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Using miniaturized radiotelemetry to discover the breeding grounds of the endangered New Zealand Storm Petrel *Fregetta maoriana*

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Identification of breeding sites remains a critical step in species conservation, particularly in procellariiform seabirds whose threat status is of global concern. We designed and conducted an integrative radiotelemetry approach to uncover the breeding grounds of the critically endangered New Zealand Storm Petrel *Fregetta maoriana* (NZSP), a species considered extinct before its rediscovery in 2003. Solar-powered automated radio receivers and hand-held telemetry were used to detect the presence of birds on three island groups in the Hauraki Gulf near Auckland, New Zealand. At least 11 NZSP captured and radiotagged at sea were detected at night near Te Hauturu-o-Toi/Little Barrier Island with the detection of an incubating bird leading to the discovery of the first known breeding site for this species. In total, four NZSP breeding burrows were detected under mature forest canopy and three adult NZSP and two NZSP chicks were ringed. Telemetry data indicated NZSP showed strong moonlight avoidance behaviour over the breeding site, had incubation shifts of approximately 5 days and had a breeding season

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extending from February to June/July, a different season from other Procellariiformes in the region. Radiotelemetry, in combination with rigorously collected field data on species distribution, offers a valuable technique for locating breeding grounds of procellariiform seabirds and gaining insights into breeding biology while minimizing disturbance to sensitive species or damage to fragile habitat. Our study suggests an avenue for other breeding ground searches in one of the most threatened avian Orders, and highlights the general need for information on the location of breeding sites and understanding the breeding biology in data-deficient birds.

Keywords: at-sea capture, bio-logging, Hydrobatidae, moonlight avoidance, Te Hauturu-o-Toi/Little Barrier Island.

Knowledge of the biology of rare or recently (re-) discovered and thus data-deficient birds is crucial to conservation management aimed at preventing extinctions (Finkelstein *et al.* 2010, Kawakami *et al.* 2012, Harrison *et al.* 2013, Ismar *et al.* 2014). However, obtaining such knowledge poses extreme challenges, as even basic information on behaviour, habitat and population dynamics is often lacking (Rayner *et al.* 2013, Simons *et al.* 2013). A prime case of such challenges is posed by procellariiform seabirds, of which at least 29 taxa (*c.* 28%) are data-deficient in terms of basic knowledge of their breeding biology, population status or trend (Croxall *et al.* 2012).

Procellariiform seabirds are among the most threatened avian Orders and their conservation status has deteriorated faster than that of any other comparable avian group in recent decades (Croxall *et al.* 2012). Threats to Procellariiformes include the impacts of commercial fisheries and pollution, terrestrial human disturbance, habitat modification and introduced predators (Moors & Atkinson 1984, Rayner *et al.* 2007, Madeiros *et al.* 2012). Impacts of introduced predators have been particularly acute for petrels and shearwaters (Procellariidae) and storm petrels (Hydrobatidae). In these groups, vulnerability is exacerbated by relatively small body size, which makes them susceptible to a broad range of avian (Votier *et al.* 2006, Matias & Catry 2010) and mammalian predators (Thayer & Bangs 1908, Totterman 2009). Introduced non-native predators in particular have resulted in catastrophic declines or extinction of many populations (Lee 2000, de León *et al.* 2006, Lawrence *et al.* 2008, Madeiros *et al.* 2012, Simons *et al.* 2013).

Critical to the conservation of threatened seabird populations is the identification of breeding sites, which allows active management of land-based threats to begin in order to assess and halt any population declines. Small seabirds present extreme challenges for detection once populations have been significantly reduced. They are generally restricted to inaccessible habitats (e.g. oceanic islands and/or remote mountain ranges), which may offer protection from exotic predators and/or human-induced disturbance (Simons *et al.* 2013). Within these habitats many species have a cryptic breeding biology, with nocturnal onshore activity (Votier *et al.* 2006, Riou & Hamer 2008). They generally nest under the ground in burrows or rock crevices, with little obvious sign of occupancy for human searchers, and can disperse quickly far from land following visitation, meaning that at-sea observations are of limited use in locating breeding sites (Rayner *et al.* 2012). It is thus little surprise that these seabirds represent some of the least studied avian species globally. Of approximately 110 taxa within the Procellariidae and Hydrobatidae, the breeding sites for nine taxa (*c.* 8%) remain unknown, taxonomic uncertainty remains for known species or species groups (Austin *et al.* 2004, Tennyson *et al.* 2012, Howell 2014) (Supporting Information Appendix S1) and new species continue to be discovered, e.g. Pincoya Storm Petrel *Oceanites pincoyae* and Bryan's Shearwater *Puffinus bryani* (Pyle *et al.* 2011, Kawakami *et al.* 2012, Harrison *et al.* 2013). When the breeding grounds are known, rare species can be well studied, e.g. Cahow *Pterodroma cahow* (Madeiros *et al.* 2012), Gould's Petrel *Pterodorma leucoptera leucoptera* (Priddel & Carlile 2009) and Chatham Island Taiko *Pterodroma magenta* (Imber *et al.* 1994a, Taylor *et al.* 2012). However, the study of aspects of procellariiform biology that can aid conservation management remains challenging.

