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Experimental management of Brown Kiwi *Apteryx mantelli* in central Northland, New Zealand

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Summary

The population growth of Brown Kiwi *Apteryx mantelli* was measured under four different management regimes: unmanaged, predator trapping, predator poisoning, and Bank of New Zealand Operation Nest Egg™ (BNZONE) — the removal of eggs for artificial incubation and return of resultant subadults to the wild. Life table analysis revealed that high adult mortality (7.3% per annum), caused mainly by domestic dog *Canis familiaris* and Ferret *Mustela furo* predation was the critical factor affecting Brown Kiwi populations in central Northland. The 13.8-year life expectancy of adults was only one-third of what can be expected in the absence of these two predators. Predation of Brown Kiwi chicks and juveniles (< 1 kg) by Stoats *Mustela erminea* and, to a lesser extent, domestic cats *Felis catus*, was also important. Unmanaged populations declined at 2.5% per annum. Trapping pests in a 200 ha area was largely ineffective, with the population declining by 1.7% per annum. Poisoning pests allowed Brown Kiwi populations to increase at 3.3% per annum. BNZONE proved to be by far the most effective tool, resulting in a 12.5% annual population increase, mainly due to 83% chick survival to six months old, compared with 10% survival in unmanaged sites. There were no observable behavioural problems associated with chicks being reared *ex situ*, but BNZONE was the most expensive tool and benefited only the Brown Kiwi. This study has helped to develop a range of tools that are now being used to facilitate recovery of populations of all four threatened species of kiwi in New Zealand, and the experimental approach used has wider application in management of other threatened species.

Introduction

Kiwis are a family of flightless, mainly nocturnal, ratite birds endemic to New Zealand. They are unusual in having no external tail, minute wings and a well-developed sense of smell, with their nostrils being positioned near the tip of their long (100–150 mm) slightly down-curved bill (Heather and Robertson 2005). Four species (Brown Kiwi *Apteryx mantelli*, Rowi *A. rowi*, Tokoeka *A. australis* and Great Spotted Kiwi *A. haastii*) are classified as threatened (BirdLife International 2008, Miskelly *et al.* 2008) following huge reductions in both the range and numbers of birds on the mainland of New Zealand over the past 100 years (Heather and Robertson 2005). The other kiwi species, the Little Spotted Kiwi *A. owenii*, was widespread on the mainland of New Zealand, but is now confined to offshore islands and a fenced mainland sanctuary (Heather and Robertson 2005) and is regarded as 'Near Threatened' (BirdLife International 2008), or 'At Risk: Recovering' (Miskelly *et al.* 2008). Since 1991, there has been considerable governmental and public conservation effort to determine the distribution, numbers, genetics, ecology and threats to the five species of kiwi (e.g. Miller and Pierce 1995, McLennan *et al.* 1996, Robertson *et al.* 1999a,b, Burbidge *et al.* 2003, Pierce and Westbrooke, 2003, Robertson *et al.* 2005).

Before this study began in early 1994, little was known about the critical factors in the decline of kiwi, apart from the obvious loss of habitat during the conversion of huge areas of forest and scrub to pastoral farmland (Miller and Pierce 1995) and the occasional catastrophic attacks by dogs (Taborsky 1988, Pierce and Sporle 1997). A meta-analysis, incorporating some early data from this study, showed that the critical factor in the demise of kiwi on the mainland of New Zealand was predation by introduced mammals, especially by Stoats *Mustela erminea* killing kiwi chicks (McLennan *et al.* 1996).

Northland has long been regarded as a stronghold for Brown Kiwi, but there was a marked decline in both the numbers and range of the species between the 1970s and early 1990s (Miller and Pierce 1995). Although more than 13,000 ha of native forest and even more shrubland were lost during this period, mainly to make way for exotic forestry, kiwi had also disappeared from several large areas of intact native forest such as the Brynderwyn Hills and the Tangihua Range. Miller and Pierce (1995) postulated that ongoing periodic incidents of dogs killing kiwi, together with the recent spread of Brush-tailed Possums *Trichosurus vulpecula* and Ferrets *Mustela furo* into Northland from the south, had caused the dramatic reduction in Brown Kiwi populations and, particularly, the rapid contraction of their range in southern Northland. Ferrets are known to kill adult kiwi (McLennan *et al.* 1996, Pierce and Sporle 1997), and possums compete with kiwi for daytime dens in burrows or hollow logs (Morrin 1989), occasionally prey on kiwi eggs, and can kill adult kiwi (McLennan *et al.* 1996); however, the greatest threat they pose is indirect, from the many accidental deaths of kiwi caught in leg-hold traps or poisoned by cyanide baits set on the ground for the possum fur industry or for possum control (Pierce and Sporle 1997).

