Costs and benefits for biodiversity following rat and cat eradication on Te Hauturu-o-Toi/Little Barrier Island

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Abstract Considerable benefits can be achieved for indigenous biodiversity when invasive vertebrates are removed from islands. In New Zealand, two logistically challenging eradications were undertaken, one to remove cats (*Felis catus*) and the other Pacific rats (*Rattus exulans*) from Te Hauturu-o-Toi/Little Barrier Island (Hauturu). Here we document the short- and long-term impacts of these interventions on the biodiversity of Hauturu. We also assess the extent to which predicted outcomes were reflected in the measured responses for a wide range of species. Short-term impacts of the eradication program encompassed individual mortality for some native species but no measurable impact to populations. In contrast, at least 11 native vertebrates and one native invertebrate species increased in abundance after rat and cat removal. Fifteen of 34 plant species monitored had significantly more seedlings on Hauturu after rat eradication compared with control islands, indicating future changes in forest composition. Several native species previously not recorded on the island were discovered, including the New Zealand storm petrel (*Fregetta maoriana*) (formerly considered extinct), the forest ringlet butterfly (*Dodonidia helmsi*) and eight species of aquatic invertebrate. The chevron skink (*Oligosoma homalonotum*) has been found in increasing numbers and tuatara (*Sphenodon punctatus*), raised in captivity on the island, are now re-established and breeding in the wild. These results illustrate an island gradually recovering after a long period of modification. We conclude that more success stories such as Hauturu must be told if we are to allay the public's concerns about such eradication campaigns. And more public support is required if the conservation community is to tackle invasive species at a scale commensurate with the threats they pose.

Keywords: conservation management, ecosystem, restoration, species recovery

INTRODUCTION

Worldwide, more than 1,000 invasive vertebrate eradications have been successfully completed to prevent biodiversity loss (DIISE, 2017) and many benefits to species and ecosystems have been documented (Jones, et al., 2016). However, eradication projects continue to attract controversy (e.g. Howald, et al., 2010; Griffiths, et al., 2012; Capizzi, et al., 2019) suggesting that, despite transparent consultation processes, sectors of the public remain unconvinced of the relative cost benefits of this conservation strategy.

To illustrate the value of invasive vertebrate eradication, we present the short- and long-term impacts on biodiversity following the removal of cats (*Felis catus*) and Pacific rats (*Rattus exulans*) from Te Hauturu-o-Toi/Little Barrier Island (hereafter referred to as Hauturu). Specifically, we ask whether the claimed benefits of cat and Pacific rat eradication were met.

The eradication of cats from Hauturu raised little public concern and, under New Zealand environmental law, did not require consent. In contrast, the proposed rat eradication raised cultural and environmental concerns and, because rodent bait was broadcast by helicopter, required local government consent (Resource Management Act 1991). Some members of the public were opposed to the aerial application of rodent bait and some Māori iwi (tribes) contested the removal of rats because of their cultural significance. Consequently, public hearings were held and an Assessment of Environmental Effects (AEE) (Griffiths, 2002) was presented to a panel of independent commissioners. The AEE identified the legal mandate for the removal of rats and the risk to native species if rats remained. The application was approved as the potential benefits to native biodiversity were judged to outweigh the short-term environmental costs.

Cats were removed from Hauturu in an operation that spanned four years from 1977 to 1980. To support this work, a 67 km long track network was established across the island and three huts built at strategic locations (Veitch, 2001). Leg-hold traps and baits containing the toxin 1080 were the principal methods employed to remove cats, although cage traps, the introduction of pathogens and dogs were also used (Veitch, 2001). Mitigation of potential impacts on non-target species was undertaken through careful placement of traps.

Rats were eradicated in 2004 by the New Zealand Department of Conservation (DOC) in an operation utilising the aerial application of Pestoff 20R™ rodent bait containing brodifacoum at 20 ppm (Griffiths, 2004). Rodent bait was applied twice by three helicopters in two successive operations during winter, the first on 8 and 9 June and the second on 12 July. At the same time, baits were placed in bait stations within all buildings and huts on the island. The operation used a total of 55 tonnes of rodent bait with rates for the first and second bait applications averaging 11.7 kg/ha (ca. 1 bait per 1.7 m^2) and 6.16 kg/ha (ca. 1 bait per 3.2 m^2), respectively, across the island. The success of the eradication operation was confirmed in January 2006 after extensive monitoring both on and off the track network across the island with tracking tunnels, spotlight searches and indicator dogs (Griffiths, 2006).

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Our findings are based on research and monitoring completed on the island from 1962 to the present. We review published and unpublished studies, but also present new data that illustrate changes following rat and cat removal.

STUDY AREA

Hauturu (3,083 ha), 36°11′56.76″S, 175°4′53.04″E is almost midway between Great Barrier Island/Aotea and the mainland (Fig. 1). Rugged and steeply dissected, the island arose from the partly eroded core of a composite volcanic cone that formed 1.5–3 Ma (Lindsay & Moore, 1995)(Fig. 2). Hauturu was first settled around the 14th C by the descendants of the Maori ancestor and voyager Toi te Huatahi and was occupied continuously until the arrival of Europeans in the 1800s. Over this and the ensuing period of European settlement, approximately one third of the island (the south-west) was cleared, burnt and subjected to grazing by sheep (*Ovis aries*) and cattle (*Bos taurus*) (most of these areas have since reverted to native vegetation and are now secondary successional forest or older). Because of its unique forest and threats to the diverse birdlife, the island was gazetted as New Zealand's first Nature Reserve in 1896 (Young, 2004).