A range of techniques have been deployed to uncover the breeding grounds of threatened seabirds, including ground searches (Crocket 1994), radar surveying (Cooper & Day 2003), observation of flyways or congregations of species offshore (Brooke 1987), spotlighting to capture individuals in flight over land or locating highly dispersed adults or fledglings on the surface (Gummer *et al.* 2015) and the use of trained scent dogs (Priddel *et al.* 2008). Where the location of breeding sites is suspected, radiotracking of tagged individuals has been an effective tool to add new breeding burrows to managed populations. For example, radiotelemetry of the endangered Chatham Petrel *Pterodroma axillaris* and Chatham Island Taiko, caught and tagged using either spotlighting or ground searches and tracked back to new burrows, has been vital in these species' conservation management (Imber *et al.* 1994a,b, Gummer *et al.* 2015). The potential of telemetry to discover hitherto unknown breeding sites has received little attention, with primary examples coming from research of Northern Hemisphere alcids (Bradley *et al.* 2004) and the Chatham Island Taiko (Imber *et al.* 1994a, 2005). Recent advances in the miniaturization of radiotags (now < 1 g) presents opportunities for radiotelemetry field studies of the smallest of seabirds such as storm petrels.

The New Zealand Storm Petrel *Fregetta maoriana* (NZSP) presents a classic example of the problems faced in seabird detection and management. The species was considered extinct for many years, known only from three museum specimens collected at sea in the 1800s, until an individual was sighted in waters off the east coast of North Island, New Zealand, in 2003 (Flood 2003, Saville *et al.* 2003, Stephenson *et al.* 2008a,b). Tissue samples from initial at-sea captures confirmed the species identity and clarified its taxonomy (Robertson *et al.* 2011) and ongoing sightings fed speculation as to whether NZSP were breeding outside or within New Zealand waters (Stephenson *et al.* 2008b, Gaskin *et al.* 2011). Subsequently, to understand the species' breeding provenance and timing, at-sea captures of NZSP were made between 2006 and 2012, and brood patch and moult status data were collected (Rayner *et al.* 2013). Birds caught in late summer had bare brood patches and a male-biased sex ratio, consistent with a female pre-laying exodus and the existence of an unknown breeding site in the region (Rayner *et al.* 2013). However, the existence of many candidate island breeding sites, and the likely cryptic biology of the species on land, meant that radiotelemetry presented a potential solution to aid ground-based searches for the species' breeding site (Gaskin *et al.* 2011). The current study reports the first discovery of a breeding site of this seabird, deploying a novel integrative approach of miniaturized radiotelemetry of NZSP caught at sea and simultaneous ground searches on multiple candidate islands.

METHODS

Study background and identification of candidate breeding sites

Since the first sighting of the species in 2003 off the Mercury Islands (36°38′15″S, 175°53′16″E) NZSP at-sea observations during the putative breeding season had been concentrated in the outer Hauraki Gulf, north of the city of Auckland, but they had been seen as far afield as the Three Kings Islands (34°10′18″S, 172°6′24″E), 500 km to the north (Gaskin & Baird 2005, Rayner *et al.* 2013) (Fig. 1). This region contains several hundred islets and islands potentially suitable for NZSP breeding sites identified on the basis of their small size, known mammalian predator history and knowledge of other breeding seabirds (Gaskin *et al.* 2011).

As storm petrel populations can be severely impacted by introduced mammalian predators (Taylor 2000), we considered that the species would probably be restricted to predator-free offshore islands or predator-free habitats on islands where predators did occur, such as sea cliffs. Islands considered candidate breeding locations for the NZSP included the Poor Knights Islands (35°28′9″S, 174°44′13″E) (always rodent-free), the Hen and Chicken Islands (35°55′37″S, 174°44′1″E) (some islets always pest-free), Mokohinau Islands (35°54′23″S, 175°6′47″E) (some islets always rodent-free) and Te Hauturu-o-Toi (hereafter Little Barrier Island; 36°11′58″S, 175°4′54″E, rat-free since 2004) (Fig. 1) (Gaskin *et al.* 2011). Between 2005 and 2012, opportunistic spotlight searches were conducted on land or by boat at these islands to provide an indication of storm petrel activity. The technique involved cruising slowly by boat around the island in the evening (when dark) when birds might be returning and using high-powered spotlights to identify the presence of NZSP in the air. Land-based spot lighting, the use of generator-powered floodlights and playback of storm petrel calls (e.g. Black-bellied Storm Petrel *Fregetta tropica* and White-bellied

Figure 1. Study area showing islands where search teams went ashore to detect radiotagged NZSP (Poor Knights Islands, Mokohinau Islands and Little Barrier Island) and capture locations of radiotagged birds (open circles).