This study identified and experimentally managed the main threats to Brown Kiwi in an area of central Northland, just to the north of the area where Brown Kiwi had largely disappeared between the 1970s and 1992–93 (Miller and Pierce 1995). The initial focus was to determine the effects on kiwi of using ground-laid baits containing Compound 1080 (sodium monofluoroacetate), and brodifacoum (Talon® or Pestoff®) in bait stations nailed to tree trunks, as alternatives to trapping or using cyanide to control possums (Robertson *et al.* 1999a,b). The study was expanded to compare the effectiveness of poisoning pests with doing nothing, with trapping predators, and with the emerging conservation method of BNZONE, which is the collection of kiwi eggs or young chicks from the wild and the subsequent release back of subadults raised in captivity or on predator-free 'crèche' islands once they are large enough to avoid predation by Stoats and cats (Colbourne *et al.* 2005).

Methods

Study area

The study was carried out in four patches of remnant broadleaf-podocarp forest within 5 km of Rarewarewa (35°37′S, 174°08′E) in central Northland, New Zealand (Figure 1). They lie just to the north of the line marking the southern limit of Brown Kiwi distribution in Northland (Miller and Pierce 1995). The vegetation of the study sites was described by Robertson *et al.* (1999a). The patches were separated from one another by 1–3 km of farmland, but were closer than is ideal for the management in them to be completely independent of treatments in the neighbouring forest patches, but there were no other suitable sites nearby which had sufficient remaining populations of kiwi. Non-treatment data was available from the study sites before any management was undertaken, or from sites over 2 km from the nearest pest control. Predator trapping was done 7 km away from the non-treatment, and 4.5 km from the nearest poisoning effort.

Aponga Reserve (33 ha) on a 365 m volcanic cone, and an adjoining valley and spur of privately-owned forest (22 ha), known collectively as Rarewarewa (55 ha), was chosen for possum poisoning because it was fully fenced, and so farm stock were not at risk from the toxins. The site had been

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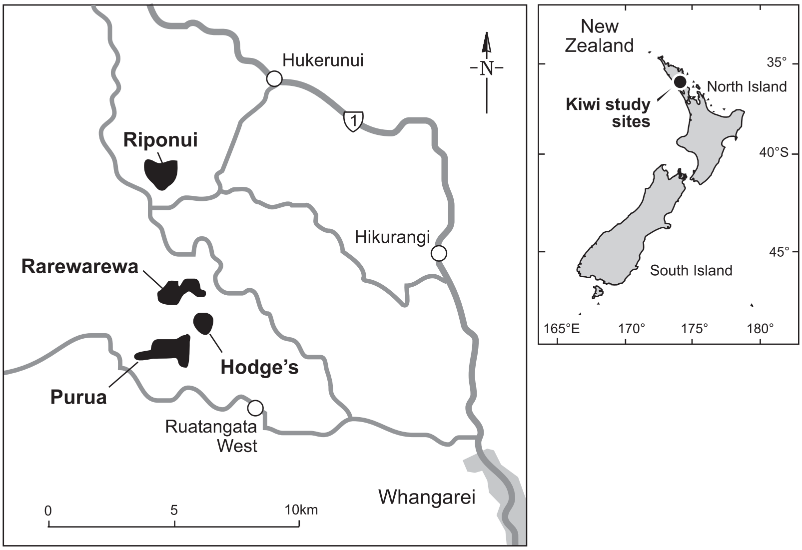

Figure 1. Map of study areas in central Northland, to the north-west of Whangarei.

modified by the pre-European construction of a *pa* (Maori fortress) on the peak, and the extraction of many emergent podocarps and Kauri *Agathis australis* in the early 1900s. The reserve and private land had been occasionally grazed by farm stock, but shortly after the study began these animals were removed from all but 8 ha of unfenced private land which had an open understorey and ground layer. A few kiwi lived in adjacent small (< 10 ha) plantations of young Radiata Pine *Pinus radiata*.

Riponui Reserve (45 ha) is on the southern side of a low ridge (*c.* 250 m asl) and is deeply incised by six roughly parallel streams running to the lower boundary (125 m asl). The vegetation is similar to that in Rarewarewa and has also suffered some extraction of timber trees and grazing by stock encroaching from nearby farmland. During this study, a neighbouring area of Totara *Podocarpus totara* and blackberry *Rubus* sp. that was used by several of the pairs was roller-crushed and then planted with Tasmanian Blackwood *Acacia melanoxylon*. Riponui was used for predator trapping in 1995/96 and 1996/97, and then possum poisoning from 1997/98 to 1999/00.

Hodge's Bush (35 ha) is a privately-owned forest in a broad valley with a similar canopy composition to the other forest patches, but was almost devoid of undergrowth because it was grazed by farm stock. An adjacent small (3 ha) patch of young Radiata Pine provided additional habitat for kiwi. This site was used for BNZONE throughout the study.

Purua Reserve (110 ha), the main non-treatment site, is a volcanic cone (387 m asl) with very similar topography and vegetation to Rarewarewa, except for being more heavily vegetated and hence damper.