Except for feral cats and rats, the island escaped many of the invasive vertebrate introductions to the main islands of New Zealand and, consequently, its fauna is still largely representative of northern New Zealand prior to European colonisation. By area, the island supports a greater diversity of native birds and reptiles than any other part of of New Zealand. Nonetheless, the introduction of rats and cats to Hauturu had a huge impact. Pacific rats, considered to have arrived early during the period of Maori settlement (Campbell, 2011), likely extirpated most of the small seabird species still seen on nearby rat-free islands. Rat predation may also explain the absence of milk tree (*Streblus banksii*), coastal maire (*Nestegis apetala*) (Campbell, 2011), large land snails and slugs on the island (Campbell, 2011). The introduction of cats sometime around 1867 resulted in the extinction of the last population of North Island snipe (*Coenocorypha barrierensis*) and extirpation of the tieke (*Philesturnus rufusater*), grey-faced petrel (*Pterodroma macroptera*), and probably other seabirds. It is likely that other species such as the black petrel (*Procellaria parkinsoni*) would have suffered a similar fate had cats not been removed.

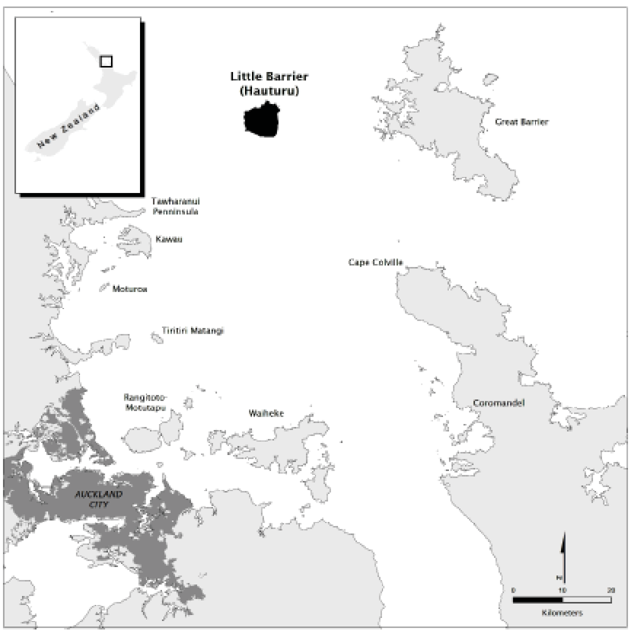

Fig. 1 Map showing the location of Hauturu.

METHODS

A literature search of published and unpublished monitoring, undertaken to measure the environmental impacts of cat and rat eradication, was conducted but also included general research and monitoring completed on Hauturu for other reasons. We assessed impacts as measured costs, measured benefits, and unknown costs or benefits to biodiversity. Unknown costs and benefits were largely a function of an absence of monitoring prior to and following eradication, and/or due to environmental changes unrelated to the eradications. For example, Hauturu supports breeding populations of the New Zealand lesser short-tailed bat (*Mystacina tuberculata*) and long-tailed bat (*Chalinolobus tuberculatus*), both endemic to New Zealand. Bat populations were not monitored before, during or after cat and rat eradication.

We first summarise the predicted outcomes (Tables 1 and 2), then collate previously published monitoring results obtained from a Web of Science and Google Scholar search completed on 24 January 2017 using the key words 'Little Barrier Island' and 'Hauturu'. We then summarise unpublished research and monitoring reports and other unpublished data including the methods used (Table 3) and analyse data on terrestrial birds (see mist-netting below). Changes in island species composition after rat and cat eradication were determined by comparing recent literature with historical reports. For simplicity, results are grouped by taxa: marine birds, terrestrial birds, reptiles, freshwater fish, terrestrial invertebrates, aquatic invertebrates and terrestrial plants.

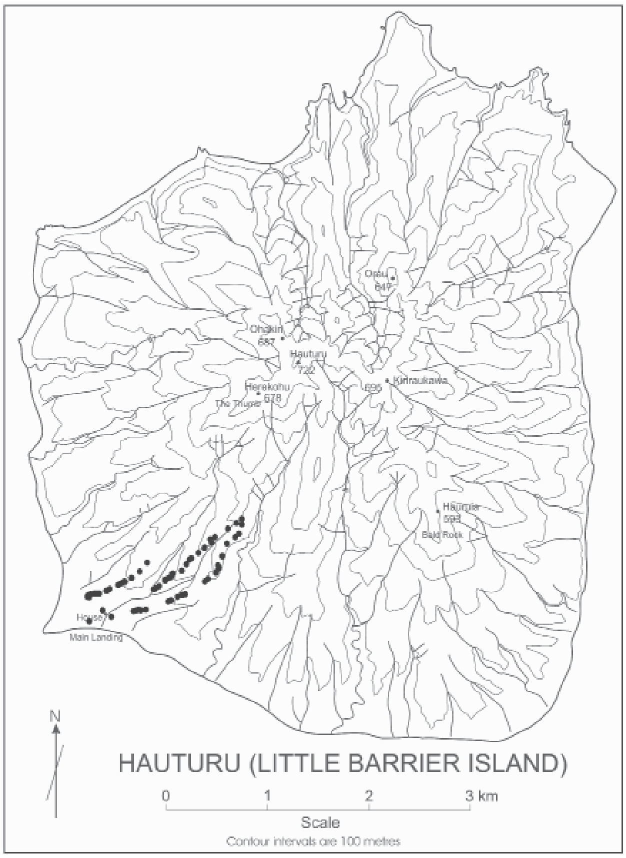

Fig. 2 The rugged nature of Hauturu and locations of mist nets (black dots) used to sample forest bird abundance before and after rat eradication.

Table 1 Predicted benefits of cat eradication from Hauturu with species marked* identified in Recovery Plans for threatened species.