Storm Petrel *Fregetta grallaria*) were also attempted on Burgess Island in the Mokohinau Islands (2005–2012).

Spotlighting revealed the presence of NZSP over land and near shore from a number of islands. In January 2006, an NZSP was brought to near ground level but not captured on Burgess Island in the Mokohinau Group during approximately 30 h of spotlighting from land. In 2012, spotlighting was conducted off Hen Island (Hens and Chicken Group) and Little Barrier Island (Fig. 1). On one night (22 May 2012; approximately 8 h spotlighting) two observations of NZSP (possibly the same bird) were made off the eastern end of Coppermine Island (Hen and Chicken Group) and over the course of six nights (28 February to 24 May 2012), 20 separate observations of NZSP were made off the northern coast of Little Barrier Island.

Radiotelemetry and at-sea captures

Field trials of radiotelemetry equipment for deployment on NZSP were conducted in the austral summer (December 2011–January 2012) on White-faced Storm Petrel *Pelagodroma marina* *maoriana* and in the austral winter (September 2012) on Common Diving Petrel *Pelecanoides urinatrix* breeding on Burgess Island, Mokohinau Group (Fig. 1). Tags trialled, and subsequently deployed, on NZSP were individually coded Lotek Nano Transmitters (model NTQB-3-2, Lotek©) weighing 0.67 g, which was approximately 2% of NZSP body mass (*c.* 35 g) (Rayner *et al.* 2013). Simultaneously, during these trials an automated tag detection system was developed and trialled featuring an automated tag reader (SRX-DL, Lotek©) with both omnidirectional (pole) and directional (yagi) mountings, solar panel (20-W photovoltaic module, SX320, bp solar©), solar charge controller (Prostar-15©) and sealed battery unit (12 V, 18 Ah, Synergy©) protected within a weather-proof casing. This system was capable of continuously logging the time, duration and signal strength of any radiotag detected for a minimum of several months. Field testing indicated the remote units had a detection range of < 1 km and < 3 km for the pole and directional antennae, respectively. Tags detected using handheld Telonics TR-4 and Biotrack Sika VHF receivers with Biotrack yagi antennae had a greater range of up to 10 km. Range increased with height, from 100 m at sea level to much greater distances when detecting from a headland or high point on an island, but the range was also impacted by sea state at low altitudes when signals could be blocked by swells.

The primary capture site was located in an area known as Nor-west Reef, used in the 2012 NZSP capture season and previously ascertained as an area of NZSP concentration as a result of enhanced productivity through marine upwelling (Rayner *et al.* 2013). Nor-west Reef lies between The Hen and Chicken Islands and Little Barrier Island (Fig. 1). At-sea captures for NZSP were conducted using methods outlined by Rayner *et al.* (2013). In brief, birds were attracted to a small (3.5-m) inflatable boat using a chum slick and captured using home-built net guns. Each net gun had four 50-mm-long aluminium barrels angled at 20° from the head of a PVC pipe chamber with 600-mm-long PVC tubes fixed into each barrel. Four projectiles (plastic tube 50 mm in diameter and 300 mm long, plugged to ensure floatation) were loaded into the PVC tubes and when fired using compressed air from a dive tank, dragged a mist-net material (30-mm mesh) out to a range of < 15 m. The projectiles and net were designed to float on the surface of the water and birds were retrieved within 20 s of capture. Captured birds were ringed with a numbered stainless steel metal band and colour ring combination. Brood patch condition was recorded for all captured birds (0: no down shed, 1: traces of down lost, 2: half of patch covered in down, 3: traces of down remaining, 4: patch free from down, 5: re-feathering present) as previous research had shown NZSP in breeding condition have bare brood patches between February and April (Rayner *et al.* 2013). Sex was determined using molecular analysis (Robertson & Stephenson 2008) of blood samples collected from the metatarsal vein and stored in lysis buffer (Seutin *et al.* 1991). Captured birds were fitted with a radiotransmitter attached to the upper surface of three central rectrices using a combination of thin (4-mm-wide) strips of self-adhesive all-weather cloth tape (Duct Tape®) and rapid set superglue (Selleys®) (Appendix S2). Birds were immediately released following handling, which lasted no more than 10 min.

Island-based detection

Based on observations of NZSP through spotlighting and the constraints of limited resources, a decision was made to focus telemetry search efforts for NZSP on Aorangi Island (101 ha, the Poor Knights Islands), Burgess Island (56 ha, Mokohinau Group) and Little Barrier Island (*c.* 3083 ha). The Mokohinau Islands were selected on the basis of the observation of a NZSP over land, and the fact that they had been rat-free for more than 20 years or included islets that had always been rat-free. Little Barrier Island was selected because of the number of observations of NZSP during spotlighting and the presence of large sea cliffs providing potentially predator-free habitat prior to eradication of Feral Cats *Felis catus* and Pacific Rats *Rattus exulans* in 1980 and 2004, respectively (Veitch 2001, Rayner *et al.* 2007). Automated tag readers on the island were located close to areas of observed nocturnal NZSP activity. The Poor Knights Islands were selected as they had always been free from rats and cats and because we were able to collaborate with a New Zealand Department of Conservation (DOC) research expedition present on the islands at the same time. While at-sea captures were being conducted, field teams were deployed on the Poor Knights Islands, Burgess Island and Little Barrier Island with the goal of detecting radiotagged NZSP coming ashore at night. Teams were present on the Poor Knights from 26 January to 11 February and on Burgess Island from 5 to 19 February. On Little Barrier Island, automated tag readers were installed on 23 January, the day before at-sea catching, and the field team for this island went ashore on 6 February.

