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Population estimation of the New Zealand storm petrel (*Fregetta maoriana*) from mark-recapture techniques at Hauturu/Little Barrier Island and from at-sea resightings of banded birds

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Abstract: Between 2014 and 2018 a mark-recapture/resighting study was conducted to ascertain the size of the population of New Zealand storm petrel (*Fregatta maoriana*) at their breeding grounds on Hauturu, Little Barrier Island, New Zealand. A total of 415 New Zealand storm petrels were captured and marked with individual colour bands using acoustic playback and night-time spotlighting on Hauturu. Two mark-recapture models were developed using the recaptures of banded birds on land and the at-sea resightings of banded birds attracted to burley on the Hauraki Gulf near Hauturu. The land-based model suggests a current population of 994 (range 446–2,116) individuals whereas the at-sea model suggests an estimate of 1,630 (range 624–3,758) individuals. The discrepancy between these models likely lies in the bias of on-land captures towards juvenile birds constituting >50% of birds caught. We consider the at-sea model most representative of total population size. Logistic population growth models anchored by on-land and at-sea population estimates suggest pre-rat eradication populations of New Zealand storm petrel of 323 and 788 individuals respectively.

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Keywords: New Zealand storm petrel, population estimate, spotlighting, Hauturu, Little Barrier Island, *Fregetta*

INTRODUCTION

The New Zealand storm petrel (*Fregetta maoriana*) (hereafter NZSP) is classified as "Threatened – Nationally Vulnerable" under the New Zealand Threat Classification Scheme (Robertson *et al*. 2017) and as "Critically Endangered" by the International Union for the Conservation of Nature (BirdLife International 2018). Endemic to New Zealand, the species was considered extinct until sighted at sea in northern New Zealand in 2003 (Flood 2003; Saville *et al*. 2003; Stephenson *et al.* 2008a). A ten-year research programme resulted in the discovery of the species' only known breeding site on Te Hauturu o Toi, Little Barrier Island (36°16′S, 175°06′E), in 2013 (hereafter Hauturu) (see Rayner *et al.* 2015 for overview). To date four NZSP breeding burrows have been discovered by using either telemetry or a trained seabird detecting dog and two chicks have been banded (Rayner *et al.* 2015). This population has been presumed to be expanding following the 2004 eradication of kiore (*Rattus exulans*), a likely predator of storm petrel eggs, chicks, and adults. The 1980 eradication of feral cats (*Felis catus*) would have removed a predator of adult birds and fledglings (Rayner *et al*. 2007).

A critical next stage in the conservation management of this poorly known seabird is understanding the distribution, size, and trajectory of this population following predator removal. However, the breeding habitat and behaviour of NZSP present challenges for population census. The small number of discovered New Zealand storm petrel nests on Hauturu lie 700–1,500 m inland under mature mixed conifer-broadleaf forest, including hard beech (*Fuscospora truncata*) and kauri (*Agathis australis*). The terrain in this area is steep with fragile slopes consisting of deep leaf litter and fragile rock scree. NZSP nests are in natural fissures and holes in this terrain, difficult to see, and likely easily damaged by field workers moving in the area. The behaviour of NZSP on land is also extremely cryptic. Birds are strictly nocturnal over the breeding site to the point where they show moonlight avoidance behaviour; visiting the colony before and after moon rise and set (Rayner *et al.* 2015). Accordingly, typical census techniques used for seabird population estimates, such as counts of birds or burrows at the colony, are not suitable and would damage areas where nesting sites have been found (Rayner *et al*. 2008; Rayner *et al*. 2015).

Mark-recapture presents a non-typical solution to the census of cryptic seabird populations and has been used with a variety of storm petrel taxa (Sydeman *et al.* 1998; Insley *et al.* 2014). This technique involves the marking of a subset of a population and later recapturing or resighting a new subset with the proportion of marked individuals allowing for estimation of the total population size. A variety of techniques have been used for capturing Procellariiformes on the wing including call playback (Insley *et al.* 2014), the use of mist nets (Becker *et al.* 2016), and spotlighting (Crockett 1994; Gummer *et al.* 2015). In 2014, we investigated the utility of using these three techniques to catch NZSP on Hauturu, concluding that a combination of call playback and spotlighting represented the best approach for a mark-recapture census (Ismar *et al*. 2015). Here we report the results of a five-year mark-recapture programme, using a combination of land- and sea-based mark-recapture and resighting, in order to quantify the population size of NZSP on Hauturu. In addition, we present a simple logistic model to estimate the growth trajectory of this population following presumed ecological release from rat predation in 2004.

