Notornis, 2019, Vol. 66: 1-15
0029-4470 © The Ornithological Society of New Zealand Inc.

Landscape-scale applications of 1080 pesticide benefit North Island brown kiwi (*Apteryx mantelli*) and New Zealand fantail (*Rhipidura fuliginosa*) in Tongariro Forest, New Zealand

HUGH A. ROBERTSON*
Terrestrial Ecosystem Unit, Biodiversity Group, Department of Conservation, PO Box 10420, Wellington, New Zealand

JEROME GUILLOTEL
TONY LAWSON
NICOLE SUTTON
Department of Conservation, PO Box 71029, Whakapapa Village, Mt Ruapehu, New Zealand

Abstract: Data on the effects of aerial 1080 operations on non-target bird species in New Zealand are scarce and largely limited to short-term colour-banding or radio-tracking studies, or standardised call counts. During a 22-year study in Tongariro Forest, all 142 radio-tagged North Island brown kiwi (*Apteryx mantelli*) survived 4 landscape-scale (20,000 ha) aerial broadcast 1080 operations targeting brush-tailed possum (*Trichosurus vulpecula*) and rats (*Rattus* spp.). Furthermore, both kiwi chick survival to 6 months old and New Zealand fantail (*Rhipidura fuliginosa*) nesting success were significantly higher in the first 2 breeding seasons following the use of 1080 poison than in subsequent years of the 5-year cycle. We observed several episodes of ferret (*Mustela furo*) killing multiple adult kiwi, particularly in the last half of the 1080 cycle. Population modelling showed that a 5-year 1080 operation cycle resulted in population gains for 2 years, followed by declines in the remaining 3 years that largely negated these benefits. Our data thus support the shift to a 3-year 1080 operation cycle which will more likely result in this kiwi population growing at close to the 2% per year target set by the 2018–2028 Kiwi Recovery Plan.

Robertson, H.A.; Guillotel, J.; Lawson, T.; Sutton, N. 2019. Landscape-scale applications of 1080 pesticide benefit North Island brown kiwi (*Apteryx mantelli*) and New Zealand fantail (*Rhipidura fuliginosa*) in Tongariro Forest, New Zealand. *Notornis 66(1)*: 1–15.

Key words: 1080 pesticide, pest control, chick survival, nesting success, population dynamics, brown kiwi, New Zealand fantail

INTRODUCTION

The pesticide sodium fluoroacetate (Compound 1080) is used widely in New Zealand to control introduced brush-tailed possum (*Trichosurus vulpecula*) and ship rat (*Rattus rattus*). Possum are the key wildlife maintenance host and vector of bovine tuberculosis (*Mycobacterium bovis*), an economically important pathogen of farmed cattle (*Bos taurus*) and deer (Cervidae) in New Zealand (Livingstone *et al*. 2015), and also cause immense damage to native forest ecosystems by browsing plants and killing wildlife, and to plantation forests by damaging young trees (Wright 2011). Ship rat also have a serious impact on native forest ecosystems by feeding on seeds and berries, and by preying on native wildlife. The use of 1080 has proven controversial due to a general wariness about the use of toxins, especially those that are distributed by air, possible sub-lethal effects on humans, the humaneness of the pesticide, and the risks of by-kill, especially of native birds and game

---

Received 13 June 2018; accepted 5 January 2019
* Correspondence: *hrobertson@doc.govt.nz*

animals (Eason *et al.* 2011; Wright 2011). These concerns have contributed to changes in the way in which 1080 is aerially distributed, with a great reduction in sowing rates, a general switch from carrot to cereal baits, the use of dyed baits to deter ingestion by birds and, in some areas, the inclusion of deer repellent in baits.

New Zealand birds evolved in the absence of mammalian carnivores. Following the accidental and deliberate introduction of mammalian predators since first human settlement *c.* 800 years ago, 53 bird species have become extinct (Robertson *et al.* 2017) and many others have suffered massive declines in abundance and range, including all 5 species of kiwi. For example, unmanaged mainland populations of the North Island brown kiwi (*Apteryx mantelli*) (hereafter referred to as brown kiwi) are declining by *c.* 2–3% per year (Holzapfel *et al.* 2008; Robertson *et al.* 2011), mainly due to adult kiwi being killed by domestic dog (*Canis familiaris*) and ferret (*Mustela furo*), and the predation of chicks by stoat (*Mustela erminea*) (McLennan *et al.* 1996; Robertson *et al.* 2011; Robertson & de Monchy 2012). At unmanaged sites, high levels of stoat predation can reduce kiwi recruitment to 5% compared with the *c.* 20% recruitment that is typically required to maintain a stable population (McLennan *et al.* 1996; Robertson *et al.* 2011; Robertson & de Monchy 2012). Although adult mortality is the key factor driving kiwi population change, the control of stoat is often the most practical and achievable way of reversing population declines (Robertson & de Monchy 2012).

Landscape-scale control by trapping stoat has had mixed results in New Zealand, working well at some sites and poorly at others (Robertson & de Monchy 2012; Tansell *et al.* 2016). Furthermore, although poison bait station operations, which result in secondary poisoning of stoat, have been shown to benefit kiwi recruitment (Robertson *et al.* 2011, 2016), the geographical scale of such protection is limited in the same way as trapping operations are constrained. By contrast, landscape-scale (10,000–50,000 ha) or super-landscape-scale (50,000–250,000 ha) aerial 1080 operations have the potential to protect significant kiwi populations through secondary poisoning of resident stoat. It is known that aerial 1080 operations kill nearly all resident possum and rat, the numbers of which can return to near their initial densities in 10–15 years for possum, but in as little as 4–5 months or as long as over 2 years for ship rat (Innes *et al*. 1995; Veltman & Pinder 2001; Powlesland *et al*. 2003). It has also been shown that in New Zealand forests, nearly all resident stoat are killed by secondary poisoning following bait station or aerial 1080 operations (Gillies & Pierce 1999; Murphy *et al*. 1999; Alterio 2000), and so landscape-scale 1080 operations in forests have the potential to suppress stoat numbers long enough to allow a cohort of kiwi chicks to reach *c.* 1 kg at 6–8 months old, at which stage they are generally safe from stoat predation (McLennan *et al*. 1996, 2004; Robertson *et al*. 2011; Robertson & de Monchy 2012).

Many studies have recorded the numbers of dead birds found following 1080 operations (e.g. Spurr & Powlesland 1997; Morriss *et al*. 2016), have measured changes in the detectability of birds before and after 1080 operations through territory mapping, stationary 5-minute bird counts or transect counts (e.g. Spurr & Powlesland 1997; Powlesland *et al*. 1999, 2000; Westbrooke *et al*. 2003; Greene *et al*. 2013; Morriss *et al*. 2016), or have recorded the survival of individually colour-banded or radio-tagged adult birds through aerial 1080 operations (e.g. Spurr & Powlesland 1997; Powlesland *et al*. 1999, 2000, 2003; Veltman & Westbrooke 2011; Greene *et al*. 2013; Horikoshi *et al*. 2018). However, few published studies have examined the breeding success of birds following aerial 1080 operations (e.g. Powlesland *et al*. 1999, 2000) and only Powlesland *et al*. (1999) assessed whether benefits that occur immediately after the 1080 operation continue into subsequent breeding seasons (Byrom *et al*. 2016). There has been no published study of the survival of young kiwi following the use of aerial 1080 nor the outcomes for the same population of birds through multiple aerial 1080 operations.

In this study, we analysed the survival of brown kiwi in Tongariro Forest through four landscape-scale aerial 1080 operations and in the years between these operations, spanning 22 years. The primary aim of these operations was to control possum in order to reduce the risk of bovine tuberculosis infecting cattle and deer herds on neighbouring farmland. The Department of Conservation increased the scale of each operation to cover the entire forest, which allowed us to investigate the effect of such landscape-scale 1080 operations on the population dynamics of the easternmost population of brown kiwi in the Whanganui-Taranaki area, at a site that is being managed as the Tongariro Kiwi Sanctuary (Robertson 2003; Robertson & de Monchy 2012).

As part of a study of the wider ecological benefits that management undertaken in the 5 kiwi sanctuaries nationwide had on forest communities, we also monitored the nesting success of New Zealand fantail (*Rhipidura fuliginosa*) through two 1080 operations at Tongariro Forest and in the years between these operations. Fantail is a common and widely-distributed endemic forest passerine, but ship rat are important predators of their nests (Moors 1983; Mudge 2002).