Native biodiversity	Evidence	References
Black petrel	Direct evidence of cat predation and declining breeding distribution	(Girardet, et al., 2001)
Cook's petrel/titi	Direct evidence of cat predation and declining breeding distribution	(Imber, et al., 2003a)
Tieke	Potential for reintroduction	(Girardet, et al., 2001; Hoosen & Jamieson, 2003)
Kakapo*	Potential for ex-situ management of Stewart Island population heavily impacted by feral cats	(Lloyd & Powlesland, 1994; Anon., 1996; Elliott, et al., 2001)
Kokako*	Potential for reintroduction	(Innes & Flux, 1999)
Grey-faced petrel	Recolonisation expected	(Girardet, et al., 2001)

Table 2 Predicted responses to rat removal from Hauturu as identified in the assessment of environmental effects (Griffiths, 2002), with conventions as in Table 1.

Native biodiversity	Evidence	References
Species that faced local extinction in the absence of intervention		
Cook's petrel	Fledgling recruitment on Whenua Hou (Codfish Island) increased to 90% following rat eradication	(Imber, et al., 2003a)
Tuatara*	Documented impacts on juvenile recruitment. Local extinction predicted by population models completed for Marotere and Taranga Islands	(Gaze, 2001; Towns, et al., 2007; Cree, 2014)
Wetapunga*	No off-site data but examples of localised extinctions in other flightless crickets e.g. tusked weta (*Motuweta isolata*; Mercury Islands)	(Towns, et al., 1990; Sherley, 1998; Towns, et al., 2006)
*Dactylanthus taylorii**	No off-site data on impacts by Pacific rats on this species but video evidence of inflorescence destruction by rats on Hauturu	(Eckroyd, 1995)
Giant-flowered broom	Examples of localised extinctions from other archipelagos (e.g. Marotere Islands)	(Towns, et al., 2003)
Species predicted to benefit from intervention		
Grey-faced petrel	Increases in abundance documented elsewhere after Pacific rat removal (e.g. Korapuki Island, Stanley Island)	(Towns & Atkinson, 2004; G Taylor pers. comm.)
Diving petrel	Localised extinctions reported in other archipelagos and increased abundance following Pacific rat removal (e.g. Mercury Islands)	(Towns & Atkinson, 2004; G Taylor, pers. comm.)
Tieke	Evidence of increased abundance after Pacific rat removal (e.g. Red Mercury Island)	(Robertson, et al., 1993)
Towns' skink	Examples of localised extinctions in other archipelagos (e.g. Mokohinau, Marotere Islands) or confinement to refugia (Hauturu)	(Towns, et al., 2003)
Duvaucel's gecko	Confined to refugia in presence of Pacific rat (Hauturu). More terrestrial activity and increased abundance after Pacific rat removed (e.g. Mercury, Marotere and Ohinau Islands)	(Towns, 1996; Hoare, et al., 2007)
Pisonia brunoniana and 10 other plant species	Examples of recovery after Pacific rat removal (e.g. Mercury Islands)	(Campbell & Atkinson, 2002)
Species that will possibly benefit from intervention		
Short-tailed bats	No off-site models for this species. Potential release from competition for invertebrates and *Dactylanthus taylorii* inflorescences	
Long-tailed bats	No off-site models for this species. Potential release from competition for invertebrates	
Smaller native passerine birds	No off-site models for these species. Potential release from competition for invertebrates and nectar sources	
Day-active skinks	Increased abundance of selected species when Pacific rats removed (e.g. Mercury Islands) but no models for chevron and striped skinks present on Hauturu	(Towns, 1991)

Table 3 Methods used to evaluate short- and long-term changes to biodiversity subsequent to cat and rat eradication on Hauturu.

Species Group	Indicator	Methods	Sources
Bats	Species composition	Literature review	(Daniel & Williams, 1984)
	Species abundance	Anecdotal reports	
	Short term mortality over the course of eradication operations	Cat trapping data and carcass searches before and after rat eradication.	(Veitch, 2001; Griffiths, 2004)
Marine birds	Species composition	Literature review	(Hutton, 1868; Turbott, 1947; Girardet, et al., 2001; Stephenson, et al., 2008; Rayner, et al., 2009; Gaskin & Rayner, 2013; Rayner, et al., 2015)
	Cooks petrel breeding success and distribution	Monitoring of marked burrows 1971 to present	(Imber, et al., 2003a; Rayner, et al., 2007b)
	Black petrel breeding success	Monitoring of marked burrows 1971 to present	(E. Bell, unpubl. data; Imber, 1987; Imber, et al., 2003b)
	New Zealand storm petrel	Monitoring of marked burrows	(M.J. Rayner, unpubl. data; Ismar, et al., 2015)
	Short term mortality over the course of eradication operations	Cat trapping data and carcass searches before and after rat eradication	(Veitch, 2001; Griffiths, 2004)
Terrestrial birds	Species composition	Literature review and bird counts	(Hutton, 1868; Turbott, 1947; Girardet, et al., 2001; Veitch, et al., 2019)
	General species abundance	Mist-netting capture rates and bird counts	(Girardet, et al., 2001; Veitch, et al., 2019). Data analysis of unpublished mist-netting data described below.
	Tieke, hihi and tui abundance.	Distance sampling and bird counts	(Toy, et al., in press; Veitch, et al., 2019)
	Kiwi	Call counts	(Wade 2009; Wade 2014a)
	Short term mortality over the course of eradication operations	Cat trapping data and carcass searches pre and post rat eradication	(Veitch, 2001; Griffiths, 2004)
Reptiles	Species abundance and distribution.	Pitfall trapping (10 L plastic buckets baited 24 h with tinned pear) and search effort	(Brown, 2013)
	Short term mortality over the course of eradication operations	Cat trapping data and carcass searches before and after rat eradication	(Veitch, 2001; Griffiths, 2004)
Freshwater fish	Species composition	Trapping and spotlight surveys	(Winterbourn, 1964; Wade, 2014b)
Terrestrial invertebrates	Species composition	Anecdotal observations	(S.Wheatley, pers. comm.; R. Walle, pers. obs.)
	Wetapunga abundance	Detections per unit of search effort	(Green, et al., 2011)
Aquatic invertebrates	Species composition	Benthic sampling and light trapping	(Winterbourn, 1964; Wade, 2014b)
Threatened native and invasive alien plants	See production, seedling recruitment; abundance and distribution	Monitoring of seed set for *D. taylorii*; search effort for other threatened species and priority weeds	(D. Havell, unpubl. data; Campbell, 2011)
Canopy trees, palms and lianes	Juvenile recruitment on rat-inhabited versus rat-free islands, post-eradication response, seedling response in exclosures	Seedling numbers of 34 species counted on marked linear plots, twice before rat eradication and two years after on Hauturu and on two control islands with rats	(Campbell, 2011)