METHODS

On land capture

NZSP are active at their breeding sites beginning in September with incubation conducted between February and April over a period of 40 days and chicks fledging in June and July following a chick

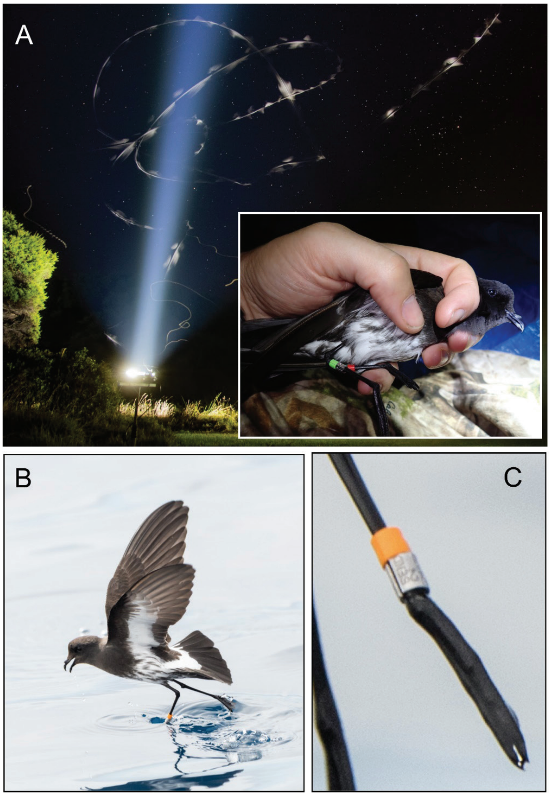

Figure 1. A. Capture site on Hauturu showing spotlight and time-lapsed New Zealand storm petrel descending before its capture (Photograph: Edin Whitehead). Inset showing banded NZSP in hand (Photograph: Andre Raine). **B.** Banded NZSP observed and photographed during at-sea resighting surveys (Photograph: Edin Whitehead). **C.** Close up of banded NZSP at sea with band number of bird legible at high resolution (Photograph: Edin Whitehead).

rearing period of 60 days (Rayner *et al.* 2015). We conducted field work on Hauturu over the course of five summer seasons: 2014 (18 Feb–2 Mar), 2015 (9–19 Feb), 2016 (8–15 Jan, 2–12 Feb, 1–5 Mar), 2017 (1 Feb–3 Mar), and 2018 (9–18 Feb). Our primary capture site was an area of clear grassland close to the likely flight path of NZSP approaching the valley containing known breeding burrows discovered in 2013 (Ismar *et al.* 2015; Rayner *et al.* 2015). Two other capture sites were used for a small number of nights over the five years: 1) several hundred metres away by the island's bunkhouse, which was used on three nights in February 2017 due to inclement weather at the main capture site; 2) on one night captures were attempted with hand-held torches on the far eastern coast of Hauturu, about five kilometres distant, in an attempt to investigate the distribution of NZSP around the island. The primary capture location presented the open space required for efficient use of hand-held spotlights and for the positioning of a generator that powered a flood light (500 W halogen). The flood light was positioned in the centre of the capture area with a baffle cone to direct light upwards in the sky so as not to impact the night vision of field workers (Fig. 1). Our previous research had demonstrated the extreme aversion of NZSP to moonlight over land (Rayner *et al.* 2015). Accordingly, most field trips were based around the new moon, with capture attempts finishing earlier or starting later in the night to account for moon rise and set.

A typical capture/recapture session began with the floodlight being turned on and a playback speaker (FOXPRO NX3) turned on playing a NZSP call previously recorded at a known breeding site (see Ismar *et al.* 2015). When a NZSP was attracted and sighted in the flood light, field workers used two Ledlenser X21 (2000 lumen) LED torches, as well as headlamps, to attempt to disorientate the storm petrel to bring it to ground in the long grass (Fig. 1).