METHODS

Study area

The Tongariro Forest Conservation Area, otherwise known as the Tongariro Kiwi Sanctuary, in the central North Island of New Zealand (39°05′S, 175°28′E) is mainly cut-over podocarp-hardwood forest; during the study a small crop of exotic *Pinus radiata* in the south-eastern part of the study area was logged and allowed to regenerate into native forest (Fig. 1). The terrain is generally flat through to rolling hills of volcanic ash on the lower flanks of the Mount Ruapehu, Mount Ngaruahoe, and Mount Tongariro complex of active volcanoes, but the area is incised by the deep, broad Waione River valley, and is flanked in the west by the Whakapapa River, in the north by the Whanganui River and in the east by the Mangatepopo Stream.

Monitoring of kiwi chicks in Tongariro Forest commenced in the May 1995 to February 1996 breeding season (hereafter referred to as 1995) and is ongoing in 2019. Most of the monitored kiwi pairs were within 1.5 km of the 42 Traverse cycle trail between the end of Kapoors Road and the Waione Valley, centred on 39°03′S, 175°29′E. The study of fantail nest survival commenced in spring 2002 and ended in early 2013, with the sample of monitored birds being split between the kiwi study area and a site on Whakapapa Bush Road to the east of the Whakapapa River (38°59′S, 175°25′E). Additional information was obtained from non-treatment sites in indigenous forest to the east of Mangatepopo Stream near the Outdoor Pursuit Centre (OPC) (39°02′S, 175°33′E) and in Rotoaira / Maungakatote Forest (39°00′S, 175°36′E) (Fig. 1).

Aerial 1080 operations

Tongariro Forest

Between 1995 and 2011, the former Animal Health Board (now OSPRI), Department of Conservation and Manawatu-Whanganui (now Horizons) Regional Council have jointly applied 1080 in 4 landscape-scale aerial poisoning operations over Tongariro Forest (19,980 ha) in an attempt to control brush-tailed possum. This was generally distributed by spreading diced carrot or cereal-based pellets

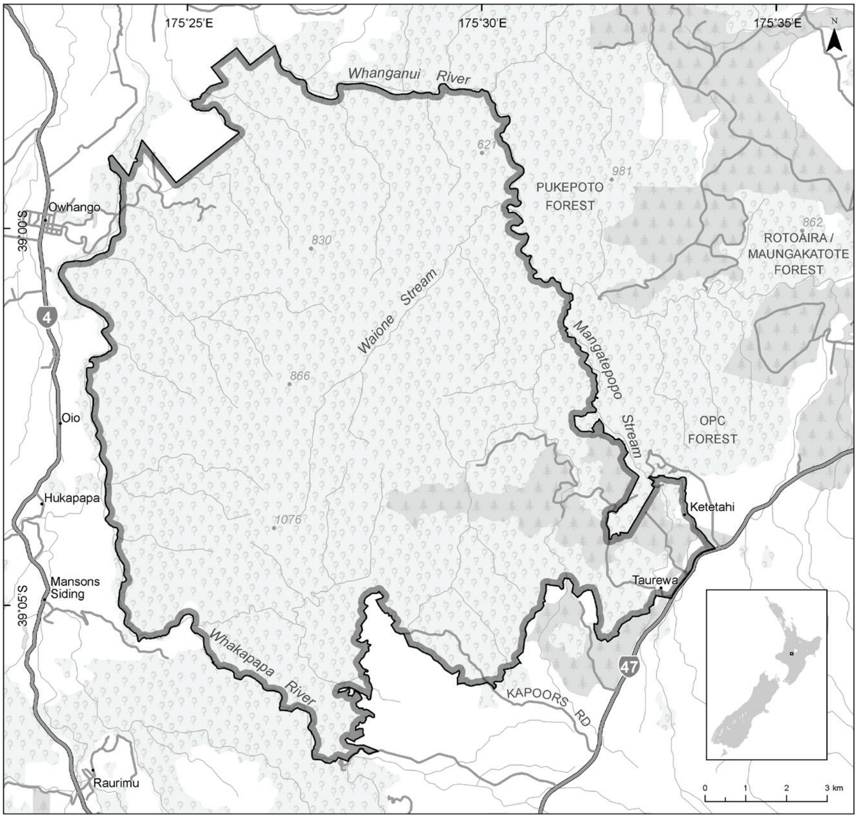

Figure 1. Tongariro Kiwi Sanctuary, north of Mount Ruapehu. Pale rounded trees represent native forest and scrub, darker triangular trees represent exotic forest, and white areas indicate farmland. Note that the exotic forest within the Tongariro Kiwi Sanctuary was logged during the study and this area was allowed to regenerate naturally.

by helicopter, but was distributed by hand or in bait stations in the 869 ha upper catchment of the Owhango township drinking water supply, to ensure that baits were kept away from streams.

In the 1995–1996 operation, the half of the forest that was being used to monitor kiwi was treated with 10 kg/ha of 0.08% w/w toxic carrots in June 1995, while the other half of the forest was treated with 5 kg/ha of 0.15% w/w 1080-impregnated cereal-based baits in July 1996. In subsequent operations, the entire forest was treated simultaneously using 3 kg/ha of 0.15% w/w cereal-based baits on 19 September 2001, 4 kg/ha of 0.08% w/w cereal-based baits on 13/14 September 2006 and 2 kg/ha of 0.15% w/w cereal-based baits on 26/27 September 2011.

There was a period of 5–6 years between each successive 1080 operation. Therefore, the survival of brown kiwi chicks and success of fantail nests were aggregated according to the number of years since the last 1080 operation.

OPC and Rotoaira/Maungakatote Forests

Following completion of the September 2006 operation in Tongariro Forest, we monitored fantail nesting success in nearby untreated OPC and Rotoaira/Maungakatote Forests. An aerial 1080 operation to control possum was then conducted in these forests by the former Animal Health Board in September 2007 and a stoat trap line was also established along the adjacent Whanganui River to protect blue duck (whio; *Hymenolaimus malacorhynchos*). These sites could therefore no longer be used as a non-treatment comparison. These non-treatment forests did not contain any known breeding pairs of brown kiwi.

Rodent and stoat monitoring

Tracking tunnels (King & Edgar 1977) were used to index rat, mouse (*Mus musculus*) and stoat abundances in Tongariro Forest from December 2001 to 2015, and at non-treatment sites in OPC, Rotoaira/Maungakatote and Pukepoto Forests (38°59′S, 175°32′E) from December 2001 to August 2007. The tunnels were normally run 4 times per year (in February, May, August, and November to 2007, and in January, February, August and November since then), with a few additional samples being collected shortly before and/or after 1080 operations to better understand the effects of these operations on rodent and mustelid populations.

There were 15 transect lines in Tongariro Forest and 15 transect lines divided among the 3 nearby untreated forests. Each line was 450 m long and had 10 tunnels at 50 m spacing, giving a total of 150 tunnels at each of the treatment and non-treatment sites. At the start of each tracking session, the inkpad in each tunnel was replenished and tracking paper was inserted either side of a peanut butter bait. The papers and bait were removed after 1 night, and new papers were then inserted with a meat bait and left for a further 3 nights to index mustelid abundance. We assumed a linear relationship between tracking rates and the actual population density (Innes *et al*. 1995; Brown *et al*. 1996).

Tracking tunnel data were modelled using general additive models (GAMS), with plotted splines showing mean tracking rates in the five years after each 1080 operation, and 95% confidence intervals were then calculated for each fitted line.

Productivity and survival of brown kiwi

From 1992 to 2005, adult male kiwi in Tongariro Forest were caught and fitted with a Sirtrack™ or Kiwitrack™ radio-transmitter according to the methods described by Miles & McLennan (1998). Since 2005, kiwi have been fitted with ‘smart’ transmitters that use the activity patterns of males to provide information in their coded signals on the time when incubation commenced (Egg Timer®) and chicks had hatched (Chick Timer®).

Productivity

Based on regular checks of the locations of radio-tagged adult males during the breeding season and, more recently, the outputs of smart transmitters, we determined how many adult males attempted to breed each year. By inspecting their nests, including during the collection of eggs for artificial incubation (Operation Nest Egg™ [ONE]; see Colbourne *et al.* 2005), we then determined the number of clutches, the size of each clutch and hatching success. Assuming an equal sex ratio, which is usual in most kiwi populations (Robertson & de Monchy 2012), we used the product of these measures to calculate the number of chicks hatched per adult per year.

