for our analysis. We then compared a range of simpler candidate models, some of which included a poison effect (an unusual survival rate for the interval after the poison drop). Under the best model (that with the lowest AIC), the survival probability was constant over time and there was no poison effect. The estimated survival probability for the 6 weeks after the poison drop was 0.95, which is slightly higher than the value of 0.89 expected based on pre- and post-poison intervals. The approximate 95% confidence interval for the probability of a bird dying due to poison ranged from -0.17 (i.e., a decrease in mortality rate due to the poison) to +0.04. We therefore concluded that the poison caused at most a negligible increase in mortality, and that mark-recapture analysis on resighting data provided a powerful method for assessing the impact of the poison drop. We discuss the relative costs and benefits of radio tagging versus resighting surveys of banded birds for estimating impacts of poison operations. For species with relatively high resighting rates, such as hihi, analysis of resighting surveys is a much more reliable and cost-efficient methodology.

Keywords: brodifacoum; hihi; mark-recapture analysis; poison operation; stitchbird; survival.

Introduction

Poison operations to control or eradicate exotic mammals are an important component of conservation management in New Zealand, but such operations also cause mortality in non-target species. The degree of impact seems to vary greatly among species and situations (Eason and Spurr, 1995; Spurr and Powlesland, 1997). It is therefore important to assess impacts on any population of high conservation value, and to do so using reliable methods (Armstrong and Ewen 2001).

The hihi (stitchbird, *Notiomystis cincta)* is an endangered New Zealand honeyeater with a single selfsustaining population on Hauturu (Little Barrier Island) (Rasch *et at.,* 1996). Hihi ranged over the North Island of New Zealand and its offshore islands until the late 1800s when the species disappeared from most of this range. Its demise coincided with the expansion of populations of introduced ship and Norway rats *(Rattus rattus* and *Rattus norvegicus),* habitat modification by humans, and a sharp decline in other bird populations which could

have been associated with disease (Mills and Williams 1979, Rasch *et at.,* 1996). Translocations to several islands free of ship rats and mustelids have been carried out since 1980 with the aim of establishing additional hihi populations (Rasch *et al.,* 1996, Castro *et at.,* 1994, Armstrong *et at.,* 1999). Hihi were reintroduced to Mokoia Island, Lake Rotorua, in September 1994 (Armstrong *et al.,* 1999) and 2 years later the island received an aerial drop of brodifacoum cereal baits. The Mokoia hi hi population consisted of about 32 birds at the time of the drop and its viability appeared marginal based on survival and recruitment rates in the first 2 years (Armstrong *et al.,* 1997).

Mokoia was the first location with hihi to have a poison operation. Consequently, the drop was a useful test case to assess the likely impact of a future operation on Hauturu. Hauturu has kiore (Pacific rat, *Rattus exulans)* and there are plans to eradicate them using an aerial poison drop. Because Hauturu is the only stronghold of hihi, it was important to assess the danger to hi hi before such an operation was carried out. The hi hi population on

Mokoia provided an ideal opportunity to assess the effect of a poison drop because all hihi on Mokoia Islandwere colour banded for individual identification and had been closely monitored since their release in 1994 (Armstrong *et al.,* 1997, 1999).

In this paper, we assess the impact of the Mokoia poison drop on hihi using mark-recapture analysis. Regular resighting surveys were undertaken over the first 3 years following reintroduction as part of a research program focused on this population (Armstrong *et. al.* 1999; Armstrong and Perrott, 2000). We used mark recapture analysis on these data to estimate the survival rate immediately after the poison drop and compare it to the survival rate at other times, taking seasonal and yearly variation into account. We argue that this is an effective method for assessing impacts of poison operations in many situations, and discuss the advantages and disadvantages of mark-recapture analysis in comparison to radio tagging.

Methods

Study area and poison operation

Mokoia is a 135-ha island in Lake Rotorua (38°06'S, 174°55'E). The vegetation is at various stages of regeneration following clearing, fires and browsing, but
most of the island has closed canopy forest (Perrott and Armstrong, 2000). Norway rats, goats *(Capra hircus)* and sheep *(Ovis aries)* were eradicated in 1989-90,leaving mice *(Mus musculus)* as the only mammalian pest on the island. There have been subsequent re-introductions of toutouwai (robin, *Petroica australis),* tieke (saddleback,*Philestumus carunculatus)* and mistletoes (Loranthaceae:*Tupeia antarctica),* as well as hihi.