Kiwi capture and monitoring

Specially trained Labrador dogs were used to find kiwi in their daytime dens. The birds were extracted by hand, measured and marked. All kiwi were permanently marked with a uniquely numbered leg band, a fish fingerling tag inserted in the patagium, or with a transponder injected subcutaneously above the ribcage. Because male Brown Kiwi do all the incubation, the male of each adult pair had a 20–25 g Sirtrack or Kiwitrack transmitter attached to its tibiotarsus with a hospital identification bracelet (Miles and McLennan 1998), so that all breeding attempts could be monitored at about monthly intervals. Resultant chicks were marked with wing-tags or transponders, and most had a 9 g Sirtrack transmitter attached to its tibiotarsus with a cut-down hospital identification bracelet (except for the first season of the study, when transmitters were glued to the chicks' backs). Chicks in the nest (up to about six weeks old) and juveniles were checked every 2–4 weeks to determine their location and fate. The transmitters were changed to more powerful 15 g Sirtrack transmitters at about 6–9 months old, once they had reached about 1,000 g in weight. After they had reached 1,500–1,600 g, they were fitted with an adult kiwi transmitter, and checked three-monthly to ensure that the leg attachment was not getting too tight.

Conservation management

Unmanaged

In 1994, no management of pests was carried out at any of the four forest patches while the sample of radio-tagged birds was established and techniques for studying nests and marking chicks were developed. Despite differences in topography and ground cover, chick survival was similarly poor in all bush patches. From 1995 to June 1999, Purua Reserve was our non-treatment site, and then Riponui Reserve became the non-treatment site from June 1999 to June 2001. Non-treatment data were supplemented with data collected from Hodge's Bush, where the only management between 1995 and late 1998 was BNZONE, leaving unharvested nests and chicks exposed to the full range of predators.

Predator trapping

Mustelids were caught in 40 'Mark 6 Fenn®' traps placed in wooden boxes with wire mesh ends and narrow entrances and baffles to reduce the chances of non-target species entering them. The bait was usually a fresh, white, hen's egg, but fresh and salted meats were also used from time to time in case resident Stoats disliked eggs. Traps were placed at about 200 m intervals around the perimeter of Riponui Reserve, on lines running along the parallel spurs within the reserve, and in the surrounding farmland and roadside verges, so that a total area of about 200 ha was protected with an average trap density of 1 per 5 ha, but 1 per 2 ha in the reserve where most of the kiwi lived. The precise sites were chosen by the trappers to maximise their catch. Ferrets and cats were also caught in cage-traps baited with fresh meat. Cats and possums were caught in Victor® soft-jaw traps mounted at the top of 1.5 m sloping boards, which were baited with meat or cinnamon-lured flour placed above the traps. Traps were set during weekdays, checked and, if necessary, re-baited daily; trapped animals were shot, in accordance with animal welfare regulations.

Pest poisoning

The initial knockdown of possums at Rarewarewa was done in May 1995 using 0.15% 1080 (sodium monofluoroacetate) poison in cereal or jam baits (Robertson *et al.* 1999a). Subsequent control, from October 1995, used brodifacoum (Talon 20P® or Pestoff®) or cholecalciferol (Campaign®) in cereal baits. These were placed in 78 Philproof® bait stations nailed to large trees so that their entrances were about 30 cm above the ground. The bait stations were about 150 m apart on tracks that followed the edge of the 47 ha of fenced forest and natural contours within it (Robertson *et al.* 1999b). About every two months, the bait stations were filled with 500–800 g of cereal baits. In the 8 ha unfenced portion of the block, possums were periodically poisoned with cyanide in raised Romak® bait stations.

In October 1997, bagged Feratox® cyanide baits were stapled to the trunks of trees at Riponui to achieve an initial knockdown of the possum population. More than 300 possums were killed, and their bodies were removed to discourage scavengers. Possums were then poisoned with brodifacoum (Pestoff) in 47 Philproof bait stations for 18 months, but after May 1999, Riponui became a non-treatment site. In November 1998, possums were controlled at Hodge's Bush with cyanide in raised Romak bait stations, and then 500 g of brodifacoum (Pestoff) pellets were placed monthly in 25 Philproof bait stations. In September 1999, more than 550 possums were removed from Purua after they had been killed with bagged Feratox cyanide baits stapled to trees. Following this initial knockdown, possums were poisoned monthly with 500 g of brodifacoum (Pestoff) pellets in 55 Philproof bait stations.

Bank of New Zealand Operation Nest Egg (BNZONE)

BNZONE was developed during the early stages of this study (Colbourne 2002, Colbourne *et al.* 2005). Eggs were collected mainly from Hodge's Bush, with a few collected from other sites (generally when nests were abandoned following inspection). Eggs were collected during daytime and placed in insulated boxes filled with shredded paper. In 1994 and 1995, most eggs were sent by air to Wellington where experimental methods for hatching eggs were being trialled (Colbourne 2002). In subsequent years, most eggs were taken 200 km by car to Auckland Zoo, although Whangarei Bird Rescue Centre and the National Wildlife Centre handled some eggs. Eggs were normally delivered on the day they were removed from nests, but were placed in a Brinksea® incubator at 35°C if they had to be held overnight. Chicks were raised in captivity at a variety of institutions (but mainly at Auckland Zoo), or on predator-free Motuora Island in the Hauraki Gulf (36°30'S, 174°48'E). Most subadults were returned to the area they originated from when they weighed more than 1,200 g, at which stage they were safe from predation by Stoats and cats, but still vulnerable to Ferrets and dogs. Subadults derived from eggs collected in 1999 and 2000 were generally used to restock kiwi populations at Whangarei Heads (35°50'S, 174°30'E).