Island-based detection of radiotagged NZSP was conducted using a combination of hand-held telemetry by field teams positioned on islands and automated radio-receivers. Automated receivers (ARs) were used on Little Barrier Island due to the large size of the potential search area at that site and were positioned on two headlands on the coast (Te Hue Point, altitude 80 m, and The Queen, altitude 120 m) approximately 4 km apart, selected based on the previous year's spot-lighting results. The two headlands were also selected to maximize signal reception and to detect any movement of birds either along the coast or moving inland. Simultaneously, field teams conducted radiotelemetry at night using hand-held antennae capable of detecting the radio-tag transmission frequency of 160 MHz but not of identifying the individual tag code. Hand-held radiotelemetry was typically conducted between *c.* 21:00 h (Austral summer dusk) and 02:00 h.

Statistical analyses

To assess whether there was an effect of body condition on the probability of NZSP being detected, we used non-parametric Mann–Whitney rank sum tests for differences in weight between NZSP detected over land with automated radiotelemetry and those tagged at sea but not subsequently detected over land. Sex-specific differences in the time in days elapsed between radiotag deployment at sea and first detection over land for male and female NZSP were assessed with unpaired two-tailed *t*-tests, as these data met normality and equal variance assumptions. To test for differences in the sex ratio between NZSP caught at sea and those subsequently detected using automated telemetry, we used contingency analysis (Fisher's exact tests) with a population sex ratio expectation of 0.5 (Ismar *et al.* 2010, Rayner *et al.* 2013). To assess whether the moon's cycle impacted the colony activity of radiotagged NZSP, we used a binomial distribution against a moon-independent expectation of 0.62 (average proportion of time the moon was below the horizon across all nights, which yielded NZSP signals on the land-based automated receivers) to calculate the probability of detecting radiotagged NZSP when the moon was above or below the horizon. Data are shown as mean ± 1 se and all analyses were conducted using JMP Pro 10 (SAS Institute), with a significance threshold of $\alpha = 0.05$.

RESULTS

At-sea captures and field team deployments

We captured 26 NZSP between 24 January and 8 February 2013, of which 24 were fitted with radiotransmitters prior to release (two birds were considered to be in poor condition with low body weight and tags were not attached). Sex was successfully identified for 21 of the captured individuals (sexing failed for two birds and feathers were not collected from three birds), showing a significantly male-biased sex ratio ($n = 21$, 17 : 4 male : female, $P < 0.01$) and a mean brood patch score of 2.16 ($n = 25$; one bird not scored). No re-feathering of the brood patch was detected. Primary moult was not detected in any bird caught, but late-stage tail moult was detected in five birds.

Island-based detection

A total of approximately 10 person-hours of hand-held radiotelemetry were conducted on the Poor Knight Islands, during which time no detections of tagged NZSP were made. On Burgess Island, approximately 30 person-hours of hand-held radiotelemetry were conducted, during which time one weak signal detection (10 s) of a radiotagged NZSP was made at 21:45 h on 8 February. ARs present on the northern Coast of Little Barrier Island first detected a radiotagged NZSP (bird 96) on 1 February, 8 days after its capture and release on the first day of at-sea capturing (Fig. 2a). Subsequently, between 1 and 12 February, the ARs detected 11 tagged NZSP (31 detection events in total) with birds first detected an average of 6.64 ± 3.41 days (range 2–12) following at-sea tag attachment (Fig. 2a).

There was no significant difference in time to first detection between sexes (male 6.83 ± 1.51 days, $n = 6$; female 6.75 ± 1.93 days, $n = 4$; $t = 0.03$, df = 8, $P = 0.97$), the sex ratio of detected birds ($n = 10$, 6 : 4 male : female) in comparison with