The aim of the poison drop was to eradicate mice. Talon® 7-20 cereal baits (3-4 g) containing 20 ppm brodifacoum were air-dropped on 18 September 1996 at a rate of 10 kg ha-l. The drop reduced mice to extremely low levels, the proportion visiting tracking tunnels dropping from a normal level of 50-100% to 0% the month after the drop (Stephenson, 1998). However, the mouse population slowly built up in the months after the drop and appeared to reach pre-poison levels within 12 months.

Data collection

Each resighting survey consisted of walking to a series of points on the island over 2-3 days, recording all hihi seen at or between these points. The entire population was colour-banded throughout the study. We selected a random point within each of 28 grid squares, selecting different points for each survey. We also did observations around nest boxes during the breeding season, and recorded birds visiting feeders. We observed feeders for

at least 6 hours in each survey, distributing observations equally among feeders. The number of feeders changed during our research program, with up to eight feeders available in individual territories in the 1995/96 and 1996/97 breeding seasons, and 0, 1 or 3 communal feeders available at other times. This variation did not reduce the validity of the mark-recapture analysis for three reasons. First, any change in re-sighting rates due to differing numbers of feeders would be accounted for in the analysis. Second, while some territories had feeders and others did not in the 1995/96 and 1996/97 breeding seasons, hihi were easily seen around nest boxes at these times and the presence of feeders had no effect on re-sighting rates. Third, hihi are highly mobile outside the breeding season, hence changes in distribution of feeders would not be expected to introduce heterogeneity in individual re-sighting rates.

We surveyed the population every 2 weeks from 5 September 1994, when hihi were reintroduced, until 2 November 1995. We performed nine surveys from November 1995 to November 1996, and six surveys from November 1996 to November 1997. One survey was conducted from 19-21 September 1996, immediately after the poison drop, and another conducted from 1-3 November 1996, 6 weeks after the drop. The interval between these two surveys was, we believed, the period when the poison could cause mortality in hihi. Brodifacoum, a second-generation anticoagulant, does not cause mortality for at least 3-4 days (Hadler and Buckle, 1992), hence birds would not be expected to die until after the 19-21 September survey.A mark-recapture analysis of Mokoia tieke confirmed that while there was extensive mortality in that population from 19-21 September to 1-3 November (see discussion), mortality was at the normal level during the previous and following interval (Davidson, 1999).

For the analysis, we disregarded the first two months after reintroduction, and selected six surveys per year from November 1994 to November 1997, with the'year' running from November to November. We selected the 1994/95 and 1995/96 surveys so the dates closely matched those of the 1996/97 surveys: mid December, early February, early April, late June, late September, and early November. The intervals between surveys therefore covered the same six 'seasons' each year, with season lengths ranging from 5 to 11 weeks. These differences in interval length were accounted for in the mark-recapture analysis.

Mark-recapture analysis

We analysed the data using MARK 1.6 (White and Burnham, 1999; a software package available from http://www.cnr.colostate.edul/~gwhite/mark/mark.htm. The reintroduced birds were considered to enter the population on the first survey in which they were recorded,

Table 1. Analysis to determine whether survival and resighting rates of hihi on Mokoia Island were affected by gender or age.

Model[1]		K[2]	AIC$_c$[3]	Δ_i[4]	w_i[5]
ϕ_t	P_t	35	1015.71	0.00	0.73
ϕ_t	P_{g*t}	53	1027.17	11.46	0.00
ϕ_{g*t}	P_t	53	1033.75	18.04	0.00
ϕ_t	P_{a6*t}	47	1018.20	2.49	0.21
ϕ_{a6*t}	P_t	47	1028.71	13.00	0.00
ϕ_t	P_{a3*t}	44	1021.02	5.31	0.05
ϕ_{a3*t}	P_t	44	1026.94	11.23	0.00

[1]Candidate models compared using MARK 1.6: t = time; g = gender; a6 = age (0-6 months versus older), a3 = age (0-3 months versus older). * indicates parameters for different time intervals calculated independently for each age class.
[2]Number of parameters in model.
[3]Akaike's Information Criterion, corrected for bias.
[4]Difference in AIC$_c$ value from the best model.
[5]Akaike weights, indicating the relative support for the models ($w_i = e^{-\Delta i/2}/\sum e^{-\Delta i/2}$).

and birds born on the island were considered to enter the population on the survey closest to their fledging date. There were encounter histories for 137 birds in the data set.