Population modelling

Population models were developed in PopTools, an Excel add-in, for each treatment. For some parameters, estimates had to be pooled to achieve adequate sample sizes and reduce the influence of stochastic events.

Adult survival

Annual survival of adults was calculated using the Mayfield method, assuming that mortality rates remained constant over time (Robertson and Westbrooke 2005). However, there is some evidence that there are pulses of mortality in adult kiwi, resulting from sporadic attacks by dogs or Ferrets at particular locations (e.g. Taborsky 1988). During our study, a Ferret killed three out of 11 radio-tagged adult male kiwi at Hodge's Bush over nine weeks in spring 1996, and a dog killed three out of eight radio-tagged adult males at Riponui over nine weeks in autumn 1999. To improve sample size and reduce the influence of these stochastic events, data were pooled across all four study blocks for the 7.5 years of the study (January 1994–June 2001), plus the 7.5 subsequent years (June 2001–December 2008), when mustelid and cat trapping, and BNZONE were applied over all the study blocks.

Productivity

For each treatment, the number of eggs laid per radio-tagged male (including non-breeding birds) was recorded, along with hatching success. From a range of behavioural observations it was assumed that kiwi were monogamous. From total captures (164 adult males and 158 adult females), and from independent surveys using dogs (Robertson and Fraser 2009), the sex ratios were close to even in all the study kiwi populations.

Chick survival

Survival of chicks from hatching to six months old, when they weighed about 1 kg and were generally safe from Stoat and cat predation, was obtained from the product of the percentage of chicks surviving from hatching to radio-tagging at about 10 days old and the Kaplan-Meier estimate of survival (Robertson and Westbrooke 2005) from 10 to 183 days (six months) old. For life-table analysis, survival during the first year was the product of chick survival to 183 days old and the Kaplan-Meier estimate for subadult survival from six months to one year old pooled across all study areas (see below).

Subadult survival

Using a staggered entry design (Pollock *et al.* 1989), based on known ages of chicks followed since they were nestlings, or estimated ages from bill length and weight of subadults found by dogs, we obtained Kaplan-Meier estimates of subadult survival. To improve the sample size of wild-hatched birds, data were pooled across all treatments and supplemented with data collected over the next 7.5 years. Subadults occasionally moved between different treatment areas, and so it would have been difficult to assign survival probabilities to birds under specific treatments. Also, subadults were large enough to avoid predation by Stoats and cats, the main targets of predator control. Data for subadult birds raised through BNZONE were analysed and presented separately, because risks in captivity, and after release to the wild, were quite different to those facing wild-hatched birds.

Age at first breeding

In life table analysis, the size of the Leslie matrix depends on the number of years to maturity (Robertson and Westbrooke 2005). Only data from males were used because they do all the incubating (Heather and Robertson 2005), and so their first breeding attempt is easier to detect. Data for the whole period from 1994 to 2008 were pooled.

Immigration and emigration

We did not include corrections for immigration or emigration in the models, because very few data were available for either parameter. We assumed, from the poor survival of chicks in unmanaged areas, that there would have been very little immigration into the treatment areas from nearby unmanaged areas. No radio-tagged chicks < 1 kg moved between different treatment areas between 1994 and 2001, and less than 10% of radio-tagged subadults moved between study blocks. However, transmitter disappearance, caused by long-distance dispersal well beyond the study boundaries, would have been hard to identify, despite regular searches for missing birds from aircraft with strut-mounted Yagi aerials. Transmitter failure, the alternative explanation for transmitter disappearance, was often proven by the discovery of birds carrying dead transmitters or without a transmitter, and so it appeared that emigration beyond the study area was minimal.

Leslie matrices and sensitivity analysis

Population data (Table 1) were analysed in life tables (Leslie matrices) in PopTools, using data estimated for each treatment. Sensitivity analysis highlighted the key factors affecting performance of unmanaged kiwi populations.

Table 1. Life history parameters, population growth rates and population projections for Brown Kiwi under four different management treatments in central Northland. Figures shown in bold have been obtained for that parameter under the specific treatment, figures shown in normal type have been pooled across treatments to improve sample size and reduce the impact of stochastic events.