Mist-netting

Data collected from mist-netting completed before and after rat eradication were used to assess the impact of the application of rodent bait on the abundance and composition of forest birds. As these data are not published we summarise it here. Four trips were completed, one prior (January 2004) and three subsequent (August/September 2004, February 2005, August 2005) to the eradication comprising 413 mist-netting events at 69 sites across five valleys in an area of approximately 350 ha on the south-west side of the island (Fig. 2). Each trip lasted for between five and seven whole days of mist-netting. Each mist-netting event had an average duration (±sd) of 399 minutes (6 hours 39 minutes) ± 170 minutes and ranged from 06:11

(opening time) to 19:47 (closing time). On average, the median time a net remained open was 11:44 hrs.

In the analyses we assessed whether temporal factors (e.g. year, season, day, time of day) were directly associated with variability in the number of individuals and species caught in mist-nets. All analyses were compiled in SAS V.9.0. Generalised linear mixed models (with Poisson distributed errors) were used to assess the variability between both the total number of individuals (bird abundance) and the number of species (species richness) caught per mist-netting event with respect to temporal factors.

With the data assumed to follow a Poisson distribution due to its non-negative, count nature, we used Basic Generalised Linear Models followed by a more complicated Generalised Linear Mixed Effects Model to tease out changes between years for individual species. Richness and Shannon diversity were the variables being predicted, with Year, Season, Total Number of Birds, and Corrected Net Length as explanatory variables. Site and Net were included in the model as random effects, separately and together. The 'best' model was then used to fit the six species most commonly caught as the predictor variable.

RESULTS

Potential and actual costs to native biodiversity

Seabirds

Thirteen Cook's petrel (*Pterodroma cookii*) were trapped in cat leg-hold traps and euthanised (Veitch, 2001). The breeding success of Cook's petrel decreased following the removal of cats then increased after rat eradication. This was hypothesised to be a function of mesopredator release resulting in higher numbers of rats at higher elevations after cat eradication leading to greater impacts on Cook's petrel breeding success (Rayner, et al., 2007b). No other short term negative impacts on seabirds as a result of cat and rat eradication were observed.

Terrestrial birds

Thirty-two kiwi (*Apteryx mantelli*) were caught in traps during the cat eradication. Two were euthanised, the rest released unharmed (Veitch, 2001). Three kiwi were found dead after application of rodent bait (Fisher, et al., 2011) and are presumed, based on the necropsy of one individual, to have died from secondary poisoning. Despite the loss of these individuals, no change in calling frequency was observed in kiwi call count surveys completed after the rat eradication (Wade, 2009).

Individual mortality following bait application to target rats was documented for eight other terrestrial bird species including blackbird (*Turdus merula*), robin (*Petroica australis*), pukeko (*Porphyrio porphyrio*), kakariki (*Cynoramphus novaezelandiae* and *C. auriceps*), harrier (*Circus approximans*), kaka (*Nestor meridionalis*) and morepork (*Ninox novaeseelandiae*) (Veitch, 2001; Fisher, et al., 2011). Numbers of each species found after the rat eradication are presented in Fisher et al. (2011). However, no significant short-term population impacts were detected in an analysis of bird count data collected over the course of the cat eradication (Girardet, et al., 2001). Bird counts from 2012 to 2017, after rat eradication, using the same methods as Girardet, et al. (2001), showed no significant change in overall abundance but significant changes in the abundance of some species (C.R. Veitch unpubl. data).

Data collected from mist-netting conducted before and after rat eradication showed no significant change (either increase or decline) in any of three components of catchability (bird abundance, species richness, species composition) analysed for forest bird species. The only change measured was a significant increase in the number of both bellbird *Anthornis melanura* and parakeet (*Cyanoramphus novaezelandiae* and/or *C. auriceps*) captured. In total, 1,570 birds (twenty-three species) were caught in mist-nets. The total number of birds (bird abundance) caught varied between seasons ($F_{1,374}$ = 5.53, P = 0.02) but did not differ between periods of mist-netting completed before and after the bait applications targeting rats ($F_{1,374}$ = 0.34, P = 0.56). Number of species (species richness) ($F_{1,374}$ = 0.01, P = 0.93) and relative similarity in the composition of forest birds caught in mist nets ($F_{1,4}$ = 0.53, P = 0.51) did not differ significantly over the course of the rat eradication. These data correspond with the findings of a non-toxic bait trial completed ahead of the rat eradication, that determined the risk to terrestrial bird populations to be low (Greene & Dilks, 2004).

Reptiles

No individual mortality as a result of the cat and rat eradications was documented. However, anecdotal evidence and pitfall trapping (Fig. 3) suggest an unexplained decline in skink numbers following cat eradication, prior to rats being removed.