Chicks

Each chick was fitted with a 5–6 g, single-stage Sirtrack™ or Kiwitrack™ transmitter at 1–32 (mean 9 ± 6) days old, before it permanently left the nest. A few chicks died in the nest before they could be radio-tagged, and so their age at death was estimated from their stage of development or the mid-point between the time when they hatched and were found dead or missing, presumed dead. When evidence from smart transmitters or examination of the nest contents revealed that the chick(s) had hatched but had disappeared within 10 days of hatching, before they could be radio-tagged, we assumed that they had died out of the nest at *c.* 8 days old, within a few days of first venturing alone from the nest. Chick transmitters were replaced with a 10–11 g, 2-stage juvenile mortality transmitter once the chicks reached *c.* 800 g (*c.* 3–5 months old). We calculated the survival of wild-hatched chicks from hatching date using the Kaplan-Meier procedure and rules promulgated by Robertson & Westbrooke (2005) for dealing with censored data and for calculating age at death when 'time-since-death' information was not available from mortality transmitters.

In some years, we used ONE as a tool to increase the sample size of radio-tagged chicks by stimulating re-nesting through removal of the first clutch and ensuring successful recruitment in years when few naturally-hatched chicks were expected to survive. We collected eggs from nests at mid- to late-incubation (50 ± 17 days) and hatched them in captivity at Rainbow & Fairy Springs / Kiwi Encounter in Rotorua. A group of chicks were radio-tagged and returned directly to Tongariro Forest at 8–37 (mean 18 ± 5) days old, which is around the age when wild-hatched brown kiwi chicks become independent (Robertson *et al.* 2016). Another group was returned to the forest at 123–182 days old, keeping them in pens at Kiwi Encounter, or holding them in predator-proof crèches at Warrenheip (37°56'S, 175°35'E) or Wairakei Golf Course (38°38'S, 176°04'E) until this time. These captive-hatched ONE chicks that were released into Tongariro Forest were added to the sample of monitored chicks using a staggered-entry design (Pollock *et al*. 1989).

Chicks were radio-tracked weekly for the first 6 months and also checked physically every month until they reached 800 g and then every 2 months. The cause of death for each chick was determined from an examination of the scene (e.g. presence of predator faeces or location of a body drowned in a river), physical inspection (e.g. measurement of inter-canine distances at wound sites or necropsy analysis at Wildbase, Massey University) and, in the case of some freshly-killed chicks, from the results of a DNA test conducted by EcoGene laboratory using saliva collected from the site of the wound. The date of death was established from mortality transmitter signal information, the recorded carcass condition, or the interval between visits using the midpoint of the interval if <15 days and 40% of the interval if ≥15 days (Miller & Johnson 1978; Robertson & Westbrooke 2005).

We had limited samples of chicks in the third year (n = 30) and fourth year (n = 33) after a 1080 operation due to local stakeholder concerns about the poor survival chances of kiwi chicks in years so long after a 1080 operation. In those years, we removed most eggs and wild-hatched chicks for ONE, and kept the chicks in captivity or in pest-free crèches until they were either returned to Tongariro Forest once they had reached *c.* 1,200 g at *c.* 6–8 months old or were used in other conservation programmes such as helping to establish a genetically diverse breeding population of brown kiwi in Maungatautari Ecological Island (38°01'S, 175°34'E) in the Waikato. In the fifth (final) year of the 1080 operation cycle, a sample of 47 wild-hatched and ONE chicks was monitored in Tongariro Forest, but again to satisfy stakeholder concerns, some were held back in pest-free crèches until released as subadults.

Subadult and adult brown kiwi

We used the Kaplan-Meier procedure to determine the survival of subadult brown kiwi from 6 months old through to 4 years old, which is their usual age at first breeding (Robertson & de Monchy 2012). Captive-hatched ONE subadults that had been transferred from crèche sites and 6 birds that had hatched at Maungatautari Sanctuary were added to the sample of Tongariro Forest subadults using a staggered-entry design (Pollock *et al*. 1989). We used the Mayfield method (Robertson & Westbrooke 2005) to calculate the survival of radio-tagged adult brown kiwi. We included a comparison of adult survival in each of the 5 years of the 1080 cycle. The cause of death of each subadult and adult was determined from an examination of the scene, physical inspection of the carcass, or a DNA test of saliva at the wound site, in the same way as done for dead chicks.

Kiwi population models

Using overall productivity and survivorship data, we developed population matrix models in the Microsoft Excel add-in PopTools (Robertson & Westbrooke 2005; Robertson & de Monchy 2012) to calculate the population growth rate of brown kiwi in each year of the 5-year 1080 cycle, pooling Year 4 and 5 data as Year 4+ to improve the sample size. We also ran the models using the average rate of adult survival rather than stage-specific rates of adult survival over the 5-year cycle in case the observed pulsed mortality was not related to the stage in the 1080 cycle.

We then estimated the population growth rates that would occur if aerial 1080 operations in spring had been carried out at different frequencies than the regular 5-year cycle observed here, or in the absence of any management. To do this, we used the population growth rates for each of the first 3 years of the cycle and used the 4+ year data for subsequent years of the cycle, as well as for the non-treatment scenario. We also ran the model using the average rate of adult survival rather than stage-specific rates of adult survival over the 5-year cycle

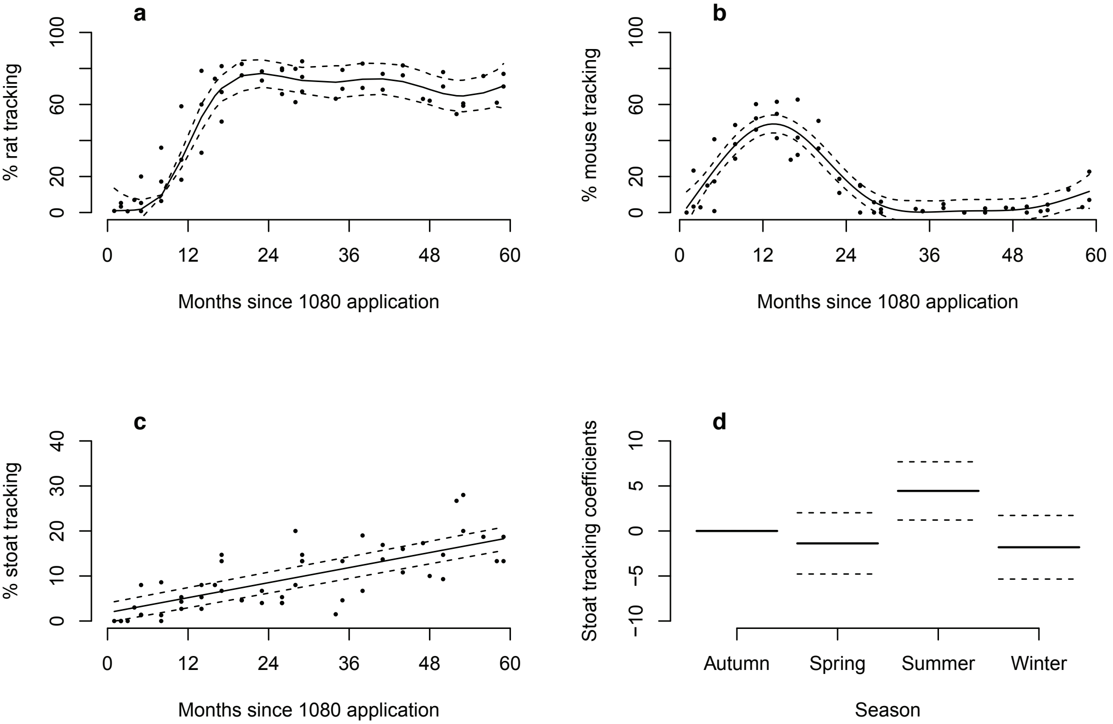

Figure 2. Footprint tracking data (dots), fitted splines (solid lines), and 95% confidence intervals (dashed lines) from general additive models of tracking rates of (a) rats (*Rattus* spp.), (b) mouse (*Mus musculus*), and (c) stoat (*Mustela erminea*) over the 5 years since each 1080 operation in Tongariro Forest. The best rat model (a) explained 88% of the deviance in rat tracking rates, the best mouse model (b) explained 83% of the deviance in mouse tracking rates, and the best stoat model (c) explained 73% of the deviance in stoat tracking rates. The stoat best fit model included a season term, indicating that stoat tracking varied significantly by season, and was higher in summer than in all other seasons; this is shown in (d) as a comparison of model coefficients for stoat detection rates by season, with autumn tracking rates set as the intercept on the plot.

in case the observed pulsed adult mortality was independent of the stage in the 1080 cycle.