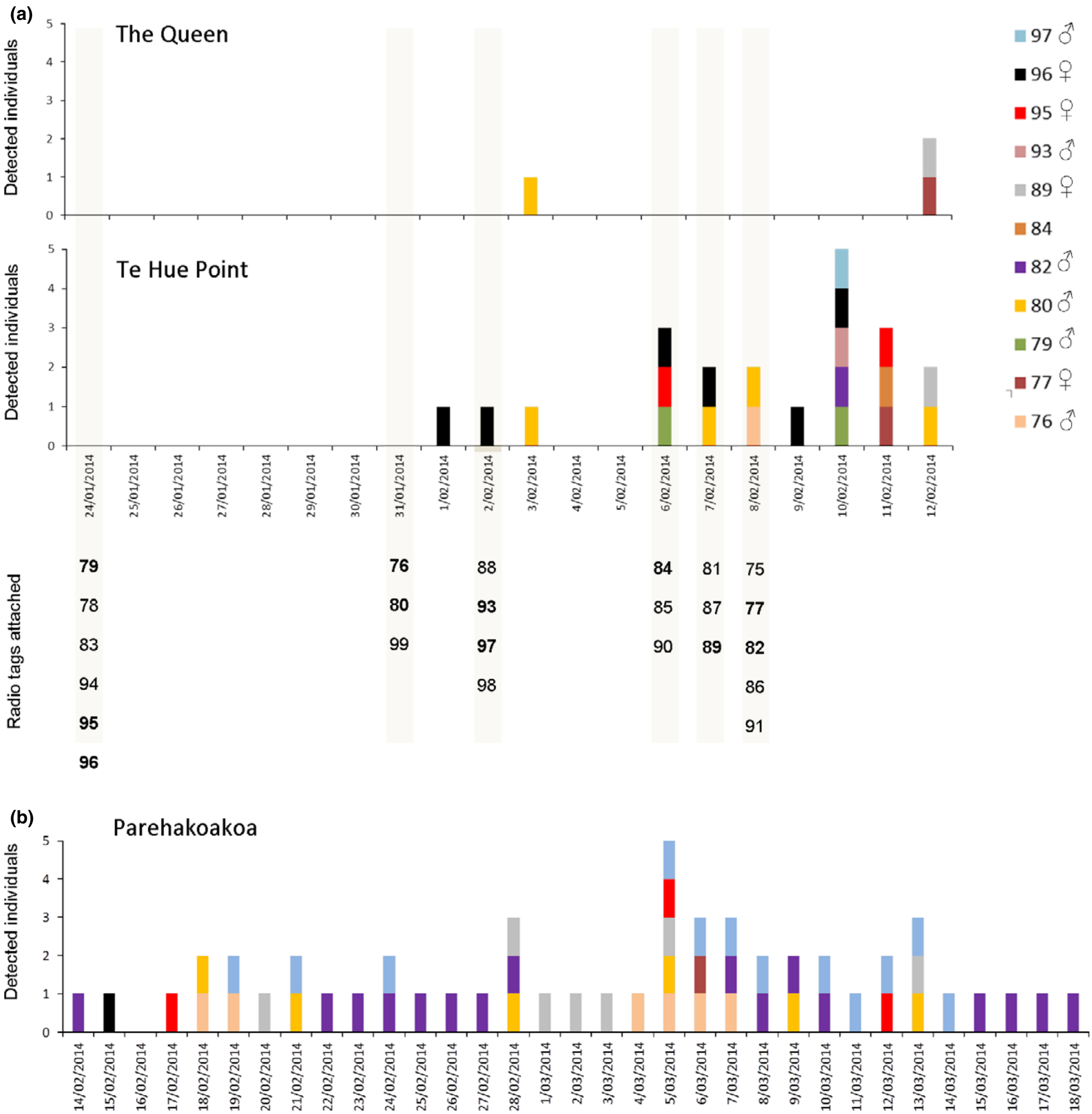

Figure 2. (a) Daily detections of coded radiotags attached to NZSP from automated receivers at The Queen and Te Hue Point, Little Barrier Island. Date of at-sea tag attachments shown below with birds subsequently detected by receivers in bold. (b) Daily detections of coded radiotags attached to NZSP from automated receiver at Parehakoakoa Valley breeding site 14 February–18 March; Bird 82 (Purple) detections represent incubation shifts in Burrow 1. Individuals colour-coded and sexed as per key.

at-sea captures ($n = 21$, 17 : 4 male : female) (Fisher's exact test, $P > 0.10$) or the weight on initial capture of birds subsequently detected vs. those not subsequently detected (detected 36.36 ± 1.46 g; undetected 34.54 ± 0.43 g; Mann–Whitney $U = 63.00$, $P > 0.10$). Brood patch scores in detected birds (1.64 ± 0.53) were significantly lower than in undetected birds (2.69 ± 0.44; $G = 6.8816$, df = 5, $P < 0.05$). All individuals were detected at the Te Hue Point receiver ($n = 28$ total detections) and three individuals were also detected at the Queen receiver ($n = 3$) with birds 80 and 89 being detected on the same night, first at The Queen receiver and then 6 and 17 min later, respectively, at Te Hue Point (Fig. 2a).