Freshwater fish

A freshwater fish survey conducted in 2000 detected redfin bullies (*Gobiomorphus huttoni*), banded kokopu (*Galaxias fasciatus*) and longfin eel (*Anguilla dieffenbachii*) (McGlynn, et al., 2000). No mortality following bait application for rats was observed, but a less extensive survey completed in 2009 detected only banded kokopu and longfin eels (Wade, 2014b).

Invertebrates

As predicted, no negative impacts on invertebrates were observed.

Plants

Aside from small-scale clearance of vegetation to form the trail network to complete cat eradication, no negative impacts on plants were observed but a greater impact on some plant species may have resulted from the release of rats from cat predation.

Potential and measured benefits to native biodiversity

Seabirds

Cooks petrel breeding success in high altitude habitats (with 90% of the population), averaged 5% prior to rat eradication but increased to approximately

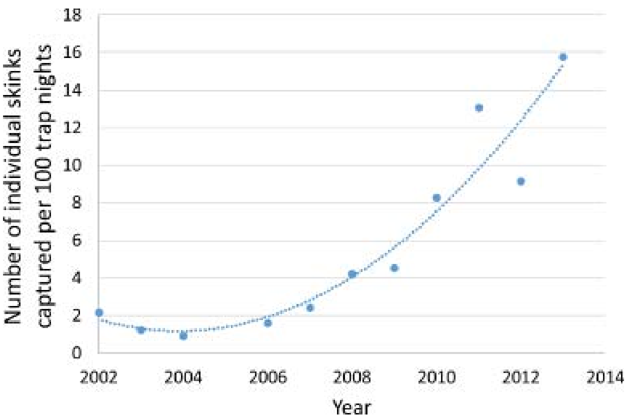

Fig. 3 Catch per unit effort for all skink species combined on Hauturu between 2002 and 2013 (Source: Department of Conservation, Warkworth, New Zealand).

60% the following breeding season as a result of reduced predation pressure (Rayner, et al., 2007a; Rayner, et al., 2007b). Improved Cook's petrel breeding success was also circumstantially reflected in a tenfold increase in the number of recently fledged chicks presented at bird rescue centres on the adjoining mainland the season following eradication and ongoing (M.J. Rayner, unpubl. data). An obvious massive increase in the extent and volume of nocturnal vocalisation by Cook's petrels has been observed over the last 12 years suggesting ongoing population recovery facilitated by increased breeding success and recruitment (M.J. Rayner, pers. obs.).

Up to 600 pairs of black petrel are now thought to breed on Hauturu (Bell, et al., 2016) up from the 50–100 pairs estimated by Imber (1987) prior to cat eradication. Similarly, breeding success increased from 1977 (50%), 1978 (60%) and 1996 (71.8%) (Imber, unpubl. data) to 2015/16 (85%). Before 1980 up to 67% of fledglings emerging from burrows were killed by cats and fewer than 5% of chicks were expected to have fledged (Imber, 1987). Between 1 and 28% of adult black petrels were also killed by cats at the colony between 1972 and 1976 (Imber, 1987). Comparisons of breeding activity within the same burrows during 1996/97 and 2015/16 showed a stable occupation rate of ca. 57% over the 19-year period and ca. 3% decline in breeding activity (Bell, et al., 2016).

New Zealand storm petrels (*Fregetta maoriana*), thought to be extinct for 110 years, were rediscovered at sea in 2003 and, after much effort, were located breeding on Hauturu in 2013 (Stephenson, et al., 2008; Rayner, et al., 2015). Mark recapture data collected between 2015 and 2017 suggest a minimum population size of 1,000 individuals (M.J. Rayner unpubl. data) and, based on at sea sightings, the population is steadily increasing.

Grey-faced petrels were discovered breeding after an apparent 60-year absence in 2009 and anecdotal observations of old colony sites suggest a gradual increase in these populations (M.J. Rayner, unpubl. data; Rayner, et al., 2009). The calls of other seabird species, such as common diving petrels (*Pelecanoides urinatrix*) and fluttering shearwaters (*Puffinus gavia*), have been also documented subsequent to rat eradication (M.J. Rayner unpubl. data) and may reflect recolonisation of the island's coastline by these predator-sensitive species.

Terrestrial birds

Three bird species have been introduced or reintroduced to Hauturu since the removal of cats: kakapo (*Strigops habroptilus*) during 1982, kokako (*Callaeus wilsoni*) during 1980–1988 and tieke during 1984–1988. Following their reintroduction, both tieke and kokako populations expanded rapidly and are now abundant across the island (K. Parker & I. Flux, pers. comm.). Kakapo were removed from the island in 1998 due to ongoing nest predation by rats but were re-established in 2012. Breeding by some individuals has subsequently been documented but whether the population will ever become self-supporting is at present unknown (L. Joyce, unpubl. data).

Annual distance sampling completed between 2005 and 2013 in the south-west of the island initially charted a decrease in numbers of hihi (*Notiomystis cincta*) and tui (*Prosthemadera novaeseelandiae*) (Toy, et al., 2018). Hihi numbers appeared to stabilise from 2009 onwards but the density of tui continued to vary. The recorded density of tieke changed little over the survey period. Forest bird counts undertaken between 2013 and 2017 within the same area recorded significantly higher numbers of bellbird, tomtit (*Petroica macrocephala*), parakeets, robin, kokako and tieke and a decline in numbers of whitehead (*Mohoua albicilla*), tui, hihi, rifleman (*Acanthisitta chloris*), grey warbler (*Gerygone igata*), blackbird and silvereye (*Zosterops lateralis*) when compared to counts undertaken before and during the cat eradication and prior to the rat eradication (C.R. Veitch, unpubl. data). No significant change was detected in the overall number of forest birds (C.R. Veitch, unpubl. data).