Nesting success of fantail

Fantail nests were found by following focal birds as they built their nests, changed over incubation spells with their partner or fed nestlings. Wherever possible, the nest contents were determined using a mirror on an extendable pole. Nests were visited every 2–4 days until the nesting attempt failed or the chicks fledged *c.* 30 days after the first egg was laid (McLean & Jenkins 1980; Powlesland 1982). A total of 21 nests were monitored using motion-activated video cameras to try to determine the causes of failure and to relate the sign left in the failed nest with that observed in successful nests. Nest success was measured using the Kaplan-Meier procedure with a staggered-entry design (Pollock *et al*. 1989) to allow the inclusion of nests found at different stages during the nesting period. The Kaplan-Meier survivorship analysis was preferred over simple percentage nesting success or the Mayfield method (Mayfield 1961, 1975) because predation risks and our ability to detect nests varied considerably over the full nesting cycle – nests were easiest to detect during nest-building and when chicks were being fed because fantail visited their nest more frequently than during egg-laying or incubation.

In 2006, the breeding success of fantail in Tongariro Forest was compared with that in nearby unmanaged OPC and Rotoaira Forests. We also obtained data on the breeding success in 2007, following an aerial 1080 operation by the former Animal Health Board to control possum, allowing a direct comparison of fantail breeding success before and after an aerial 1080 operation.

RESULTS

Effects of 1080 operations on rodents and mustelids

The tracking rates of rats (presumably mainly ship rat), mouse, and stoat were each averaged across three 1080 cycles starting in 2001, 2006, and 2011. There was a very sudden and dramatic decline in the tracking rates of all 3 mammalian pest species immediately after each 1080 operation, regardless of the sowing rate, which varied from 2 to 4 kg/ha, with rat tracking decreasing from *c.* 70% beforehand (60 months after the last 1080 operation) to <1%, mouse tracking decreasing from 15% to 1–3% and stoat tracking decreasing from 20% to 0% (Fig. 2A–C).

Mouse tracking rates recovered faster than rat tracking rates, reaching a peak of 50% *c.* 1 year after the 1080 operation before falling away to <20% after 2 years, following which they remained well below 10% for most of the remaining 3 years of the cycle. Rat tracking rates generally built up slowly over the first 9 months after each operation, and then increased rapidly between 9 and 20 months to reach a plateau at *c.* 70–80% that was maintained, with some variation between 55% and 84%, for the next 40 months. Stoat tracking rates took much longer to recover to pre-poison levels, with a slow linear increase until the following 1080 operation, but with summer peaks (Fig. 2D).

There was also marked variation in the recovery rates of each pest species following the different 1080 operations, which may have been related to sowing rates or the completeness of sowing coverage. The mouse population grew fastest after the high-bait-density (4 kg/ha) operation in 2006, to reach 41% tracking in 5 months (February 2007) compared with <1% tracking over the same period after the 2001 operation (3 kg/ha). By contrast, rats recovered fastest after the low-bait-density (2 kg/ha) operation in 2011, reaching 59% tracking within 11 months (November 2012) compared with only 18% tracking at the same stage after the 2006 operation. The tracking rates of stoat remained below 7% for at least 26 months after the 2001 operation, but reached 13% within 17 months after both the 2006 and 2011 operations.

Comparison of treatment and non-treatment sites in 2006 and 2007

Following the 1080 operation in Tongariro Forest in September 2006, the tracking rates of rat, mouse, and stoat dropped to 0–1% in October (Fig. 2). Mouse numbers then rebounded quickly to reach 23% in November 2006 and climbed to 60% by August 2007, whereas the tracking rates of both rat and stoat remained below 10% until at least May 2007. At the nearby non-treatment sites in OPC and Rotoaira/Maungakatote Forest, the tracking rates of mouse increased from 3% in August to 19% in November, and then remained in the range of 9–17% from February to August 2007, whereas the tracking rates of rat and stoat were high through the following spring and summer, tracking at 65% and at 47%, respectively, in November 2006, and at 52% and 44%, respectively, in February 2007.

Survival of brown kiwi chicks

A total of 207 brown kiwi chicks in Tongariro Forest were radio-tagged at <37 days old and monitored between 2 January 1996 and 30 June 2014. An additional 22 radio-tagged ONE juveniles were released at 123–182 days old and included in the analyses from their time of release.

Chick survival to 6 months old, by which time they weighed 986 ± 134 g (range = 700–1,223 g, *n* = 51) and were generally safe from stoat predation in the wild, varied significantly according to the stage of the 1080 cycle (Table 1). In the breeding season that coincided with an early spring aerial application of 1080 toxin, the mean survival rate

Table 1. Kaplan-Meier estimates of the survival of North Island brown kiwi (*Apteryx mantelli*) chicks to 6 months old in Tongariro Forest in relation to the stage of the 5-year cycle of aerial 1080 operations. Year 1 refers to the breeding season immediately after each September 1080 operation. Data from Years 4 and 5 have been pooled.

Time since 1080 operation	Chick survival to 6 months old	95% confidence interval	Years with chicks at risk	Number of chicks monitored
Year 1	0.500	0.366–0.620	1996, 2001, 2006, 2011	62
Year 2	0.287	0.166–0.420	1997, 2002, 2007, 2012	58
Year 3	0.171	0.062–0.326	2008	30
Year 4+	0.148	0.064–0.266	1999, 2000, 2004, 2005, 2009, 2010	80

Table 2. Life history parameters of North Island brown kiwi (*Apteryx mantelli*) in Tongariro Forest through the 5-year 1080 cycle. Year 1 refers to the breeding season immediately after each September 1080 operation. Data from Years 4 and 5 have been pooled. The Leslie Matrix λ and resultant percentage annual population growth were calculated in PopTools by entering the appropriate values into 4 separate 5x5 Leslie matrices for each year class of the 1080 cycle. The final row was derived by entering the averaged adult survival figure of 0.9179 into each year class matrix rather than the observed adult survival for that year class.

Parameter	Year 1	Year 2	Year 3	Year 4+
Adult years	86.4	93.7	101.1	162.0
Adult deaths	1	3	11	21
No. confirmed killed by ferret	0	1	5	14
Ferrect kills/100 bird-years	0.00	1.07	4.94	8.64
Adult survival	0.9884	0.9680	0.8912	0.8704
Chicks per adult	0.6158	0.6158	0.6158	0.6158
Chick survival to 6 months	0.5004	0.2868	0.1710	0.1482
Survival 6 months – 1 year	0.9022	0.9545	0.7456	0.8354
Survival 0-1 year	0.4497	0.2738	0.1275	0.1238
Survival 1-2 years	0.8910	0.6461	0.9375	0.7777
Survival 2-3 years	0.8586	0.8081	0.8615	1.0000
Survival 3-4 years	1.0000	0.8750	1.0000	0.9600
Total subadults monitored	71	85	53	116
Leslie matrix, λ	1.1224	1.0317	0.9645	0.9425
Annual population growth, r (%)	**11.5**	**3.1**	**-3.6**	**-5.9**
r % at a constant adult survival rate across years (0.9179)	7.4	-0.4	-1.5	-2.1

of chicks to 6 months old was close to 50%, but this dropped to 29% the following year (Mantel-Haenszel test, $X^2 = 4.34$, $P = 0.037$), and then halved to *c.* 15% in the 3 remaining years in the treatment cycle (Mantel-Haenszel test, $X^2 = 5.04$, $P = 0.025$), before significantly increasing in the breeding season of the next 1080 operation (Mantel-Haenszel test, $X^2 = 19.85$, $P < 0.001$).

There was also some variation in the survival rate following each 1080 operation. For example, chick survival was 37% in the breeding season of the 2001 operation ($n = 15$), 69% after the 2006 operation ($n = 21$) and 44% after the 2011 operation ($n = 24$).

In all years, predation was the main cause of death for kiwi chicks. Based on evidence at the scene, necropsies or DNA tests of predator saliva, the cause of death could be narrowed down for 99 (82%) of the 121 chicks found dead – the remaining 22 chicks were often too decayed or scavenged to make a determination. Of the 99 chicks that died of known causes, 82 (82%) appeared to have been killed by cat or mustelid, including stoat (at least 42). Of the 18 chicks that died from causes other than predation, 10 (10%) died by misadventure (drowning, falling in holes, or being impaled on sharp sticks), 6 (6%) died as a result of hatching difficulties or being malformed, one died of hypothermia, and one injured its leg so badly in a fall that it had to be taken for successful veterinary treatment (but was considered to have died for the purposes of this analysis).