	Unmanaged	Poisoning	Trapping	BNZONE
Adult survival (1994–2008)	0.9273	0.9273	0.9273	0.9273
No. bird years	880	880	880	880
No. nests	**206**	**270**	**22**	**68**
No. eggs	**313**	**457**	**34**	**111**
No. eggs taken for BNZONE	**73**	**28**	**0**	**111**
No. eggs of known outcome in wild	**232**	**412**	**33**	**0**
Eggs per adult	**1.32**	**1.17**	**1.06**	**1.25**
% eggs hatched	**53.0**	**56.1**	**54.5**	**70.0**
Chicks per adult	**0.700**	**0.656**	**0.578**	**0.875**
No. chicks monitored	**136**	**240**	**18**	**72***
Chick survival (0–10 days)	**0.904**	**0.929**	**1.000**	**0.956**
No. 10-day-old chicks monitored	**63**	**115**	**15**	**69**
Chick survival (10–183 days)	**0.111**	**0.326**	**0.147**	**0.869**
Subadult survival (183 d – 1 y)	0.820	0.820	0.820	**0.858**
Survival (0–1 y)	**0.082**	**0.248**	**0.121**	**0.713**
Subadult survival (1–2 y)	0.886	0.886	0.886	**0.746**
Subadult survival (2–3 y)	0.880	0.880	0.880	**0.908**
Subadult survival (3– 4 r)	0.958	0.958	0.958	**0.805**
Age at first breeding (years)	4	4	4	**4**
Leslie matrix, λ	**0.975**	**1.034**	**0.983**	**1.133**
Leslie matrix, r	**−2.54**	**3.33**	**−1.71**	**12.52**
Estimated population in 2001	**172**	**244**	**180**	**424**

*61 hatched in captivity and 11 chicks transferred to crèches at 8–50 days old

Results

Adult survival

Between January 1994 and December 2008, 248 different adult kiwi (157 males and 91 females) were radio-tracked for 880 bird-years (range 1–5,339 days). Sixty-four radio-tagged adults died during the 15-year study, and a specific cause of death could be attributed in 44 cases from scene and/or necropsy evidence (e.g. spacing of teeth). Causes of mortality were: dog (22), Ferret (9), drowning (4), bee stings (2), possum (1), cat (1), stood on by a cow (1), cliff fall (1), tree fall (1), bill-tip injury (1), and disease (1). The annual survivorship was 92.7% and life expectancy (1/m) was 13.8 years (Table 1).

Productivity

Between 30 and 52 adult males were radio-tracked throughout each breeding season from 1994/95 to 2000/01, and 90% (84–94%) of them bred each year. Hatching success in the wild was similar (53–56 %) for all three treatments (Table 1). In 1994 and 1995, during the experimental stage of BNZONE, only 18 (33%) of 54 eggs hatched; 16 (30%) of the eggs were either infertile or dead on arrival in captivity, and three were accidentally cracked by air baggage handlers, and so 51% of viable eggs hatched. Subsequently, 42 (63%) of 67 BNZONE eggs hatched. Hatching success was 70% if we excluded seven freshly-laid eggs deliberately collected in 1997 to experimentally devise incubation protocols from laying. Since 2001, as BNZONE techniques have become more refined, hatching success has risen to 82% of all 172 eggs collected, or 93% of 152 viable eggs.

Chick survival

Under the different treatments, between 0% and 9.6% of chicks died when they were less than 10 days old (Table 1). Most deaths were due to hatching difficulties.

In the unmanaged sites, 41 (65%) of 63 radio-tagged chicks died, and only one (1.6%) definitely survived to 183 days old. The Kaplan-Meier estimate of survival from 10 to 183 days was 11.1%, taking into account the projected survival of 21 chicks whose records were censored when their transmitters fell off or failed, or when they disappeared. The median survival time was 26 days. Causes of mortality in 31 cases where the agent could be identified were: Stoats 19 (63%), cats 4 (13%), drowning 3 (10%), Ferrets 2 (7%), and Australasian Harrier *Circus approximans*, unknown predator, and being stood on by a cow, 1 each (3%).

In the areas where pests were poisoned, 115 chicks were radio-tagged. A total of 59 (51%) of these died before reaching six months old, but 16 (14%) definitely survived. The Kaplan-Meier estimate of survival from 10 to 183 days was 32.6%, and the median survival time was 94 days. Of the 42 deaths for which cause was determined, 27 (64%) were killed by Stoats, 8 (19%) by cats, 4 (10%) died of disease, 2 (5%) drowned and 1 (2%) was killed by a Ferret.

In the two years of trapping at Riponui, 15 chicks were radio-tagged, and none was known to have survived to 183 days old. The oldest chick dropped its transmitter at 134 days old. A 14.7% survival rate from 10 to 183 days was estimated as the product of the Kaplan-Meier estimate to 134 days (15.7%) and the 94% survival between 134 days old and 183 days old in the poisoned area. The median survival time was 43 days. Of the nine deaths for which cause was determined, 6 (67%) were killed by Stoats, 2 (22%) by cats and 1 (11%) died of disease.

Subadult survival

Between January 1994 and December 2008, 197 wild-reared subadult birds (aged between six months and four years, and which had not bred) were radio-tracked for a total of 220 bird-years (range 0–1,278 days). The Kaplan-Meier estimate of survivorship from 183 days to one year was 82.0%, then 88.6% survived from one to two years, 88.0% from two to three years, and 95.8% from three to four years. There were 36 deaths of subadult birds, of which the cause could be identified in 25 cases from scene evidence or necropsy analysis. The identified causes of mortality were: dog (8), drowning (4), cat (3), Stoat (3), broken bill (2), disease (2), Ferret (1), undetermined mustelid (1), and hit by a falling tree (1).