Recaptured birds were marked with a thin stripe of white correction fluid (Liquid paper®) on the centre of the head and banded with a unique four-band combination consisting of one numbered metal New Zealand Department of Conservation stainless steel B size (4.0 mm) leg band and a three-colour combination of Darvic® leg band sequence (Fig. 1). The breeding status of captured birds was assessed through evaluation of brood patch moult following the protocols of (Rayner *et al.* 2013) (0 = fully downy to 4 = fully bare, and R = refeathering).

In the 2014 season processed captured birds were allowed to recuperate in a cardboard bird box away from light and noise and then released on the coast. From 2015 to 2018 captured birds were released into a trial NZSP colony consisting of 50 artificial plywood nest boxes, with 6 cm diameter Novacoil plastic drainage pipe entrance tunnels, and a sound playback system playing NZSP calls. The aim was to encourage the birds to anchor to the site for future nesting, in addition to the birds leaving scent in nest boxes at the trial colony to encourage other birds to stay. Birds were left to depart the nest boxes on their own accord before the following morning, although on occasion birds spent the following day in the box before leaving the subsequent night.

At-sea resighting

In 2016-2018 we conducted boat-based at-sea surveys for both unmarked and banded NZSP between January and March. This research was conducted at known locations where birds had been captured during our previous research programme (2006–2013) into the breeding location of the species including Northwest Reef (10 km north of Hauturu) and Simpsons Rock in the Mokohinau group, (36°00′26.93″S, 175°07′09.08″E) (see Stephenson *et al.* 2008b; Rayner *et al.* 2013; Rayner *et al.* 2015). During each resighting session, a sea anchor was deployed allowing the boat to drift slowly. Subsequently, a bait of frozen salmon burley in a mesh bag was deployed on a rope behind the boat as per Rayner *et al.* (2013). Observers on the boat used binoculars to observe any NZSP approaching the burley (typically within <50 m of observers) and identify birds possessing metal and colour band combinations. High-resolution digital photography was also used to record and confirm band combinations (Fig. 1). Birds were only added to the count of banded individuals if they could be individually identified by their unique metal and colour band sequence. Numbers of unmarked NZSP were also recorded at each location per timed session.

Mark-recapture estimates

Population size (N) was estimated based on the following mark-recapture equation:

$N = n*M/m$,

where n is the number of NZSP caught on-land or sighted at-sea in session i,
M the number of NZSP banded prior to capture/resighting session i,
and m the number of banded NZSP recaptured or resighted in the same session.

This mark-recapture equation was applied to all on-land capture and at-sea resighting sessions that yielded banded NZSP; the mean of all estimates for N was taken to represent the average population estimate of the respective study year, and minimum and maximum values of estimates were used as conservative indicators of confidence.

Population growth modelling

We used simple logistic population growth models, to calculate seasonal population size change and size at the time of rat eradication in 2004. Models