We used the Cormack-Jolly-Seber model $\{\phi_t, P_t\}$ (Lebreton *et al.,* 1992) as the global model for assessing the effect of the poison drop. Survival and re-sighting rates are estimated separately for each interval under $\{\phi_t, P_t\}$, but there is no distinction between ages or genders. The symbols ϕ and P indicate the factors affecting survival probability and re-sighting probability (probability of a live bird being recorded in a survey) respectively. We initially assessed goodness-of-fit of $\{\phi_t, P_t\}$ using program RELEASE (available within MARK). We also assessed whether the model was improved by adding gender or age structure. To do this, we modified the encounter histories file to recognise two groups, males and females, and modified the parameter index matrices to create age structure (Table 1). We considered two age structures, both recognising two categories, adults and juveniles. In one case, birds were considered juveniles for 3 months after fledging and in the other case they were considered juveniles for 6 months after fledging. We added age and sex structure separately for both re-sighting and survival models. We compared the alternative models to $\{\phi_t, P_t\}$ based on AIC$_c$ (Akaike's Information Criterion, corrected for bias), a lower AIC$_c$ value indicating a better model.

After confirming acceptability of $\{\phi_t, P_t\}$ as a global model, we assessed the effect of the poison drop by comparing eight simpler candidate models (Table 2). Under $\{\phi_{s + y}\}$ there are differences in survival between the 6 seasons (s) and 3 years (y), and the effects act in parallel, i.e., the model assumes the same relative changes between seasons in all years (Lebreton *et al.,* 1992). There are differences between seasons only under $\{\phi_s\}$, between years only under $\{\phi_y\}$, and survival is constant

Table 2. Analysis to determine whether hihi on Mokoia Island had an unusual survival rate in the 6-week interval after the brodifacoum poison drop on 18 September 1996.

Model[1]		K	AIC$_c$	Δ_i[2]	w_i[2]
Resighting:					
ϕ_t	P_t	35	1015.71	0.00	1.00
ϕ_t	$P_{s + y + p}$	27	1031.83	16.13	0.00
ϕ_t	$P_{s + y}$	26	1040.53	24.82	0.00
ϕ_t	$P_{s + p}$	25	1049.24	33.53	0.00
ϕ_t	P_s	24	1051.94	36.23	0.00
ϕ_t	$P_{y + p}$	22	1072.43	56.72	0.00
ϕ_t	P_y	21	1070.52	54.81	0.00
ϕ_t	P_p	20	1080.98	65.27	0.00
ϕ_t	$P.$	18	1077.14	61.43	0.00
Survival:					
ϕ_t	P_t	35	1015.71	23.93	0.00
$\phi_{s + y + p}$	P_t	27	1002.25	10.47	0.00
$\phi_{s + y}$	P_t	26	1000.31	8.53	0.00
$\phi_{s + p}$	P_t	25	1001.12	9.34	0.00
ϕ_s	P_t	24	999.94	8.16	0.01
$\phi_{y + p}$	P_t	22	994.77	2.99	0.10
ϕ_y	P_t	21	993.11	1.33	0.22
ϕ_p	P_t	20	993.07	1.29	0.23
$\phi.$	P_t	19	991.78	0.00	0.43

[1]Candidate models compared using MARK 1.6: t = time; s = season; y = year; p = 6-week interval immediately after poison drop. + indicates that factors act in parallel.
[2]Δ_i and w_i calculated separately for comparison of resighting and survival models.

under $\{\phi\}$. The models $\{\phi_{s + y + p}\}$, $\{\phi_{s + p}\}$, $\{\phi_{y + p}\}$ and $\{\phi_p\}$ are similar to the four models just described, but have a different survival rate for the interval after the poison drop (p). Support for any of the models with the poison parameter would indicate an unusual survival rate in the interval after the poison drop, whereas support for any of the other models would indicate this was not the case. If $\{\phi_t\}$ was the best survival model, this would indicate that survival varied unpredictably over time, making it impossible to assess the effect of the poison.