The high detection rate of the ARs on Little Barrier Island was matched by hand-held detections made by field workers. Between 6 and 11 February, approximately 37 person-hours of hand-held radiotelemetry were conducted on the northern coast of Little Barrier Island with a minimum of 13 detections of radiotagged NZSP made. These birds could not be individually identified with hand-held receivers. Spotlighting, from shore and boat, also confirmed the presence of NZSP over water and flying near large sea cliffs. Hand-held radio detections during this period suggested that tagged birds were flying up and over the cliffs. These observations were confirmed on 9 February when DOC rangers opportunistically detected two separate signals of radiotagged NZSP flying near the summit of the island at night (> 650 m a.s.l.). A further four radio detections, made by DOC staff near the Ranger's Base on 10 February, of birds flying inland, confirmed the presence of NZSP over most of the island, significantly enlarging the required search area. Subsequently (on 11 February) the decision was made to move the field team from the northern coast, where sea cliffs prevented teams from accessing the island's interior, to the western side of the island. ARs were removed from the northern coast on 12 February.

Breeding site discovery and monitoring

On the night of 11 February, four detections of NZSP were made from the western side of the island, with birds flying along the coast and also inland up the island's steep valleys. The following night of 12 February, approximately five NZSP (individual tag signatures were not discernible with hand-held telemetry) were detected flying inland, approximately 500 m from the coast. One signal was triangulated as stationary and located to within 1 m^2 of ground within the steep-sided Parihakoakoa Stream valley in dense forest at approximately 02:00 h. The ground was fragile, covered in dense Kie Kie *Freycinetia banksii*, making identification of a burrow entrance difficult. Subsequently (on 14 February) an AR was established to monitor the site, which immediately identified the NZSP radiotag (attached at sea to bird 82; male) in an unknown underground burrow or cavity (Burrow 1). Between 14 February and 18 March, the AR detected eight tagged individual NZSP (77 total detection events) flying over the site. All these birds had previously been detected by the Te Hue or Queen ARs (Fig. 2b). Bird 82 was present in Burrow 1 continuously from 22 to 28 February, 7 to 10 March and 15 to 18 March (Fig. 2b), after which time no further radio signals were detected at the site. It is presumed that the radiotag battery of bird 82 (and batteries of all other tags on NZSP) had failed after about 60 days.

Between late February and June, nest searches were conducted through a variety of means, including ground searches during the day, night-time monitoring, searches using a trained scent dog and installation of remote sensor cameras (PC900 Hyperfire Professional IR) at known burrow sites. Night-time monitoring during 20–23 February near Burrow 1 resulted in the capture of one adult NZSP (B94540), the first of the species caught and ringed on land. On 9 March, a second radiotagged NZSP was detected underground using hand-held radiotelemetry (a site subsequently labelled Burrow 2), *c.* 200 m up the valley from Burrow 1. This nest was not accessible, being located in a deep rock crevice on a cliff ledge. Further monitoring in March resulted in the capture of a second adult (B94541) nearby on the ground and NZSP were also observed flying past. Signals were detected using hand-held telemetry on three separate occasions. In early April a third bird was captured (B94542), and another one was seen entering a crevice among rubble (subsequently named Burrow 3). This bird eluded capture when it rapidly departed the burrow an hour later but a sensor camera was installed which subsequently recorded NZSP(s) entering and departing the site.

On 18 April an approximately 1-week-old chick was extracted from Burrow 1. A fourth burrow (Burrow 4) was found at the upper site on 16 May during a second dog search and a well-developed chick, considered to be < 3 weeks from fledging, was extracted, measured, ringed (B94543) and photographed. On 11 June, the chick in Burrow 1 was extracted, measured, ringed (B94544) and photographed. This chick appeared to be under-developed and doubts were expressed about its survival. However, two sensor cameras above the burrow captured not only one of the parent birds (bird 82, with radiotag still attached) on the ground close to the burrow on 27 and 28

June, but also (in July) the chick outside the burrow exercising its wings over nine nights prior to its presumed departure (approximately 10 July).

NZSP activity over land

Radiotagged NZSP were significantly more often present over land and detected when the moon was below the horizon (94 detections) than when the moon was above the horizon (14 detections; $P < 0.001$). The arrival time of birds followed changes in the timing of moon rise and set, with birds arriving early in the night at the beginning of the study, prior to moon rise, and several weeks later arriving later in the night following moon set (Fig. 3).

DISCUSSION

Radiotelemetry methods

Critical to the success of this project was the development of understanding of NZSP behaviour