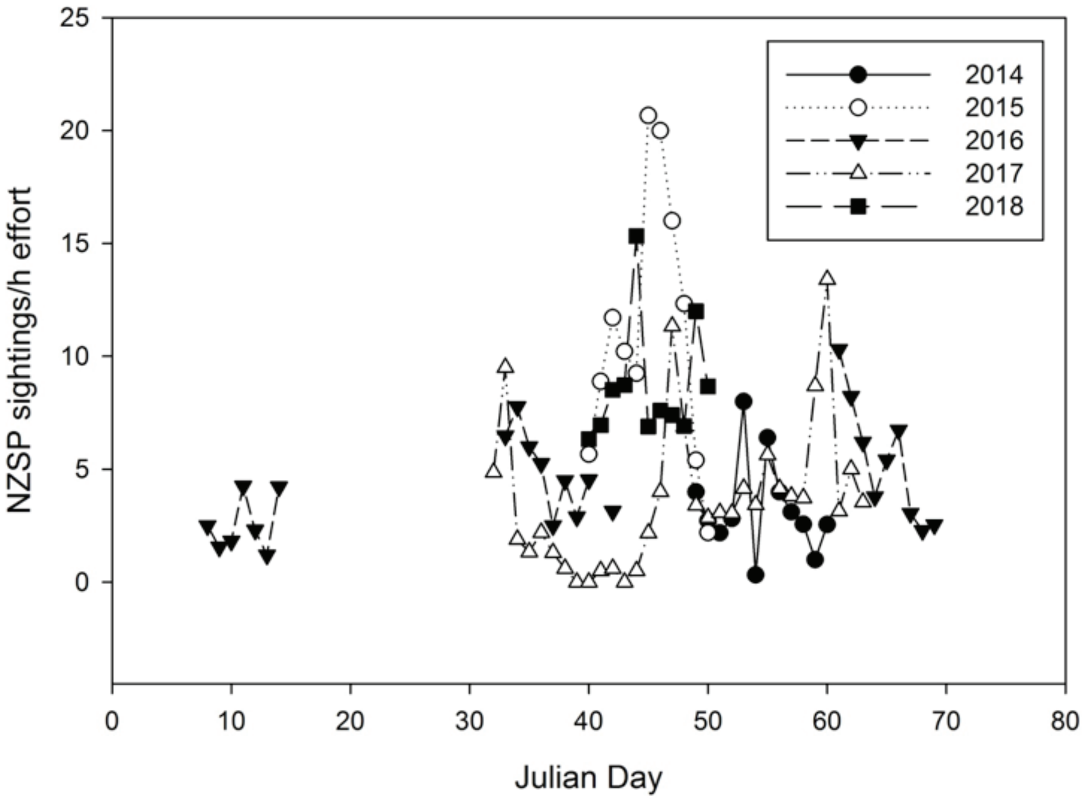

Figure 2. Sightings of New Zealand storm petrels per hour spotlighting and playback effort on Hauturu, across the prospecting, mating, and early incubation stages in breeding seasons 2014–2018. Julian day represents days passed since the beginning of the calendar new year.

were based upon mark-recapture population estimates and presumed population parameters including: reproductive success of 0.7 per storm petrel nest and season based on *Pelagodroma marina* breeding in the Hauraki Gulf (see Rayner *et al.* 2017); post-fledging survival to adulthood of 0.5, annual adult survival of 0.91 and age at first breeding of four years (based on *Fregetta tropica*; Beck & Brown 1971). The reproductive rate *r* was calculated as a product of the factors of successful recruitment probability from a nest in a given year and eventual recruitment probability of fledglings into the breeding population. We assumed a static population prior to rat eradication in 2004 and for 2003 (pre-rat eradication) estimates we averaged the results of individual models for mark-recapture on land (2015–2017) and boat-based surveys (2016–2018). Our population model describes the population size *N* in the year i+1 based on the population size in the previous year i, and the numbers of fledglings from four years prior to the estimate (i-3) by the following formula:

$$N_{i+1} = r * N_{i-3}/2 + s * N_i$$

We used the averaged model for estimates based upon land-based mark-recapture (2015–2017) and at-sea resightings (2016–2018).

RESULTS

Between 2014 and 2018, 399 field hours (91 field nights) of field work were conducted during which 6.4 ± 1.5 SE (0–20.7) sightings of NZSP per hour were made at the spotlighting site on Hauturu. There was a significant difference in sightings between years (Welch ANOVA F_4 = 11.2; P = < 0.0001; Fig. 2) with sightings per hour in 2015 (11.12 ± 5.8 SE) and 2018 (8.7 ± 2.7 SE) being consistently different from sightings in 2014 (3.3 ± 0.9 SE), 2016 (3.8 ± 0.8 SE) and 2017 (3.7 ± 0.6 SE; Wilcoxon comparisons all < 0.001), but not from each other (Wilcoxon P = 0.2). Across years sightings of NZSP per unit effort on Hauturu peaked in mid-February (Fig. 2).

In total, we captured, banded and released 415 NZSP. Over half of all birds captured (52%) had brood patches with no down shed (score 0) with the remainder being evenly distributed between brood patch scores of 1–4 (Fig. 3). No refeathering of the brood patch was observed.

We recaptured a total of 14 NZSP on land in 2015, 2016, and 2017 (Table 1). No banded birds were recaptured in 2018. These data provided a population estimate from averaged annual models of 994 (range 446–2,116) individuals (Table 1). We conducted a total of 21 hrs. of boat-based surveys in 2016 (10 hrs.), 2017 (7 hrs), and 2018 (4 hrs.) during which we were able to identify 20 NZSP by their unique band combinations (Table 1) providing a population estimate from averaged annual models of 1,630 (range 624–3,758) individuals (Table 1).