No significant change in calling frequency was detected in kiwi call count surveys over the period 1993 to 2014 although frequencies recorded were consistently higher than sites monitored on the North Island of New Zealand (Wade, 2014a). Despite the return of the brown teal (*Anas chlorotis*) that were removed during the rat eradication and the introduction of additional individuals, the brown teal population has not expanded. The brown teal population is considered permanent, but numbers present may be more a reflection of the species' breeding success on nearby Great Barrier Island (Aotea).

Banded rail (*Gallirallus philippensis*), last seen on the island in 1946 (Sibson, 1947), have returned to the island and reared young (C.R. Veitch, unpubl. data) and spotless crake (*Porzana tabuensis*), never previously recorded on the island, are now present and breeding (C.R. Veitch, unpubl. data). Another short-term impact worthy of note is the appearance and establishment of bellbirds at Tawharanui Regional Park subsequent to rat eradication (Brunton, et al., 2008). Invasive vertebrates were removed from Tawharanui at the same time as the rat eradication on Hauturu and this coupled with an increase in the number of bellbirds (as indicated by mist-netting data) may have created conditions suitable for dispersal and subsequent population establishment.

Reptiles

Following rat removal, numbers of reptiles caught in pitfall traps steadily increased (Fig. 3). Towns (*Oligosoma townsi*), moko (*O. moko*) and shore skink (*O. smithi*) showed the biggest increase (see Fig. 4), contributing to an 18-fold increase in the total number of skinks caught per 100 trap nights since the rat eradication (Brown, 2013). Although numbers are too low to quantify changes to the island's chevron skink (*Oligosoma homalonotum*) population, the number of additional skinks found after rat eradication may indicate population recovery. Prior to the rat eradication only one chevron skink had ever been found on the island. Four have been found since rats were removed.

Limited monitoring of the island's gecko populations was undertaken, but spotlight surveys completed in 2009 and 2013 suggest populations are recovering

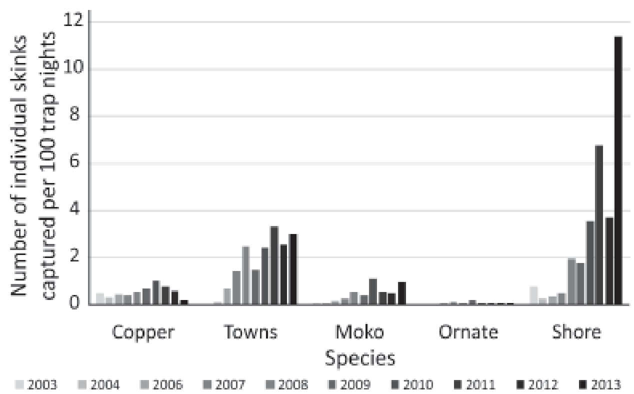

Fig. 4 Catch per unit effort for five species of skinks on Hauturu between 2002 and 2013 (Source: Department of Conservation, Warkworth, New Zealand).

from pre-eradication declines. Sighting rates of Pacific (*Dactylocnemis pacificus*), forest (*Mokopirirakau granulatus*) and common (*Woodworthia maculatus*) gecko in 2013 more than doubled relative to 2009 (Brown, 2013) and Duvaucel's gecko (*Hoplodactylus duvaucelli)* have been sighted more frequently (Hoare, 2009).

Tuatara (*Sphenodon punctatus*) were thought to be extinct on Hauturu until the species was rediscovered in 1991–1992 (Whitaker & Daugherty, 1991). Nine adults were taken into captivity on the island to ensure the relict population did not go extinct before rats were removed (Moore, et al., 2008). Since the rat eradication was confirmed successful in 2006 more than 196 young tuatara, raised in captivity, have been released at three sites and all captive adult tuatara have been returned to the wild. Additional adult survivors have been detected, breeding in the wild population has been noted and the population appears to be expanding (S. Keall, pers. comm.).

Aquatic invertebrates

A survey of aquatic invertebrates completed in 1963 was repeated in 2014 to identify changes in faunal composition. In total, 33 macroinvertebrate taxa from 12 orders were recorded from benthic samples. Six species of mayfly (*Mauiulus luma, Isothraulus abditus, Zephlebia spectabilis, Arachnocolus phillipsi, Ichthybotus hudsoni* and *Neozephlebia scita*), and two species of caddisfly (Trichoptera) (*Oxyethira albiceps* and a Chathamiidae sp.) not recorded in the 1963 survey, were found in 2014 (Wade, 2014b).

Terrestrial invertebrates

An annual monitoring programme to assess the recovery of wetapunga (*Deinacrida heteracantha*), New Zealand's largest giant weta, was instigated in 2005, a year after rats were removed. Numbers of wetapunga found in each survey had more than doubled by 2009 (Green, et al., 2011). Results indicate that the numbers increased by 50% every second year. Subsequent captive breeding, for translocation to other islands, showed that wetapunga have a two to three-year life cycle (P. Barrett, pers. comm.), potentially explaining the stepped rate of increase on Hauturu. During the monitoring programme, occupancy of daytime refuge sites remained low, suggesting the population may increase further over time. A repeat of the programme would be required to verify the level of increase and thus give a longer-term measure of the benefit of the rat eradication.

In 2017, surveys throughout New Zealand for the endemic forest ringlet butterfly (*Dodonidia helmsii*) revealed the species' presence on Hauturu. This species was widespread throughout much of the country but is now rare or absent from many areas of its previous distribution (S. Wheatley, pers. comm.). Despite the presence of suitable habitat, the forest ringlet had not previously been recorded on the island. Multiple individuals were found, indicating a resident population (L. Wade, unpubl. data; J. Knight, pers. comm.). Gibbs (1980) highlights the potential for introduced social wasps, the German wasp (*Vespula germanica*) and European common wasp (*V. vulgaris*), as a cause for the decline in forest ringlet populations. Interestingly, the European common wasp was noted by previous island rangers as a significant nuisance on Hauturu (C. Smuts-Kennedy, pers. comm.) but subsequent to the rat eradication social wasps have not been reported. The relationship between rat eradication and social wasp populations is currently the subject of a PhD study at the University of Auckland (J. Schmack, pers. comm.).