A total of 99 BNZONE-reared subadult birds were followed for a total of 126 bird-years (range 3–1,278 days) in captivity, or after they were radio-tracked following release into the wild from captivity or from island crèches. The Kaplan-Meier estimate of survival from 183 days to 1 year was 85.8%, then 74.8% survived from one to two years, 90.8% from two to three years, and 80.5% from three to four years. There were 26 deaths of BNZONE subadults, including 18 for which the cause of mortality could be established from scene and/or necropsy evidence. The causes identified were: dog (8), Ferret (4), cliff fall (2), starvation (1), drowning (1), disease (1) and fell into a hole (1). Nine (35%) of the deaths, including four dog kills, both cliff falls, and the death from starvation, were in the first month after release of captive-reared birds to the wild, presumably due to their naïve behaviour, or failure to adapt to conditions in the wild.

Age at first breeding

From a sample of 20 wild-hatched subadult males, the estimated age at first breeding was 1,449 ± 531 days (4.0 ± 1.5 years) with a very wide range from 756 days (2.1 years) to 2,996 days (8.0 years). Earlier breeding attempts by some of these males may have been missed if their nests failed early in incubation, especially because they were checked visually only every 2–3 months.

Leslie matrix and sensitivity analysis

The finite rate of population increase, λ, ranged from 0.975 in the unmanaged population to 1.133 for BNZONE, and the corresponding growth rate, r, ranged from −2.5% to +12.5% per annum (Table 1). Sensitivity analysis of the non-treatment matrix (Table 2) showed that the key factor in unmanaged populations was adult survival rate (0.84), followed by survival of chicks from 0–12 months (0.48).

Discussion

All five species of kiwi have declined significantly in both range and abundance since human settlement of New Zealand just over 1,000 years ago. Four threatened species persist in mainland forests, despite over 100 years of coexistence with the introduced mammals that are known to prey on them (McLennan *et al.* 1996). Forest clearance by both Maori and European settlers had a huge initial impact on kiwi populations, but during the past 30 years the rate of loss of native forest and scrubland throughout New Zealand has declined markedly as a result of government and local legislation, and the removal of incentives for land development (Miller and Pierce 1995). There are now many areas of suitable native or exotic forests from which kiwi have either disappeared or declined significantly over this same period, and so habitat loss is not now regarded as a significant driver of the decline of kiwi. McLennan *et al.* (1996) provided the first quantitative data to show that introduced mammalian predators, especially Stoats, were now the key factor driving the decline of kiwi population in mainland forests. Kiwi evolved in the absence of predatory mammals and as a result, lack natural defence mechanisms, they have a strong scent, have prolonged incubation in burrows or on the surface under dense vegetation, there is no parental care of chicks away from the nest, and kiwi have exceptionally slow growth rates.

Non-treatment

Unmanaged populations of Brown Kiwi in Northland are in serious trouble, because an annual decline of 2.5 % per annum would result in the population halving every 27 years. This observed rate of decline is, however, far less than the catastrophic decline of 5.8% per annum (populations halving every 11 years) calculated by McLennan *et al.* (1996). Their estimate was based on pooled data from a number of mainland studies, including the initial stages of this one, but their samples were very small (i.e. only 122 bird-years of adult survival data, 58 nesting attempts, and 49 monitored chicks from Brown Kiwi and 37.5 years of adult survival data, 19 nesting attempts and no monitored chicks from Great Spotted Kiwi). McLennan *et al.* (1996) did, however, note considerable variation between sites in the annual rate of decline, ranging from 18% at Urewera to 3.2% for this study population. The data reported by McLennan *et al.* (1996) were clearly affected by a few unusual events, such as mass adult mortality caused by an outbreak of Ferrets at Urewera. The use of simple statistics, rather than more rigorous survival analysis tools, also hampered their analysis and thus painted a gloomier picture than was warranted. Nevertheless,

Table 2. Leslie matrix and sensitivity matrix for unmanaged populations of Brown Kiwi in central Northland.

Leslie Matrix - unmanaged					Sensitivity matrix - unmanaged				
0	0	0	0	0.6996	0	0	0	0	0.0569
0.0823	0	0	0	0	0.4840	0	0	0	0
0	0.8863	0	0	0	0	0.0449	0	0	0
0	0	0.8802	0	0	0	0	0.0452	0	0
0	0	0	0.9576	0.9273	0	0	0	0.0416	0.8366

the paper by McLennan *et al.* (1996) galvanised considerable governmental, corporate, and community group efforts to try to protect kiwi, and reverse the declines that many mainland populations of kiwi are clearly undergoing (see www.savethekiwi.org.nz).

McLennan *et al.* (1996) concluded that predation of young kiwi by Stoats was the single most important factor contributing to the demise of mainland populations of kiwi. This is not the situation in central Northland, where predation of adult kiwi by dogs and Ferrets has been the key factor affecting unmanaged Brown Kiwi populations. With adult mortality rates of 7.3% per annum, the life expectancy of adult Brown Kiwi in Northland is just 13.8 years, whereas other studies in the central North Island have demonstrated that mean life expectancy of Brown Kiwi, in the absence or near absence of dog and Ferret predation, can be over 40 years (H. Robertson unpublished data), or three times the Northland average. By varying adult survival figures in the life table, protection of chicks through Stoat and cat control would not be needed in central Northland if the life expectancy of adult Brown Kiwi could be increased to 23 years, which is still less than two-thirds of their potential average life-span.