Our logistic growth models using on-land mark-recapture and at-sea resightings indicate a 2004 pre-rat eradication population of 323 and 788 NZSP individuals with averaged annual population growth rates (2004–2020), following rat eradication (Fig. 4), of 6.0 ± 0.2% and 5.1 ± 0.2%.

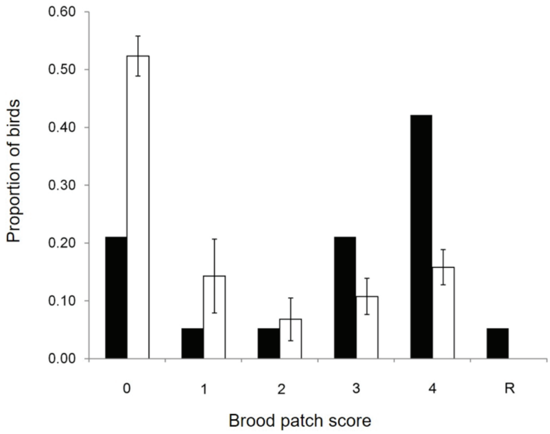

Figure 3. Brood patch score proportions (0 = fully downy to 4 = fully bare, and R = refeathering) of New Zealand storm petrels captured at sea in February 2012 (filled bars; n = 19) (Rayner *et al.* 2013) compared with scores of birds captured through spotlighting and playback on Hauturu (January–March, 2014–2018) (unfilled bars; mean ± SE, see Table 1 for sample sizes).

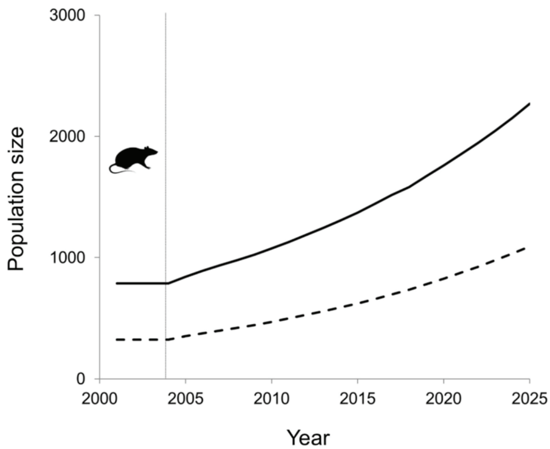

Figure 4. Estimates of New Zealand storm petrel population size trajectory on Hauturu between 2004 rat eradication and 2025. Models are anchored by and based on averaged mark-recapture calculations from land captures (2015–2017, dashed line), at sea resightings (2016–2018, solid line), and presumed population breeding and life history parameters (see methods).

Table 1. New Zealand storm petrel population estimates based on mark-recapture calculations from land-based captures 2015–2017 and on resighting of banded versus unbanded birds at sea 2016–2018.

Year	Location	Annual captures on land, and total sightings at-sea	Annual resightings/ recaptures	Population size, mean (min–max)
2014	Hauturu	40	0	
2015	Hauturu	114	6	704 (502–924)
2016	Hauturu	92	4	1,001 (732–1,405)
2017	Hauturu	114	4	1,276 (105–4,018)
2018	Hauturu	57	0	
	Model average			**994 (446–2,116)**
2016	At-sea	82	7	1,931 (1,040–4,158)
2017	At-sea	120	12	2,250 (409–4,499)
2018	At-sea	37	1	708 (424–2,616)
	Model average			**1,630 (624–3,758)**

DISCUSSION

Our five-year study provides the first population data for the NZSP suggesting a population size of fewer than two thousand individuals of this Threatened – Nationally Vulnerable seabird (Robertson *et al.* 2017). Our use of mark-recapture provided a useful alternative to census methods involving counts of burrows and/or burrow occupancy which were not possible in the fragile habitat supporting a cryptic population of unknown distribution. The capture of birds for mark-recapture was challenging, especially given the size of the available habitat on Hauturu. Techniques such as mist-netting, used on storm petrels breeding on islands an order of magnitude smaller than Hauturu (Sydeman *et al.* 1998; Insley *et al.* 2014), proved unsuccessful as a result of the low densities of flying NZSP. However, a combination of acoustic lures and floodlights proved ideal for drawing in NZSP to then be captured with handheld spotlights (Ismar *et al.* 2015). This technique would be suitable for other studies seeking to capture storm petrels in large landscape situations.