Plants

Nineteen of 34 plant species monitored on fixed plots had more than 20 seedlings and were analysed further (Campbell, 2011). Significantly more seedlings were found for 14 species following rat eradication, *Pisonia brunoniana*, *Coprosma macrocarpa*, *Ixerba brexioides*, *Knightia excelsa*, *Rhopalostylis sapida*, *Phyllocladus trichomanoides*, *Nestegis lanceolata*, *Dacrycarpus dacrydioides*, *Ripogonum scandens*, *Hedycarya arborea*, *Dysoxylum spectabile*, *Pittosporum umbellatum*, *Macropiper excelsum* and *Corynocarpus laevigatus* (Fig. 5). Seedlings of 11 others were searched for in 2008 and 2009. In 2009 *Coprosma arborea* seedlings were very abundant. Fewer seedlings were counted of *Agathis australis*, *Beilschmiedia tarairi*, *B. tawa*, *Prumnopitys ferruginea* and *Vitex lucens*. A few species that Pacific rats severely affect (e.g. *Coprosma repens*, *Elaeocarpus dentatus*, *Melicytus novae-zelandiae*, *Pouteria costata*), showed little early response because of their initial rarity (Campbell & Atkinson 2002; Campbell, 2011).

Prior to rat eradication, seedlings of *N. lanceolata*, *R. sapida* and *R. scandens* were rare, but in 2008, *N. lanceolata* was found on most plots, and *R. sapida* and *R. scandens* seedlings were common in moister sites. The number of seedlings of other tree species had also significantly increased. Seedlings of *B. tarairi*, *C. laevigatus* and *P. trichomanoides* were twice as numerous in *Kunzea ericoides* stands after rat eradication, *D. spectabile* was five times more common and *R. scandens* 41 times.

Threatened plants also showed a positive response to the removal of rats. Improved seed set by the endangered *Carmichaelia williamsii* was noted and the endangered *Euphorbia glauca* colonised new areas. Seed production

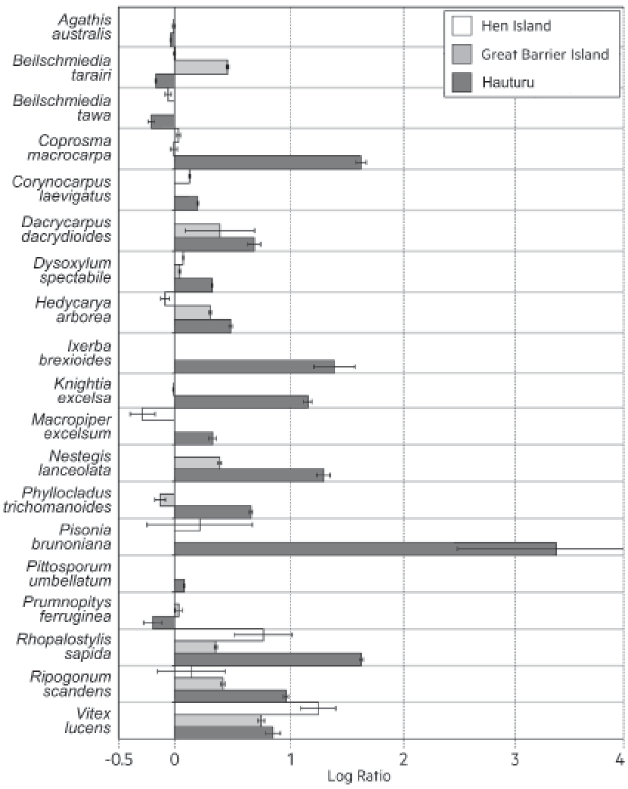

Fig. 5 Log ratios of seedling numbers on Hauturu (after eradication) and control islands with rats, with 95% confidence intervals. Log ratios of < 0, 0, > 0 indicate seedling counts that decreased, remained the same or increased, respectively.

in the endangered *Dactylanthus taylorii* increased and individuals have been discovered at new locations on the island including a site where seeds were hand sown (D. Havell, pers. comm.). No increase in seedling recruitment was noted for the invasive plant species *Asparagus scandens, Cortaderia jubata*, *C. selloana* and *Araujia hortorum* (managed as part of an ongoing eradication/ control programme) following rat and cat eradication.

DISCUSSION

The legislation that defines the management of Nature Reserves such as Hauturu, the Reserves Act 1977, mandates the removal of exotic species to protect native ecosystems. Cat and rat eradication on Hauturu became a matter of urgency because of their impacts on individual species. For cats, these impacts included extirpation of tieke and grey faced petrels as well as threats to other seabird species. The effects of rats were much wider and included impacts on seabirds, tuatara, lizards, invertebrates and an array of plants (Griffiths, 2002). Cats, rats or the two in combination were probably also responsible for the extinction of the last population of North Island snipe (Tennyson & Martinson, 2006).

Short term negative impacts from the cat eradication operation on Hauturu were minor and limited to the mortality of some non-target bird species caught in traps, apparent declines in skink populations and the removal of relatively small amounts of vegetation as a consequence of track and hut construction. An unanticipated outcome of the cat eradication, was a reduction in breeding success of Cook's petrel nesting at higher elevations. This was attributed to mesopredator release leading to increased predation pressure by a rat population no longer suppressed by cats (Rayner, et al., 2007b). This mechanism may also explain why pitfall trapping charted a decline in skink capture rates between cat and rat removal. Increased pressure on other rat foods (invertebrates, seeds and seedlings) may also have been sustained, but was not monitored.