The impact of dogs and Ferrets on kiwi populations is both unpredictable and episodic, but both species can cause massive and rapid declines in local populations (Taborsky 1988, McLennan *et al.* 1996). The predation events observed with dogs and Ferrets do not fit with traditional predator-prey models because these predators kill far more prey than is needed to sustain them. The best example of the potential scale of destruction by dogs comes from Waitangi Forest, 60 km north of the study area, where a single dog is believed to have killed about 500 Brown Kiwi (most of which were not eaten) over a six week period (Taborsky 1988). This was by no means an isolated instance, because Pierce and Sporle (1997) documented 70 separate reported incidents (involving 135 birds) of dogs killing kiwi in Northland between 1990 and 1995. Despite advocacy to land-owners near our study sites about the need for their dogs to be tied up or housed in kennels at night, dogs were still responsible for 22 (50%) of the 44 deaths of adult birds where a cause of death could be identified.

Despite trapping and poisoning many Ferrets in the study area, Ferrets were still responsible for nine (20%) of the attributed adult kiwi deaths. The situation could have been even worse because, following deaths of three of 11 radio-tagged males used for BNZONE at Hodge's Bush, a male Ferret was trapped and the killing ceased. It is possible that female kiwi are less vulnerable to Ferrets than the smaller males, because all known resident female kiwi at Hodge's Bush were later found alive.

Ferrets were scarce in Northland until the 1980s, when they spread northwards, and were supplemented by the release of many domesticated Ferrets (fitch), bred for fur production, when the fur market collapsed in the mid-1980s (Miller and Pierce 1995, Bill Lovell pers. comm.). Ferrets are relatively easy to control because they are widely regarded as vermin and are readily trapped, but in Northland they live in a wide variety of habitats including wet broadleaf forests, as well as in wetlands and on drier farmland. As for dogs, it is only the occasional Ferret that develops the habit of killing kiwi, but once they begin, they can eliminate a population very quickly. The rapid extirpation of Brown Kiwi from southern Northland coincided with the arrival of Ferrets, and the pattern of disappearance of Brown Kiwi from Paerata Wildlife Management Reserve (210 ha) in south-western Northland is consistent with the involvement of Ferrets. Potter (1990) caught 20 adult female Brown Kiwi, but only 11 adult males and one subadult out of an estimated population of 80–90 birds in 1985–87. All males were paired and attempted to breed each year, but some females did not, which suggested a real skew in the actual sex ratio. Although no deaths of kiwi were attributed to Ferrets during the study, the apparent sex bias is consistent with males being more vulnerable to predation by Ferrets. By 1994, there were no more than 30 birds left (H. Robertson unpubl. data) and by 2003, less than one kiwi generation after Potter's study, they had apparently disappeared (Glen Coulston pers. comm.) from what was one of two reserves in New Zealand that had been created specifically for the protection of kiwi (Potter 1990).

Because dog and Ferret control and advocacy was higher in the vicinity of the study area than in most other parts of Northland, we would expect the situation for adult kiwi over most of

Northland to be even worse than we recorded, and so the decline rate in unmanaged parts of Northland is likely to be at about 3% per annum. Pierce and Westbrooke (2003) found a moderate positive relationship between changes in Brown Kiwi call rates from 1995 to 2000 in Northland and different levels of predator control and advocacy, but because predator control and advocacy were strongly correlated, as in this study, it was not possible to separate their effects.

Trapping

Predation of kiwi chicks by Stoats and, to a lesser extent, cats, is certainly helping to drive populations in Northland to extinction, with more than 70% of chick deaths being attributed to these two predators. Trapping predators was ineffective in protecting kiwi at the 200-ha scale used in this study, and removal of these higher-level predators led to an increase in rat (*Rattus* spp.) populations. Rats potentially compete with kiwi, especially kiwi chicks, for invertebrates and fallen fruits in the litter layer, so an increase in rats could lead to slower growth rates of kiwi chicks and, hence, a longer time for them to reach a size that makes them safe from Stoat and cat predation. Animal welfare requirements at the time of this project meant that traps had to be checked daily. However, from 2001, when the traps we used were approved as 'kill traps', which do not require daily checks, the cost-effectiveness of trapping improved greatly, allowing 6,000 ha to be trapped fortnightly with the same effort used previously in the trapping of 200 ha.

Pest poisoning

Pest control using brodifacoum was effective at protecting kiwi through primary poisoning of possums and rats and then secondary poisoning of Stoats, Ferrets and cats. Since about 2000, the Department of Conservation has phased out the use brodifacoum for predator control on the mainland of New Zealand because of risks to non-target native wildlife and potential contamination of game meat exports; however, it is still used to eradicate pests from islands and within predator-proof fenced sites on the mainland. Traces of brodifacoum were detected in some kiwi eggs, chicks and adults from the study areas, and one chick killed by a Stoat may have eaten a potentially fatal dose (Robertson *et al.* 1999a, H. Robertson unpubl. data). Overall, however, the benefits to kiwi of brodifacoum poisoning outweighed the risks, because pest poisoning lowered the populations of all mammalian pests. At an ecosystem scale, the brodifacoum gave good control of pests, but posed a potentially serious hazard to other biota, hence the shift after 2001 to landscape-scale trapping of predators rather than landscape-scale pest poisoning.