Sightings in our study support previous assertions of a February activity peak for NZSP over Hauturu, associated with estimated peak laying for the species (Ismar *et al.* 2015; Rayner *et al.* 2015), though a study weakness was that capture sessions did not extend beyond March to the known June chick fledging period. Interannual variation in NZSP sightings at the capture site were intriguing and we believe related to inter-seasonal differences in the timing of capture trips, moon phase, and prevailing weather conditions. Overall, NZSP were more likely to be sighted in greater numbers on moonless nights with cloud cover and/or light rain conditions (Rayner *et al.* 2015) as has been observed in other small Procellariiformes that seek to minimize predation risk during nocturnal activity over land (Yutaka 1986; Mougeot & Bretagnolle 2000).

Of interest is the difference between the land-based and at-sea based components of our study which yielded different population results. Land- and sea-based mark-recapture/resighting are important tools for the population assessment of Procellariiformes (Gummer *et al.* 2015; Rowe *et al.* 2018) including storm petrels (Zuberogoitia *et al.* 2007; Insley *et al.* 2014; Becker *et al.* 2016), but have inherent biases that can skew population estimates. On land the use of sound playback lures is known to bias capture rates towards pre-breeding individuals more attracted by the sound cues of conspecifics and/or more susceptible to the disorientation of flood lights. This is the case with NZSP (Ismar *et al.* 2015). Across the four years of our study over 50% of the birds had a downy brood patch (Ismar *et al.* 2015) at a time of year when breeding NZSP are either losing down in preparation for incubation (February) and/or sitting on eggs (March) (Rayner *et al.* 2015). The hypothesis that our on-land captures were dominated by young NZSP is supported by the remarkable recapture of a NZSP in March 2016 which had been banded as a chick two years earlier in May 2014; it had a fully downy brood patch (score 0) at the time of capture.

Capture bias over land towards a smaller pool of pre-breeding NZSP explains the smaller population size estimate for on land compared with at sea. NZSP visiting the burley oil slick likely have less demographic imbalance, as supported by the wide spread of brood scores from birds caught using scent-based burley attraction and a net gun during previous studies (Fig. 3) (Rayner *et al.* 2013). We thus consider the at-sea population estimate more representative of the total NZSP population on Hauturu and the land-based estimate a good indicator of the juvenile component of the population. However, caution must be exercised given the low recapture rates and the fact that our models could not account for changes in recapture rates on land as birds age. Regardless the current data provide a useful baseline for the ongoing monitoring of the population growth rate of NZSP on Hauturu using the same census techniques.

Our simple logistic growth models of the NZSP population based on mark-recapture estimates and generic storm petrel demographic parameters indicate the likely population expansion of NZSP from a potential low of between 300 and 800 individuals following the eradication of kiore from Hauturu. Before their eradication, kiore were likely a major predator of NZSP storm petrel eggs, chicks and adults (Booth 1995; Taylor 2000; Rayner *et al.* 2007) and may have experienced an ecological release of their population following the removal of feral cats, also a likely storm petrel predator, from Hauturu in 1980 – this may have further impacted a declining NZSP population (see Rayner *et al.* [2007, 2015] for discussion). The current data suggest that the 2004 eradication of kiore from Hauturu unknowingly prevented the continued decline of a relict NZSP population headed towards extinction.

The results of our study suggest that NZSP remain qualified as Threatened – Nationally Vulnerable under the New Zealand threat classification scheme by having a small increasing population of 250–1,000 mature individuals (Robertson *et al.* 2017). The species is also vulnerable as it only breeds at one location. Future census work for NZSP should focus on repeating night-time counts of NZSP at the current study site on Hauturu to provide a comparative data set by which to assess ongoing population recovery. This study should be conducted in February, and/or March, five years after the completion of field work in the current study.

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