As predicted in the AEE for rat eradication (Griffiths, 2002), negative impacts of the application of rodent bait were short-lived and minor and included no more than the loss of some individuals of at least eight bird species. Monitoring could not detect changes in abundance for these species indicating that they were not affected at the population level. The only native species not detected subsequent to the rat eradication was the red-finned bully. The absence of this species in the survey completed 10 years after the rat eradication could have been a consequence of the application of rodent bait for rats but equally the species could have been extirpated by a storm event or simply that insufficient search effort has been undertaken. This species is diadromous and likely to recolonise or could be reintroduced provided that suitable habitat on Hauturu is still available.

In contrast, the benefits of cat and rat eradication have been significant, and all species deemed vulnerable to extinction have since recovered. Tieke and kokako were successfully established following cat removal. Rat eradication resulted in recolonisation of the island by grey faced petrels and immediate recovery of the island's Cook's petrel population. As predicted by Griffiths (2002), there were increases in the abundance of skinks, geckos and invertebrates such as the wetapunga and in seedling recruitment by numerous tree species. All but one of the species identified as likely to benefit from rat eradication have shown evidence of recovery. The exception is the reintroduced tieke which could have reached carrying capacity ahead of the rat eradication.

Some species previously not recorded from Hauturu have made remarkable appearances. Examples include the New Zealand storm petrel, forest ringlet butterfly and eight new aquatic invertebrates. All such species were likely present in refugia but undetectable until rats were removed. It is unlikely that these will be the last discoveries to be made on the island. Several seabird species are expected to recolonise and highly cryptic species are still likely waiting discovery or rediscovery on Hauturu in the future. For example, only one record of striped skink has been made on the island, but this cryptic species will likely be found again in the future. As noteworthy as unexpected appearances is the disappearance of German and common wasps following rat eradication. The disappearance of these two highly invasive species may have enabled the recovery of the forest ringlet.

Other ecological changes post rat and cat eradication have been unclear. Predicted increases in the abundance of forest birds after cat and rat removal have yet to eventuate. Some species undoubtedly benefited following the removal of cats, but monitoring methods were insufficiently sensitive to detect population changes; bird counts were too variable to discern significant trends (Girardet, et al., 2001). It is also likely that some of the potential benefits of cat removal were confounded by the presence of rats. Attempts to manage kakapo on the island post cat eradication, for example, were thwarted by the continued presence of rats that preyed upon eggs and chicks.

After the removal of rats, initial positive trends for species such as hihi and tui were followed by declines to pre-eradication levels. Whether, this was a result of insufficient sampling effort, inadequacy of the methods used, changes in inter-specific competition among birds, or simply that the removal of cats and rats had little effect is not well understood. Forest birds were also monitored in the most accessible part of the island, the island's SW corner, which had been subject to the greatest impacts of logging and grazing. Consequently, ongoing forest successional changes may confound monitoring results. The most recent set of bird counts completed in 2017 suggest that some forest bird species have increased in abundance whereas others have declined (Veitch unpubl. data). Further monitoring is needed to confirm these trends. The effects of cat and rat removal on black petrel is also less straightforward. Although petrel numbers appear stable and breeding success has improved, the influence of other factors such as birds fledged from Hauturu being lured away to the much larger and noisier colony on Great Barrier Island (E. Bell, unpubl. data) may be affecting population recruitment.

As evidenced by altered patterns of seedling recruitment following rat eradication, changes in forest composition will occur. Future changes within the island's plant, invertebrate and reptile communities are likely to be strongly influenced by the recovery of Cook's petrel and the return of other seabirds. The enormous influence of seabirds on ecological communities has been well described (e.g. Jones, 2010; Smith, et al., 2011). However, given the large size of Hauturu and the extent of its forest communities, the full impact of these 'ecosystem engineers' is at present unknown.

On a global scale, there are no comparative invasive mammal eradications that have been completed in such a complex environment. The value of these eradications thus derives not only from the responses of resident species and recolonisation of those lost, but also in increasing our understanding of the ways invasive species influence island community structure. The changes reported here have been documented over only 13 years, but the removal of cats and rats has instigated a process of recovery that for many species on Hauturu will not be realised for decades. For those species reduced to relict populations and with low reproductive output, the post-eradication response will be slow. Other species such as snipe and some large species of lizards have been lost and will not contribute to Hauturu's ecosystems without intervention to re-establish them. The timescales involved for the recovery process are daunting. For example, the release of the near extinct tuatara population has begun a process of recovery for this species that may require centuries to play out.

From a social perspective, the islands of Auckland's Hauraki Gulf have been a source of inspiration for many members of the public. The removal of rats and subsequent reforestation of Tiritiri Matangi Island inspired volunteers to invest tens of thousands of hours to plant trees (Galbraith & Cooper, 2013). Hauturu has been no exception with its own Community Trust formed in 1997. The Little Barrier Island/Hauturu Supporters Trust provides on average $100,000 NZD annually to conservation programmes on the island. Visitors to Hauturu often return awe struck (R. Griffiths, pers. obs.) from their first view of 'primeval' New Zealand.

It is now important that the story of Hauturu, the impact that invasive species had on the island, and the recovery witnessed subsequent to cat and rat removal is shared on the world stage. It is only through the telling of such stories that the public's imagination will be captured along with the attention of government and private agencies. This and other projects have served to cement a sense of pride in New Zealand's biodiversity and have culminated in a pledge by New Zealand's Government for the country to be free of introduced predators by 2050 (Parkes, et al., 2017).

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