Before comparing survival models, we followed a similar procedure to select the best re-sighting model (Table 2). We used $\{\phi_t\}$ as the survival model when comparing re-sighting models, then used the best re-sighting model when comparing survival models, as recommended by Lebreton *et al.* (1992).

Results

The global model $\{\phi_t, P_t\}$ had 8 degrees of freedom, and Test 2 *(P = 0.129)* and Test 3 *(P = 0.835)* in RELEASE indicated a good fit to the data. Addition of genders or age structure did not improve the model (Table I). The best re-sighting model was clearly $\{P_t\}$, indicating unpredictable changes in re-sighting rates over time

(Table 2). Resighting probability varied from 0.48 to 1.00, with a mean of 0.80.

The best survival model was $\{\phi.\}$ indicating a constant survival probability. The models $\{\phi_p\}$ and $\{\phi_y\}$ also had reasonable support ($\Delta_i< 2.0$; Table 2). However, while support for $\{\phi_p\}$ suggests the possibility of an unusual survival rate after the poison drop, the survival rate was higher than normal for that period rather than lower. The estimated survival probability for the 6 weeks after the poison drops; $\hat{S}_{p,}$ was 0.95 (se=0.047, 95% CI=0.73-0.99) under $\{\phi_p\}$. In contrast the expected survival probability for a 6-week period, $\hat{S}_e$, based on the other intervals was 0.89 (se = 0.010, 95% CI = 0.87-0.91).

The mortality due to a poison drop can be estimated as $1- \hat{S}_p / \hat{S}_e$, giving -0.06 in this case, i.e., a 6% decrease in mortality. The standard error for this estimate can be calculated using the delta method (Seber, 1982: 7-8), which can be used to find an approximate mean, variance or covariance for a function of two or more variables. Solving the variance equation for a quotient of two variables yields

$$se\left[\frac{\hat{S}_p}{\hat{S}_e}\right] = \frac{\hat{S}_p}{\hat{S}_e}\sqrt{\left(\frac{se[\hat{S}_p]}{\hat{S}_p}\right)^2 + \left(\frac{se[\hat{S}_e]}{\hat{S}_e}\right)^2 - \frac{2cov[\hat{S}_p,\hat{S}_e]}{\hat{S}_p\hat{S}_e}}$$

The survival probability was also similar to the normal level in the interval immediately before the poison drop (0.87 for a 6-week period under $\{\phi_t, P_t\}$, confirming that there had been no immediate die-off affecting the survey conducted 1-3 days after the drop.

The approximate covariance between $\hat{S}_p$ and $\hat{S}_e$, was -0.00002, and was obtained from the variance-covariance table produced by MARK for model $\{\phi_p, P_t\}$. Substituting this value into the equation, along with the estimates and standard errors.given above, gives a standard error of 0.052 for. $\hat{S}_p/\hat{S}_e,$. The approximate 95% confidence interval ($\hat{S}\pm2se$) for the probability of being killed by the poison drop is therefore -0.16 to +0.04 (-0.06±0.10).The interval after the poison drop was therefore not significantly different, and we can be confident that the probability of mortality could not have increased more than 4%.

Discussion

Our analysis shows that the brodifacoum poison drop on Mokoia Island had no or negligible effect on hihi survival. Empson and Miskelly (1999) also assessed hihi survival before and after the brodifacoum poison drops on Kapiti Island, using *ad hoc* estimates based on minimum number alive. They noted that there was no evidence of hihi being kiIled by the poison, and noted that survival rates became higher after the poison drop, presumably due to the eradication of Norway rats. Survival estimates based on minimum number alive can be unreliable, especially if

Re-sighting rates are low or variable (Seber, 1982). Nevertheless, we suspect Empson and Miskelly (1999) were correct that the Kapiti poison drops had no impact on the hihi population and that hihi are not susceptible to poisoning from brodifacoum cereal pellets.