Survival of subadult and adult brown kiwi

Direct effect of 1080 on kiwi

None of the 85 radio-tagged adults and 57 radio-tagged subadults that were exposed to aerially-sown 1080 were accidentally killed by 1080 poison over the 4 different operations. The only death that was recorded in the 2 months after these operations was a subadult that died from transmitter entanglement in vegetation 52 days after the poison drop.

Table 3. Predicted population growth of North Island brown kiwi (*Apteryx mantelli)* in Tongariro Forest at different 1080 operation intervals, based on observed adult survival data (Scenario 1) and averaged adult survival data (Scenario 2).

Frequency of 1080 operation	Scenario 1 population growth rate	Scenario 2 population growth rate
1-yearly	11.5	7.4
2-yearly	7.3	3.4
3-yearly	3.5	1.8
4-yearly	1.1	0.8
5-yearly	-0.4	0.2
6-yearly	-1.3	-0.2
7-yearly	-2.0	-0.4
No treatments	-5.9	-2.1

Subadults

Of the 163 subadults that were radio-tagged in Tongariro Forest between 1996 and 2014, 47 died. The cause of death could not be determined for 20 of these birds, but 15 of the remaining 27 birds were killed by predators: 5 by ferret, 2 by stoat, 3 by either stoat or ferret, 3 by pig, 1 by a dog and 1 by an unidentified predator. In addition, 3 subadults drowned, 2 were hit by vehicles, 2 had entangled transmitters, and 1 each died of disease, bill deformity, hypothermia, burrow collapse, and by falling into a hole.

Based on radio-tracking data from these 163 individuals over 167 tracking sessions (some individuals were lost from the sample and then later recaptured), the overall Kaplan-Meier estimate of survival from 6 months old through to adulthood at 4 years old was 59%. The overall chances of survival generally increased as the subadults grew older, but small sample sizes and chance events meant that patterns within cohorts varied considerably (Table 2). Subadult survival approximated that of adults after reaching *c.* 2 years old.

Adults

Over the 22 calendar years of study from 1992 to 2014, 102 adults were followed in Tongariro Forest during 113 radio-tracking periods, equating to 439 bird-years; 42 of these adults had graduated as radio-tagged subadults. During this time, 36 radio-tagged adults died, giving a mean life expectancy (L) of 12.2 years and a mean annual survival rate (s = [L-1]/L) of 91.8%.

The probability of an adult surviving to the next year varied considerably during the 5 years between 1080 operations, ranging from 98.8% survival in the year immediately after the 1080 operation to 87.1% survival averaged over the fourth and fifth years (Table 2). The main driver of this annual variation was the episodic impact of ferret, especially in Years 3 to 5 of the 1080 cycle between the 2006 and 2011 operations.

Up to June 2008, ferret had not been blamed for any deaths of adult kiwi in Tongariro Forest over 252 bird-years of radio-tracking. However, ferret were believed to have killed at least 20 adult kiwi (56% of all deaths and 74% of deaths where a cause was determined) between June 2008 and April 2014. These deaths occurred in 3 main episodes: 4 deaths between 8 February and 5 March 2009, 6 deaths between 23 December 2009 and 20 February 2010, and 3 deaths between 19 July and 23 September 2010, with sporadic deaths in between and through to 32 days before the 1080 operation in September 2011. Traps were set for ferret during the first pulse of deaths and this killing ceased after a female ferret was caught in March 2009. Trapping during subsequent mortality episodes resulted in the capture of another female ferret but the killing continued after her death. The only adult death that was ascribed to a ferret after September 2011 occurred in April 2014, which was around the same time as 2 subadults were identified as having been killed by a ferret. These kiwi deaths were 1.3 to 6.8 km into the forest from the nearest farmland. The average distance between successive kiwi that were killed during the 3 mortality episodes was 1.6 km, with a range of 0.5–4.9 km; 2 kills that happened on the same date were 0.51 km apart, while 8 days separated kills that were 4.9 km apart.

In addition to these deaths, 9 adults (25%) died of unknown causes, 2 (6%) were killed by dog, 2 (6%) apparently drowned, and 1 (3%) each died from a burrow collapse, disease, and old age.

Population models

During this study, 56 radio-tagged males were followed for a grand total of 297 breeding seasons (range = 1–18 per individual). Each year, an average of 77% of males bred, and they were associated with 1.65 ± 0.66 (range = 1–4) nests/year and 2.67 ± 1.22 (range = 1–6) eggs/year. In the wild, 60.1% of 164 eggs hatched giving an estimated chick productivity of 0.616 per adult, assuming an equal sex ratio in the adult population and accounting for 23% of adults not breeding.

In the models, we assumed that productivity was constant over time and not affected by the stage of the 1080 cycle. In the basic model, we used the observed survival of chicks through to adulthood at 4 years old from each cohort in the cycle, and the observed adult survival for each year of the 1080 cycle (Table 2). There was very strong population growth of 11.5% in the year following the aerial 1080 operation, good growth of 3.1% in the second year, but a population decline of 3.6% in the third year, and an average decline of 5.9% in the pooled fourth and fifth years. In an alternative model, in which annual adult survival was held constant at 0.9179 (36 deaths in 438.7 bird-years) based on the assumption that the pulsed impact of ferret may have happened by chance in years late in the 1080 cycle, there was strong growth of 7.4% in the year following the aerial 1080 application, but progressively lower growth in subsequent years, reaching an average 2.1% loss in the fourth and fifth years, which was assumed to represent the population growth rate in the absence of 1080 (Table 2).

Frequency of 1080 operations

Modelling showed that there was a progressive decline in the population growth rate as the interval

Table 4. Kaplan-Meier estimates of the survival of New Zealand fantail (*Rhipidura fuliginosa*) nests to fledging at 30 days in Tongariro Forest in relation to the stage of the 5-year cycle of aerial 1080 operations. Year 1 refers to the breeding season immediately after each September 1080 operation. Data from Years 4 and 5 have been pooled.

	Nest survival to 30 days old	95% confidence interval	Years	Number of nests
Year 1	0.252	0.131–0.393	2006, 2011	45
Year 2	0.300	0.207–0.398	2002, 2007, 2012	93
Year 3	0.124	0.062–0.208	2003, 2008	70
Year 4 +	0.093	0.045–0.161	2004, 2009, 2010	85

between 1080 operations increased, regardless of whether adult survival was held constant (Table 3). However, even infrequent 1080 operations helped to reduce the decline of kiwi populations by allowing a flush of recruitment in the 2 breeding seasons after sowing.

The 5-year return time that occurred during this study held the population approximately constant under both adult survival scenarios. Three-yearly operations, which are being used in the Kia Wharite Project in and around Whanganui National Park by the Department of Conservation and Horizons (Manawatu-Whanganui) Regional Council, and which have been implemented in Tongariro Forest since 2014 are projected to result in growth rates of 3.5% per year if adult mortality varies through the cycle as observed in our study, or by 1.8% per year if adult mortality is independent of the stage of the 1080 cycle.

The models predicted that if 1080 had never been used in Tongariro Forest, the kiwi population would have declined by 2% per year if periodic ferret attacks occur randomly, or by 6% per year if ferret attacks would have continued unabated in the absence of periodic 1080 operations.

Nesting success of fantail

We followed a total of 293 nesting attempts of fantail in Tongariro Forest during 10 of the 11 breeding seasons between 2002 and 2012. Although an additional 26 nests were followed in 2005 (the fifth year of the 1080 cycle), the raw data were lost due to a computer malfunction, and so only summarised data were available for that year.

The nesting success of fantail in Tongariro Forest was highly variable between years during the 11-year study and was significantly related to the time since aerial application of 1080 (Table 4). Kaplan-Meier analysis showed that nest survival to 30 days (fledging) was similar between the year of treatment (25.2%) and the following year (30.0%) (Mantel-Haenzsel test, $X^2 = 0.13$, $P = 0.72$). However, survival then dropped significantly in the third year of the cycle to 12.4% (Mantel-Haenzsel test, Year 2 vs Year 3, $X^2 = 5.7$, $P = 0.017$) and further still in the fourth and fifth years combined to 9.3% (Mantel-Haenzsel test, Year 3 vs Year 4+, $X^2 = 1.5$, $P = 0.22$). Thus, there was a very pronounced difference in nest survival between the first 2 years (29.2%) and the last 3 years (10.9%) of the cycle (Mantel-Haenzsel test, $X^2 = 15.5$, $P < 0.0001$).