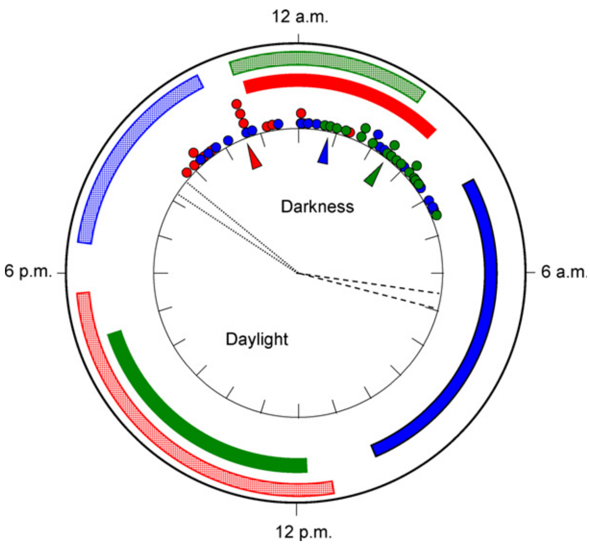

Figure 3. Timing of arrival of radiotagged New Zealand Storm Petrels detected by automated receivers (1–21 February 2013) (week 1: red circles, week 2: blue circles, week 3: green circles; mean values shown by respectively coloured triangles). Figure indicates how the arrival time of birds followed changes in the timing of moon rise (week 1: solid red bar, week 2: solid blue bar, week 3: solid green bar) and set (dotted bars coloured as per moon rise) with birds arriving early in the night at the beginning of the study, prior to moon rise, and several weeks later, arriving later in the night following moon set. Three-week range of sunset and sunrise shown by dotted and dashed lines, respectively.

at an increasingly finer spatial and temporal resolution. Initial observations confirmed the species' presence in an area totalling thousands of square kilometres of ocean habitat. This area was subsequently refined by boat-based observations to a reduced geographical area containing potential candidate breeding islands off the northeastern North Island (Gaskin & Baird 2005, Stephenson *et al.* 2008a, Gaskin *et al.* 2011). This ground work was essential to build up an understanding of the birds' occurrence and distribution, and constituted the greatest expense to the project in terms of boat charter costs. A possible alternative for research of larger seabird species (> 300 g) of unknown breeding provenance is the use of at-sea capture and tracking with lightweight satellite telemetry to refine search areas. On a finer spatial scale, boat and/or island-based searches, including spotlighting surveys, were critical for isolating candidate breeding sites for NZSP and for identifying the best locations for conducting telemetry operations, including the establishment of ARs.

The development of a technique to capture NZSP at sea was essential to the project's success (Rayner *et al.* 2013). At-sea capture has been used for research of a range of seabirds (Ronconi *et al.* 2010). Methods have most frequently involved the use of cast or hoop nets in combination with chum or using spotlights at night (Adams *et al.* 2012). The use of net guns is not widely adopted and has been cautioned against due to potential of risk of injury and or to the experience required (Ronconi *et al.* 2010). Research with NZSP demonstrates that net guns provide an effective technique to capture fast-flying seabirds without injury. No injuries have been sustained during captures of 54 NZSP (Rayner *et al.* 2013 and current study) or other storm petrels including 12 Pincoya Storm-Petrels *Oceanites pincoyae* (Harrison *et al.* 2013) and 141 White-vented Storm-Petrels O. *gracilis galapagoensis* caught in 2014 (C. P. Gaskin unpubl. data). Moreover, observations of species attracted to chum in the Hauraki Gulf suggest that the technique would be useful for studying a range of Procellariiformes including other storm petrels (e.g. White-faced Storm Petrel, Grey-backed Storm Petrel *Garrodia nereis*, Wilson's Storm Petrel *Oceanites oceanicus*), petrels (e.g. Cape Petrel *Daption capense*, Black Petrel *Procellaria parkinsoni*, Cook's Petrel *Pterodroma cookii*), shearwaters (e.g. Flesh-footed Shearwater *Puffinus carneipes*, Buller's Shearwater *Puffinus bulleri*, Fluttering Shearwater

Puffinus gavia) and a prion (Fairy Prion *Pachytila turtur*). These species landed on the water in the chum slick within range of the capture boat or approached the boat on the wing (e.g. Cook's Petrel) and could potentially have been captured by the net gun in flight.

Simultaneously with refining search areas, time spent developing and trialling ARs and refining of biologging techniques for radiotag attachment was essential for best practice. Initial radiotags trialled on White-faced Storm Petrels failed due to water leakage or tag loss through poor attachment technique and revealed issues with AR solar power supply, setting adjustments or antennae arrangements. These issues were subsequently resolved through a second trial on Common Diving Petrels of an improved set of tags supplied by Lotek, meaning a receiver tag system was able to be deployed on NZSP with the confidence that detections could be made under a variety of field conditions.

Burrowing Procellariiformes typically occupy breeding sites for brief periods during mating and/or chick feeding, often being ashore for less than an hour before birds depart for sea (Rayner *et al.* 2012). However, birds spend long periods (> 1 day) on nests during incubation and this time thus provides the best opportunity for the detection of a species ashore. Analysis of NZSP brood patch status from birds caught at sea over time was critical, as it confirmed that birds were in breeding condition and provided data on the likely egg-laying and incubation timetable. Male capture sex bias was also present and was consistent with the conclusion of Rayner *et al.* (2013) that females are absent from waters near the breeding colony during egg formation. Such understanding enabled radiotelemetry to be conducted at a time when the probability of birds being ashore, and thus being detected, was highest, maximizing the chances of the project succeeding.