Bank of New Zealand Operation Nest Egg (BNZONE)

Artificial incubation of eggs and raising chicks on predator-free island 'crèches' until they were old and big enough to survive in the presence of Stoats and cats, was clearly the most effective tool for increasing the kiwi population. Once initial teething problems were ironed out, such as the failure to hatch eggs that were less than 10 days old at collection (Colbourne *et al.* 2005, Robertson *et al.* 2006), population growth was over 12.5% per annum, or a doubling of the population every six years. Since 2000, most subadults raised through BNZONE have been released at Whangarei Heads Peninsula (about 50 km south-east of the study area) to restore severely depleted kiwi populations there, or to establish a new population behind a predator-proof fence at Tawharanui Peninsula (about 100 km south-east of the study area). By the end of 2008, more than 170 subadults had been released to the wild, and many had bred with wild-hatched resident birds or with other BNZONE birds. Age at first breeding was similar to that of wild-hatched chicks, and behaviour of BNZONE birds appeared to be normal (Colbourne *et al.* 2005), apart from higher than expected mortality in the first month after release to the wild.

Although BNZONE is an exceptional tool for recovering depleted kiwi populations, it is also the most expensive of the four treatments used here. Adult males must be captured and then recaptured annually to change their transmitters. The eggs have to be collected at mid-term incubation, transported to captivity, and then managed in incubators by well-trained staff. Captive-reared chicks need good husbandry and access to veterinary care, and need health screening and quarantining before being transferred to island crèches or to the wild. Finally, subadults need to be recaptured at their crèches for return to the mainland. BNZONE benefits only kiwi, and so is effectively neutral to the environment; and without additional pest control, kiwi habitat will continue to deteriorate. However, to its credit, the BNZONE process does not upset predator-prey equilibria, which is an undesired consequence of continuous intensive trapping of Stoats and cats.

Synthesis

When this study began in 1994, little was known of the threats to kiwi, apart from well-illustrated cases of habitat loss and dog attacks on adults (Taborsky 1988, Miller and Pierce 1995, Pierce and Sporle 1997). This study showed that unmanaged populations of Brown Kiwi in Northland are in serious trouble, mainly because of predation of adults by dogs and Ferrets and, to a lesser extent, by predation of young kiwi by Stoats and cats. In this study, possums had only minor direct impacts on kiwi; however, indirect impacts of possums were reduced by ensuring that traps were set 70 cm off the ground so that kiwi were not at risk of accidental capture. Although Stoat and cat control would not be necessary if predation of adult kiwi by dogs and Ferrets could be halved, improving survival chances of kiwi through the first six months of life appears to be the easiest way to halt the decline of kiwi in Northland. Advocacy to dog owners is the main tool currently available to protect adult kiwi, but changing well-established behaviour patterns of dog owners can be a slow process, as indicated by the high mortality of adult kiwi in our study area, despite many discussions with nearby landowners. Research is now underway to test if dogs can be trained to avoid kiwi, and then retain that avoidance behaviour.

Miller and Pierce (1995) suggested that the spectacular reduction in the range and numbers of kiwi in Northland between the 1970s and 1990s was due to habitat loss, ongoing attacks by dogs, and the recent arrival of possums and Ferrets in the province. This study suggested that ongoing predation of adult kiwi by dogs and predation of chicks by Stoats and cats were slowly reducing all kiwi populations in Northland. The sudden decline of kiwi populations in southern Northland was probably caused by an increase in adult mortality caused by the rapid build-up of Ferrets in the area, and by indirect effects of a wave of possums spreading through the province from the south, especially from accidental captures of kiwi in traps set on the ground, or from kiwi ingesting cyanide baits placed on the ground. Carrion, in the form of discarded skinned possum carcasses, probably helped to support higher than usual populations of predators.

This study has helped to identify the critical factors affecting the survival of kiwi populations in Northland, and has developed a range of tools now being used by the Department of Conservation and numerous community groups to manage kiwi populations in over 70,000 ha of Northland. BNZONE is now being used to successfully grow populations of Rowi and Haast Tokoeka *Apteryx australis* 'Haast', the two most endangered taxa of kiwi (Miskelly *et al.* 2008), and to restore many other Brown Kiwi populations outside Northland.

The experimental approach used here, comparing population dynamics of a species under different management regimes, has application to the management of other threatened species. In particular, identification of critical factors through a life table analysis showed that the most common predation event (a Stoat-killed chick) was nowhere near as important to the population as the occasional dog-killed adult, because in long-lived species, adults are extremely valuable. Having said that, good management of the minor predators allowed the population to increase, and gave us time to devise effective control of dogs, the most critical predator.

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