In 2005 (fifth year of the 1080 cycle, when data were lost), we know that only 3 (12%) of 26 nests produced fledglings. Therefore, the Kaplan-Meier estimate of nest survival to fledging was unlikely to have been much different from the 9.3% survival recorded over the other 3 years that were monitored during the fourth or fifth year of the 1080 cycle.

Comparison between treatment and non-treatment sites

In 2006, nest survival to fledging at 30 days was significantly higher in Tongariro Forest, where aerial 1080 was applied (23.5%, $n = 31$), than in the nearby, untreated OPC and Rotoaira Forests (6.8%, $n = 19$) (Mantel-Haenszel test, $X^2 = 4.75$, $P = 0.029$).

Furthermore, nesting success in OPC and Rotoaira Forests was significantly higher in 2007, following the application of aerial 1080 (57.1%, $n = 9$), than in the 2006 season (6.8%) (Mantel-Haenszel $X^2 = 6.28$, $P = 0.012$).

Causes of fantail nest failure

Many fantail nests were abandoned for no obvious reason, but camera footage related some of these losses to prolonged spells of cold weather, often accompanied by snow or hail – the adults left these nests unattended for increasingly long periods, presumably prioritising their own survival over that of their eggs or chicks. Some nests were also lost in strong winds, when the nest tipped over or when the nest, or branch holding the nest, was hit by windfall debris.

In some nests where eggs or chicks had been depredated, there was clear evidence of rat predation, i.e. fragments of egg shell remaining in or below the nest, jagged or inward-folded edges of shell, chewed pin feathers left behind, sometimes with rat hairs adhering to them, or rat droppings in the nest. In most cases of losses to predators, however, there was no obvious evidence at or below the nest, and so these were referred to as "clean takes". "Clean takes" mainly occurred after October in each season and also increased during the course of the study from 3 (30%) of 10 predation events in 2002/03 to 15 (75%) of 20 predation events in 2012/13 where the nest could be examined. Camera footage at 7 nests showed that all "clean takes" followed long-tailed cuckoo (*Eudynamys taitensis*) preying on eggs or large chicks one by one, or even taking all small nestlings in a single short visit. Long-tailed cuckoo return to Tongariro Forest from their Pacific wintering quarters in mid-October, coinciding with the observed increase in "clean takes".

DISCUSSION

1080 has been used for many decades to control possum and rat in New Zealand forests; however, this is the first published longitudinal study of the effects of a series of 1080 operations on non-target protected wildlife. As expected from other research (e.g. Murphy *et al*. 1999), populations of both rodents and stoat crashed following exposure to 1080 due to primary or secondary poisoning. Mouse numbers quickly recovered and soon surpassed their pre-poisoning levels, capitalising on the temporary reduction in rat and stoat numbers. By contrast, it took rat 14–21 months to recover to pre-poisoning levels, with some suggestion that rat numbers were suppressed for longer following operations with higher baiting densities. The numbers of stoat detected at the study site increased slowly throughout the 5-year operation cycle, with a discernible peak each summer; however, they had still not reached a plateau before the next 1080 operation. Although we did not monitor ferret numbers, the timing of their predation on kiwi was clearly weighted towards the final 3 years of the 5-year 1080 cycle. Ferret usually inhabit open country, but penetrated far into Tongariro Forest, perhaps being attracted to pockets of rabbit (*Oryctolagus cuniculus*) seen on tracks and clearings left by earlier logging operations.

Because kiwi chicks are particularly vulnerable to predation by stoat during their first 6 months of life (McLennan *et al*. 1996; Basse *et al*. 1999; Robertson *et al*. 2011; Robertson & de Monchy 2012), the temporary absence or low densities of stoat following the aerial 1080 operations provided a window for kiwi chicks to survive well in Tongariro Forest. The very good (50%) survival in the first year after each 1080 operation was not unexpected and was similar to the 56% and 62% survival rates recorded in 2 forest patches in Northland following a bait station 1080 operation that was conducted in conjunction with a long-term trapping programme (Robertson *et al*. 2016). The good (29%) survival in the second breeding season after the use of 1080 and the slow recovery of the stoat population in Tongariro Forest was unexpected given the known high dispersal ability of juvenile stoat – for example, a juvenile female in Fiordland travelled 65 km in a straight line within 4 weeks (Murphy & Dowding 1995). A stoat trapping programme that was established in 2007 to protect blue duck (whio) along the Whanganui River, about 6 km northwest of the centre of the kiwi study area, and in 2008 along the Mangatepopo Stream, 5 km to the east, may have slowed re-invasion by stoat after the 2011 operation; however, their recovery was equally slow after both the 2001 and 2006 operations when no stoat control occurred along nearby rivers. In the 3 remaining years of the 1080 cycle, chick survival to 6 months old (15–17%) was less than the 22.7% survival required to maintain a stable population.

As is usually found for matrix models of kiwi demographic data (e.g. Robertson *et al*. 2011; Robertson & de Monchy 2012; Tansell *et al*. 2016), annual adult survival was consistently the key factor that affected the finite growth rate of the population. Consequently, the 19 adult deaths that were caused by ferret (or perhaps 1 individual ferret) between May 2009 and August 2011 had a significant impact on the growth rate of this population. In their analysis of the first 5 years of the kiwi sanctuaries programme established in 2000, Robertson & de Monchy (2012) reported that the mean life expectancy of adults in Tongariro Forest was 30.7 years based on annual survival of 96.7% from 276 bird-years of radio-tracking data. However, the recent ferret kills have reduced the mean adult life expectancy to just 12.2 years based on an annual survival rate of 91.8% from 439 bird-years of tracking, and even this could be optimistic given that it is likely that a ferret that was responsible for killing adult kiwi was trapped. If adult survival in the last 2 years of the 1080 cycle (87.0%) was typical of an unmanaged situation, the life expectancy of adults would be a mere 7.7 years.

If adult survival of 96.7% (from Robertson & de Monchy 2012) is substituted in the Leslie matrix generated by the data shown in Table 2, the population growth rate would be close to 2% in the last years of the 1080 cycle, which are equivalent to an unmanaged state. However, this seems highly unlikely given that other unmanaged mainland populations of kiwi are declining by 2–3% per year (Holzapfel *et al*. 2008) and the long-standing Tongariro population includes only several hundred birds that are sparsely distributed in the forest, rather than representing a flourishing newly-established population. On the other hand, when adult survival of 87.0% is substituted in the model, the population decline is 5.9% per annum, or halving every decade, which is similar to the 5.8% per annum decline estimated by McLennan *et al*. (1996) from a meta-analysis of a small set of radio-tracking data from around the North Island. These survival estimates appear far too pessimistic, however, and are likely unduly influenced by chance catastrophic events in small datasets, because it is very unlikely that the Tongariro population was 4–5 times larger at the beginning of our 22-year programme than at the end. The average long-term (22-year) adult survival value of 91.8% produced a predicted annual population decline in the last 2 years of the cycle of 2.1%, which lies between the estimated declines of 2.5% for unmanaged populations in Northland (Robertson *et al*. 2011) and 1.6% for unmanaged southern brown kiwi (tokoeka; *Apteryx australis*) in Fiordland (Tansell *et al*. 2016).

The finite rate of growth of the kiwi population in Tongariro Forest was >1 (i.e. increasing) in the first 2 years of the cycle, but <1 (i.e. declining) from the third year onwards. Population modelling showed that the 5-year 1080 cycle used during this study could approximately maintain the population, with a small decline predicted when the observed ferret-driven variation in adult survival through the 1080 cycle was included and a small increase predicted if ferret predation was considered to be randomly timed and so adult survival was independent of the stage of the 1080 cycle. Although annual or biennial 1080 operations were predicted to provide a huge benefit to kiwi due to the strong finite rate of growth in the 2 years after 1080 is used, ingestion of sub-lethal doses of 1080 baits can lead to bait shyness among surviving possum for at least 30 months (O'Connor & Matthews 1999). Consequently, a cycle of <3 years is not likely to be very effective for controlling possum – although the use of pre-feed to minimise the number of possum eating sub-lethal doses during 1080 operations (Moss *et al*. 1998; Ross *et al*. 2000), and a switch of lure flavour (e.g. from cinnamon to orange) and the bait base (e.g. from cereal to carrot) can improve bait acceptance among bait-shy possum when aerial 1080 operations are next done at the same site (Morgan *et al*. 1996; O'Connor & Matthews 1999). By contrast, the shorter lifespan of rat means that bait shyness among survivors is less likely to be a problem if 1080 operations are run at least 3-yearly because any surviving bait-shy rats would make up a very small portion of the population 3 years later.