In contrast to hihi, a similar mark-recapture analysis for Mokoia Island tieke estimated that 45% of that population died as a result of the same poison drop (Davidson, 1999). In addition, Stephenson *el al*. (1999) found that 3 of 14 radio-tagged ruru *(Ninox novaeseelandiae)* died after the Mokoia poison drop, and suggested this was greatly in excess of the normal mortality rate although they did not estimate that rate. The feeding habits of tieke and ruru presumably make them more vulnerable to poison consumption. Tieke feed opportunistically on a range of food sources, but feed extensively on ground invertebrates on the forest floor. They would therefore have frequent contact with poisoned cereal pellets and may also consume poisoned invertebrates. We observed tieke pecking at cereal pellets on Mokoia, and Spurr (1993) noted that non-toxic cereal pellets were consumed by captive tieke. Ruru are unlikely to consume cereal pellets, but they prey on mice. Mice remains made up about 40% (by volume) of ruru pellets at the time of the poison drop (Stephenson *elal.,* 1999),giving strong potential for secondary poisoning.

Hihi feed on a combination of nectar, fruits and invertebrates which varies seasonally (Gravatt, 1970; Castro and Robertson, 1997; Perrott, 1997). They sometimes feed on invertebrates on or near the ground, which potentialIy exposes them to secondary poisoning, but they mainly glean invertebrates from leaves at least 2 m from the ground. Hihi do relatively little invertebrate feeding (20% of foraging time) in September on Mokoia (Armstrong and Perrott, 2000), hence they may have been particularly invulnerable to poisoning at that time.

While mark-recapture analysis proved to be a powerful method for assessing the impact of the poison drop, the re-sighting data were not colIected with the poison operation in mind. The entire monitoring program for the poison drop, and the associated budget, was devoted to using radio-tagged birds to assess post-poison mortality. Sixteen hihi were radio tagged before the poison drop for this purpose. However, the Mokoia poison drop was delayed 8 weeks because of rain and the radio tags ran out of battery life before the drop (Castro, 1996). This was unlucky, but such delays are common given the frequency of winter rains in most parts of NewZealand. We question whether radio tagging would have provided any additional information even if the tags had been operational over the right period. Radio tags would have provided a reasonable estimate of mortality after the poison drop, but would have given a less precise estimate than that from the re-sighting data due to the smaller sample size. The higher detection rates that radio tags allow can more than compensate for a lower sample size,

but not if resighting rates are relatively high as they are for Mokoia hihi. More importantly, it is insufficient to estimate mortality just for the post-poison period because this provides no information on the background mortality rate. One benefit of radio tags is that they could have allowed bodies to be recovered and assessed for brodifacoum levels (Stephenson *et al.,* 1999). It is difficult, however, to know what constitutes a lethal level without sampling tissues from birds that survived.

Kenward 1993) discusses the general advantages and disadvantages of using radio tagging to estimate survival rates, in comparison to doing mark-recapture analysis using banded birds. He lists four potential advantages of radio tags: (1) they allow survival to be estimated more rapidly, (2) juvenile survival rates can be estimated for species in which juveniles are difficult to detect, (3) they avoid biases associated with some mark recapture procedures, especially analysis of dead recoveries, and (4) detailed data can be obtained on individual movements of birds. He lists four disadvantages: (1) signals can be lost, (2) battery life is limited, (3) radio tags may affect survival, and (4) radio tags are expensive.

The best method for estimating survival will depend on the species and situation. For example, ruru are nocturnal and difficult to see but are large enough to carry a tag that will last for many months. Radio tags were therefore the best method of estimating survival of ruru on Mokoia (Stephenson *et al.,* 1999), even .though the expense limited the sample size. The best strategy in some situations may be to collect both radio tracking and re-sighting data, and statistical methods have recently been developed to make simultaneous use of both types of data (Powell *et al.,* 2000). For Mokoia hihi, however, radio tagging simply placed unnecessary stress on the birds, and diverted funding and labour that could have been used elsewhere. Mokoia hihi were already being colour banded on the nest, were already being surveyed regularly, and were known to have high re-sighting rates. Analysis of re-sighting data was therefore completely adequate for this population, and allowed us to conclude with confidence that the poison drop had negligible impact.

Acknowledgements

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