NZSP breeding biology

While radiotelemetry was effective in enabling discovery of NZSP breeding sites, it also provided the first data on the species' breeding biology without major intervention in the fragile breeding habitat and at a time of year when storm petrels can be sensitive to disturbance (Lockley 1983). NZSP breed under forest canopy, as do other storm petrel taxa including White-faced Storm Petrel (West & Nilsson 1994) and Leach's Storm Petrel *Oceanodroma leucorhoa* (Stenhouse & Montevecchi 2000). However, NZSP is unusual in that it breeds in mature mixed subtropical forest, including Hard Beech *Nothofagus truncata* and Kauri *Agathis australis*, with canopy heights exceeding 30 m. In this habitat, birds were observed to fly below the canopy while active over the colony site (authors' pers. obs.) presumably using acute night vision to prevent collision with vegetation. Automated detections indicated incubation shift lengths of approximately 5 days in NZSP (bird 82, Burrow 1; observed shifts 7 and 4 days; Fig. 2b), longer than those observed in the species' sister taxon Black-bellied Storm Petrel (3 days) (Beck & Brown 1971), but comparable to those of Fork-tailed Storm Petrels *Oceanodroma furcata* (2–5 days) (Boersma *et al.* 1980). Moreover, discovery of an approximately 1-week-old chick from the first discovered burrow provided a likely hatch date (11 April, based on chick age at discovery), indicating that incubation for NZSP extends from early February until at least mid-April over approximately 40 days (Rayner *et al.* 2013). Using a chick-rearing period of 60 days (Rayner *et al.* 2013) suggests fledging for chicks in early to mid-June, consistent with the fledging date of the chick from Burrow 4. However, the chick from Burrow 1 fledged later (10 July), suggesting either a protracted breeding season for the species, or, in this instance, possibly some reduction in adult provisioning, possibly the loss of a parent, that impaired or delayed chick development.

By commencing incubation in February, the breeding timetable of NZSP is unique among procellariiforms in the Hauraki Gulf, where the 13 species lay eggs either in the austral spring and early summer (September to December) or winter (June to August) (Rayner & Gaskin 2013). White-faced Storm Petrels breeding in the Hauraki Gulf commence laying in November and fledge chicks in February–March (Young 2013), when NZSP commence incubation, suggesting possible niche partitioning between the two species, which are likely to use the same foraging habitat. Future research will focus on developing a more complete understanding of the species' breeding biology.

Population biology

Colony activity by NZSP was strictly nocturnal and birds showed strong moonlight avoidance behaviour typical of other storm petrel species experiencing nocturnal predation (Watanuki 1986, Votier *et al.* 2006). The native New Zealand Owl (Morepork) *Ninox novaezelandiae* is present on Little Barrier Island, predates seabirds much larger than NZSP (Anderson 1992) and presents a potential threat to birds on the surface, which moonlight avoidance would give protection from. It is unclear, however, how NZSP persisted in the historical presence of two introduced mammalian predators: Feral Cats and Pacific Rats. Cats were introduced to Little Barrier Island in the late 1880s (Hamilton 1961) and eradicated in 1980 following their documented impacts on Cook's Petrel and Black Petrel (Imber 1987, Imber *et al.* 2003, Rayner *et al.* 2007). Cats would have presented a nocturnal threat to adult NZSP and particularly fledglings, with our camera observations indicating extended periods spent exercising on the surface during the emergence period (*c.* nine nights). It is unknown when Pacific Rats first reached Little Barrier Island, but they were present from the 1880s until eradication in 2004 and predated Cook's Petrel eggs and chicks (Rayner *et al.* 2007). NZSP would have been extremely vulnerable to rat predation across all life stages, with rat impact enhanced by the ecological release of rat populations following cat eradication in 1980, as was the case with Cook's Petrel (Rayner *et al.* 2007).

Introduced predators such as cats and rats can result in catastrophic seabird population declines (Lawrence *et al.* 2008) and the NZSP population we discovered could represent the last remnant of a historically large population in the same habitat. However, we consider this unlikely, as this is the first account of the species despite the presence of conservation workers and ornithologists in the documented habitat since the late 1800s. A more plausible alternative is that the current breeding sites represent an expansion from refugia such as inland or sea cliffs present in the area, which offered protection from predators as observed in other New Zealand vertebrates following predator eradications (Hoare *et al.* 2007). Further research will seek to understand the size and distribution of this population across the island, and to identify the potential bottleneck width that the remnant NZSP population has experienced.

We suggest that radiotelemetry of Procellariiformes caught and tagged at sea provides an effective method with which to detect unknown breeding grounds and or gain an understanding of species biology while minimizing interference at fragile or sensitive breeding sites. Moreover, the discovery of NZSP breeding on Little Barrier Island using miniaturized radiotelemetry reinforces the idea that predator eradications can have both intended and unintended benefits. In this case, the survival of a presumed extinct species can be considered an unintended benefit of the coincidental protection of its breeding habitat.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Table summarizing Procellariidae and Hydrobatiidae taxa with breeding sites unknown or poor biological knowledge with key references.

Appendix S2 Images of field work for New Zealand Storm Petrel breeding site discovery with captions.