In 2014, the frequency of aerial 1080 operations in Tongariro Forest was changed from 5-yearly to 3-yearly to align with that being used in the super-landscape-scale (180,000 ha) Kia Wharite project in and around Whanganui National Park. Our data suggest that this increased frequency of 1080 application will allow the kiwi population in Tongariro Forest to recover by an average of 3.6% per annum if the rate of adult mortality varies through the 1080 cycle, or by an average of 1.8% if the timing of adult mortality is random. The improved prognosis from this shorter cycle is largely driven by poor breeding seasons in the 1080 cycle being excluded, and the expected gains are close to the Kiwi Recovery Plan's goal of achieving at least 2% increase per annum for each kiwi species (Germano *et al*. 2018). Although switching to *ex-situ* techniques such as ONE may yield higher levels of initial population growth, there are capacity issues for hatching eggs and raising chicks at secure sites until they are safe from stoat at *c.* 6 months old, difficulties in increasing the scale of *ex-situ* management to sustain that population growth, a lack of suitably large managed sites for the release of such progeny, risks of a loss of genetic diversity if only a small proportion of the population is managed by these tools and, perhaps most importantly, *ex-situ* techniques are very kiwi-focussed rather than ecosystem-focussed. Our research has shown that fantail also received a significant benefit in the first 2 years of the 1080 cycle, whereas they would receive no benefit if kiwi were managed *ex-situ*. Ironically, the increased rate of "clean takes" of fantail nest contents in the latter years of the study, which was associated with long-tailed cuckoo predation, may have resulted from long-tailed cuckoo enjoying increased breeding success as a result of their host, the whitehead (*Mohoua albicilla*), also having better nesting success in years when rat and stoat were scarce following each 1080 operation. However, we also note that video footage of predation at nests of the North Island robin (*Petroica longipes*) and tomtit (*P. macrocephala*) showed that "clean takes" of eggs or chicks could be attributed to morepork (*Ninox novaeseelandiae*) and ship rat (Brown *et al*. 1998), and so some of the "clean takes" that we did not film, especially those early in the season before long-tailed cuckoos returned, could have been these predators.

The aerial application of 1080 remains controversial; however, from a kiwi perspective, it appears to pose a minimal risk of accidental poisoning by ingestion of baits or secondary poisoning as a result of eating invertebrates that had fed on baits. Moreover, these operations provide a significant benefit to kiwi by creating a window where all resident stoat, and likely all resident ferret, are killed and their numbers are suppressed long enough for the kiwi to have survival and recruitment levels that are well above the threshold required to maintain their population. Likewise, fantail benefitted from the effective removal of rat from the forest and their continued low numbers through 2 breeding seasons after a spring 1080 operation. The 2-year window of opportunity resulting from an unexpectedly slow return of stoat into Tongariro Forest, the apparent 3-year window of opportunity where there is little ferret predation and the shorter, 14–21 month, window of opportunity for fantail while rat numbers recover is likely to provide similar benefits to a wider range of forest passerines and other native wildlife in this forest; however, this may not be typical of all forest situations in New Zealand. Therefore, we urge that similar long-term studies of kiwi chick survival and forest passerine nesting success are conducted in other forest ecosystems, especially in South Island beech forests, following repeated landscape-scale aerial 1080 operations.

ACKNOWLEDGEMENTS

The kiwi research in Tongariro Forest was started by Jonathan Miles and continued by Cam Speedy. During this study, numerous field assistants have helped to catch adult kiwi, radio-track them, find nests, conduct Operation Nest Egg, or radio-track chicks and subadults following current Kiwi Best Practice, as required under the Animal Welfare Act 1999. We especially thank Ben Barr, Alison Beath, Mike Brown, Lance Dew, Antonia Dix, Mike Fawcett, Dean Flavell, Cindy Jenkins, Sarah Kivi, Ross Martin, Jonathan Miles, Renee Potae, Murray Potter, Steve Sawyer, Mithuna Sothieson, Malcolm Swanney, Jo Tilson, Robert White and Robyn Whyman. Emma Bean and Claire Travers led a team at Kiwi Encounter in Rotorua that successfully hatched hundreds of eggs from Tongariro Forest and raised them to return weight, or transferred them to David and Juiliette Wallace's private predator-proof "Warrenheip Sanctuary" for growing-on.

The fantail research was initiated by Ian Flux and carried out by numerous field assistants, including Mark Clancy, Antonia Dix, Sarah Kivi, Kaitlin Morrison, Alison Perfect, Tim Raemaekers, Mithuna Sothieson, Rebecca Stirnemann, Kristina Thompson, Tertia Thurley, and Mel Whiting.

Ngati Hikairo, as kaitiaki for Tongariro Forest, supported our kiwi and fantail work in many ways. Deb Atkinson, Alison Beath, Murray Bott, Craig Gillies, Paul Green, Bhrent Guy, Amanda Haigh, Rob Hood, Harry Keys, Pete Morton, John Polstra, Nick Poutu, Jess Scrimgeour, Bubs Smith, Cam Speedy, and Project Tongariro provided invaluable operational support and/or advice over the years.

James Griffiths carried out the GAM models and supplied the small mammal index graphs. Geraldine Moore drew the map. John Innes, Jess Scrimgeour, Amanda Todd, Craig Symes and two anonymous referees improved the manuscript.

LITERATURE CITED

Alterio, N. 2000. Controlling small mammal predators using sodium monofluoroacetate (1080) in bait stations along forestry roads in a New Zealand beech forest. *New Zealand Journal of Ecology 24*: 3–9.

Basse, B.; McLennan, J.A.; Wake, G.C. 1999. Analysis of the impact of stoats, *Mustela erminea*, on northern brown kiwi, *Apteryx mantelli*, in New Zealand. *Wildlife Research 26*: 227–237.

Brown, K.P.; Moller, H.; Innes, J.; Alterio, N. 1996. Calibration of tunnel tracking rates to estimate relative abundance of ship rats (*Rattus rattus*) and mice (*Mus musculus*) in a New Zealand forest. *New Zealand Journal of Ecology 20*: 271–275.

Brown, K.P.; Moller, H.; Innes, J.; Jansen, P. 1998. Identifying predators at nests of small birds in a New Zealand forest. *Ibis 140*: 274–279.

Byrom, A.E.; Innes, J.; Binny, R.N. 2016. A review of biodiversity outcomes from possum-focused pest control in New Zealand. *Wildlife Research 43*: 228–253.

Colbourne, R.; Bassett, S.; Billing, T.; McCormick, H.; McLennan, J.; Nelson, A.; Robertson, H. 2005. The development of Operation Nest Egg as a tool in the conservation management of kiwi. *Science for Conservation 259*. Wellington, Department of Conservation.

Eason, C.; Miller, A.; Ogilvie, S.; Fairweather, A. 2011. An updated review of the toxicology and ecotoxicology of sodium fluoroacetate (1080) in relation to its use as a pest control tool in New Zealand. *New Zealand Journal of Ecology 35*: 1–20.

Germano, J.; Barlow, S.; Castro, I.; Colbourne, R.; Cox, M.; Gillies, C.; Hackwell, K.; Harawira, J.; Impey, M.; Reuben, A.; Robertson, H.; Scrimgeour, J.; Sporle, W.; Yong, S. 2018. Kiwi Recovery Plan 2018–2028. *Threatened Species Recovery Plan* 64. Wellington, Department of Conservation.

Gillies, C.A.; Pierce, R.J. 1999. Secondary poisoning of introduced mammalian carnivores during possum and rodent control operations at Trounson Kauri Park, Northland. *New Zealand Journal of Ecology 23*: 183–192.

Greene, T.C.; Dilks, P.J.; Westbrooke, I.M.; Pryde, M.A. 2013. Monitoring selected forest bird species through aerial application of 1080 baits, Waitutu, New Zealand. *New Zealand Journal of Ecology 37*: 41–50.

Holzapfel, S.A.; Robertson, H.A.; McLennan, J.A.; Sporle, W.; Hackwell, K.; Impey, M. 2008. Kiwi (*Apteryx* spp.) recovery plan 2008–2018. *Threatened Species Recovery Plan 60*. Wellington, Department of Conservation.

Horikoshi, C.; Battley, P.F.; Minot, E.O. 2018. Annual survival estimates and risk of fluoroacetate (1080) secondary poisoning for New Zealand falcons (*Falco novaeseelandiae*) in a managed exotic forest. *Wildlife Research 45*: 155–163.

Innes, J.; Warburton, B.; Williams, D.; Speed, H.;

Bradfield, P. 1995. Large-scale poisoning of ship rats (*Rattus rattus*) in indigenous forests of the North Island, New Zealand. *New Zealand Journal of Ecology 19*: 5–17.

King, C.M.; Edgar, R.L. 1977. Techniques for trapping and tracking stoats (*Mustela erminea*): a review and a new system. *New Zealand Journal of Zoology 4*: 193–212.

Livingstone, P.G.; Hancox, N.; Nugent, G.; de Lisle, G.W. 2015. Toward eradication: the effect of *Mycobacterium bovis* infection in wildlife and the evolution and future direction of bovine tuberculosis management in New Zealand. *New Zealand Veterinary Journal 63 (Supplement)*: 4–18.

Mayfield, H.F. 1961. Nesting success calculated from exposure. *Wilson Bulletin 73*: 255–261.

Mayfield, H.F. 1975. Suggestions for calculating nest success. *Wilson Bulletin 87*: 456–466.

McLean, I.G.; Jenkins, P.F. 1980. Breeding and development of the New Zealand fantail *Rhipidura fuliginosa*. *Notornis 27*: 105–113.

McLennan, J.A.; Dew, L.; Miles, J.; Gillingham, N.; Waiwai, R. 2004. Size matters: predation risk and juvenile growth in North Island brown kiwi (*Apteryx mantelli*). *New Zealand Journal of Ecology 28*: 241–250.

McLennan, J.A.; Potter, M.A.; Robertson, H.A.; Wake, G.C.; Colbourne, R.; Dew, L.; McCann, A.J.; Miles, J.; Miller, P.J.; Reid, J. 1996. Role of predation in the decline of kiwi *Apteryx* spp. in New Zealand. *New Zealand Journal of Ecology 20*: 27–35.

Miles, J.; McLennan, J. 1998. A new technique for radio-tagging immature kiwi (*Apteryx* spp.) *Notornis 45*: 44–48.

Miller, H.W.; Johnson, D.H. 1978. Interpreting results of nesting studies. *Journal of Wildlife Management 42*: 471–476.

Moors, P.J. 1983. Predation by mustelids and rodents on the eggs and chicks of native and introduced birds in Kowhai Bush, New Zealand. *Ibis 125*: 137–154.

Morgan, D.R.; Morriss, G.; Hickling, G.J. 1996. Induced bait-shyness in captive brushtail possums and implications for management. *Wildlife Research 23*: 207–211.

Morriss, G.A.; Nugent, G.; Whitford, J. 2016. Dead birds found after aerial poisoning operations targeting small mammal pests in New Zealand 2003–14. *New Zealand Journal of Ecology 40*: 361–370.

Moss, Z.N.; O'Connor, C.E.; Hickling, G.J. 1998. Implications of prefeeding for the development of bait aversion in brushtail possums (*Trichosurus vulpecula*). *Wildlife Research 25*: 133–138.

Mudge, D. 2002. Silence of the fantails. *New Zealand Geographic 55*: 71–85.

Murphy, E.C.; Dowding, J.E. 1995. Ecology of the stoat in *Nothofagus* forest: home range, habitat use and diet at different stages of the beech mast cycle. *New Zealand Journal of Ecology 19*: 97–109.

Murphy, E.C.; Robbins, L.; Young, J.B.; Dowding, J.E. 1999. Secondary poisoning of stoats after an aerial 1080 poison operation in Pureora Forest, New Zealand. *New Zealand Journal of Ecology 23*: 175–182.

O'Connor, C.E.; Matthews, L.R. 1999. 1080-induced bait aversion in wild possums: influence of bait characteristics and prevalence. *Wildlife Research 26*: 375–381.

Pollock, K.H.; Winterstein, S.R.; Bunck, C.M.; Curtis, P.D. 1989. Survival analysis in telemetry studies: the staggered entry design. *Journal of Wildlife Management 53*: 7–15.

Powlesland, M.H. 1982. A breeding study of the South Island fantail (*Rhipidura fuliginosa fuliginosa*). *Notornis 29*: 181–195.

Powlesland, R.G.; Knegtmans, J.W.; Marshall, I.S.J. 1999. Costs and benefits of aerial 1080 possum control operations using carrot baits to North Island robins (*Petroica australis longipes*), Pureora Forest Park. *New Zealand Journal of Ecology 23*: 149–159.

Powlesland, R.G.; Knegtmans, J.W.; Styche, A. 2000. Mortality of North Island tomtits (*Petroica macrocephala toitoi*) caused by aerial 1080 possum control operations, 1997–98, Pureora Forest Park. *New Zealand Journal of Ecology 24*: 161–168.

Powlesland, R.G.; Wills, D.E.; August, A.C.L.; August, C.K. 2003. Effects of a 1080 operation on kaka and kereru survival and nesting success, Whirinaki Forest Park. *New Zealand Journal of Ecology 27*: 125–137.

Robertson, H.A. 2003. Research and monitoring plan for the kiwi sanctuaries. *Science for Conservation 241*. Wellington, Department of Conservation.

Robertson, H.A.; Baird, K.; Dowding, J.E.; Elliott, G.P.; Hitchmough, R.A.; Miskelly, C.M.; McArthur, N.; O'Donnell, C.F.J.; Sagar, P.M.; Scofield, R.P.; Taylor, G.A. 2017. Conservation status of New Zealand birds, 2016. *New Zealand Threat Classification Series 19*. Wellington, Department of Conservation.

Robertson, H.A.; Colbourne, R.C.; Graham, P.J.; Miller, P.J.; Pierce, R.J. 2011. Experimental management of brown kiwi (*Apteryx mantelli*) in central Northland, New Zealand. *Bird Conservation International 21*: 207–221.

Robertson, H.A.; Craig, E.; Gardiner, C.; Graham, P.J. 2016. Short pulse of 1080 improves the survival of brown kiwi chicks in an area subjected to long-term stoat trapping. *New Zealand Journal of Zoology 43*: 351–362.

Robertson, H.A.; de Monchy, P.J.M. 2012. Varied success from the landscape-scale management of kiwi *Apteryx* spp. in five sanctuaries in New

Zealand. *Bird Conservation International 22*: 429–444.

Robertson, H.A.; Westbrooke, I.M. 2005. A practical guide to the management and analysis of survivorship data from radio-tracking studies. *Department of Conservation Technical Series 31*. Wellington, Department of Conservation.

Ross, J.G.; Hickling, G.J.; Morgan, D.R.; Eason, C.T. 2000. The role of non-toxic prefeed and postfeed in the development and maintenance of 1080 bait shyness in captive brushtail possums. *Wildlife Research 27*: 69–74.

Spurr, E.B. Powlesland, R.G. 1997. Impacts of aerial application of 1080 on non-target native fauna: review and priorities for research. *Science for Conservation 62*. Wellington, Department of Conservation.

Tansell, J.; Edmonds, H.K.; Robertson, H.A. 2016. Landscape-scale trapping of stoats (*Mustela erminea*) benefits tokoeka (*Apteryx australis*) in the Murchison Mountains, Fiordland, New Zealand. *Notornis 63*: 1–8.

Veltman, C.J.; Pinder, D.N. 2001. Brushtail possum mortality and ambient temperatures following aerial poisoning using 1080. *Journal of Wildlife Management 65*: 476–481.

Veltman, C.J.; Westbrooke, I.M. 2011. Forest bird mortality and baiting practices in New Zealand 1080 operations from 1986 to 2009. *New Zealand Journal of Ecology 35*: 21–29.

Westbrooke, I.M.; Etheridge, N.D.; Powlesland, R.G. 2003. Comparing methods for assessing mortality impacts of an aerial 1080 pest control operation on tomtits (*Petroica macrocephala toitoi*) in Tongariro Forest. *New Zealand Journal of Ecology 27*: 115–123.

Wright, J. 2011. *Evaluating the use of 1080: predators, poisons and silent forest*. Wellington, Parliamentary Commissioner for the Environment.