Developing a national framework for monitoring the grey-faced petrel (*Pterodroma gouldi*) as an indicator species

J.C. Russell, J.R. Welch, S. Dromzée, K. Bourgeois, J. Thoresen, R. Earl, B. Greene, I. Westbrooke and K. McNutt

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JR, KM, BG and JW wrote the manuscript
JR, KM, BG and IW designed the study
JW and IW analysed the data
JW, KB, SD and JT undertook fieldwork
RE drew the maps

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Abstract

Populations of seabirds such as the grey-faced petrel (*Pterodroma gouldi*) are sensitive to changes in the marine environment, making them useful indicators of marine environmental conditions. During September–October 2014, we piloted different sampling designs and monitoring methods for grey-faced petrel populations on three islands off the east coast of the North Island of New Zealand: Otata Island, The Noises, inner Hauraki Gulf; Burgess Island (Pokohinu), Mokohinau Islands, outer Hauraki Gulf; and Moutohora Island, Bay of Plenty. Each of these islands was known to support colonies of more than 100 pairs at low, moderate and high densities, respectively. We first sampled Otata Island by visiting 15 spatially balanced random sample points and counting the number of burrows that were present in 1- and 2.5-m-radius circular plots, and 20 × 20 m square plots; however, no burrows were detected. Next, we sampled Burgess Island using a revised sampling method that involved visiting up to 20 random sample points within each of four catchments to reduce travel time, which gave island-wide estimates of 8500 ± 4300 and 10 000 ± 3000 burrows using 1- and 2.5-m-radius plots, respectively. Finally, we sampled Motouhora Island by visiting up to ten random sample points within each of five catchments and using larger 5-m-radius plots, from which we estimated that there were 155 300 ± 25 900 burrows with 30.4 ± 8.3% occupancy, giving a total population estimate of 49 300 ± 6700 occupied burrows over the 72% of the island that could be surveyed. This within-catchment sampling of 5-m-radius randomised plots has the potential to become a standard sampling design and method for monitoring grey-faced petrel burrows as part of a national indicator species framework.

Keywords: grey-faced petrel, *Pterodroma gouldi*, indicator species, sampling design, monitoring framework.

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1. Introduction

Since 2005, the Department of Conservation (DOC) has been progressively developing and implementing a national system for monitoring and reporting on New Zealand's biodiversity (Lee et al. 2005; Hoare et al. 2010). This biodiversity outcomes framework is arranged in a hierarchical order of outcomes, indicators and measures to monitor and report on ecological integrity (McGlone & Dalley 2015), and allows indicators that are measured locally to be aggregated regionally and nationally over different temporal and spatial scales. DOC now routinely reports on several indicators and measures in its annual report (DOC 2016b), and the higher-level outcomes inform DOC's key performance measures (DOC 2016a; MfE & Statistics New Zealand 2015).

One of these measures (Measure 5.1.2) is the demography of widespread animal species (Lee et al. 2005), changes in the state (e.g. demography or distribution) of which can be correlated with changes in the state of the environment. Monks et al. (2013) described a process for selecting these so-called indicator species and taxa from terrestrial, freshwater and marine environments, which identified 106 species and groups, among which the grey-faced petrel (*Pterodroma gouldi*) (Fig. 1) was selected as an indicator of the marine environment.

Grey-faced petrel (*Pterodroma gouldi*) on Te Hawere a Maki (Goat Island). *Photo: James Russell*.

1.1 Grey-faced petrel as an indicator species

1.1.1 Natural history

The grey-faced petrel is an endemic New Zealand species that belongs to the diverse seabird order Procellariiformes (Onley & Scofield 2007). This species is classified as Not Threatened under the New Zealand Threat Classification System (Taylor 2000; Miskelly et al. 2008; Townsend et al. 2008), with national estimates suggesting an increasing population of 200 000 to 300 000 breeding pairs, indicating a total population in excess of one million birds (Robertson & Bell 1984; Taylor 2000).

More than 100 grey-faced petrel colonies are present from the Three Kings Islands in the north of the North Island south to New Plymouth on the west coast and Mahia Peninsula on the east coast (Taylor 2000, 2013). These colonies are largely limited to islands, stacks and headlands that are free from, or generally inaccessible to, introduced mammalian predators (Taylor 2000). Small mainland colonies supporting tens to hundreds of breeding pairs occur at Cape Reinga / Te Rerenga Wairau, the Waitakere Ranges, Mount Karioi, Mount Maunganui, Rapanui Reserve and various other locations. However, the majority of colonies are found on islands scattered along the species' eastern breeding range. Most of these islands support fewer than 500 breeding pairs, but at least 14 larger offshore islands that are more than 2 km from the mainland are believed to support more than 5000 breeding pairs, including Moutohora and Hongiora Islands, each of which supports an estimated 20 000 to 50 000 breeding pairs.

The grey-faced petrel and its conspecific the great-winged petrel (*P. macroptera*) tend to nest in habitats with deep soil supported by large root systems or boulders on particular slopes that have a lower risk of burrow collapse or flooding (Schramm 1986; Buxton et al. 2015). While burrow location and density are correlated with predictable environmental covariates such as vegetation and soil structure, social attraction is one of the most important drivers of burrow site selection (Taylor 2000; Buxton et al. 2014) and so burrows are typically densely clumped where they occur.

The grey-faced petrel is philopatric, with fledglings typically returning to their natal colony to breed. Prospecting birds return to colonies to engage in courtship in February, with activity typically peaking in April. Copulation is presumed to occur near the end of the courtship period (Imber 1976), following which birds depart the colony, with females returning in June to July to lay a single egg that is not replaced if lost. Incubation is shared by both parents, as is the subsequent care of the chick after hatching occurs in August to September (Imber 1976; Taylor 2013). Parents continue to feed chicks until fledging occurs in December to January.

1.1.2 Population regulation

Before using the grey-faced petrel as an indicator, it is important to assess which environmental parameters it is a suitable indicator of (Greene et al. 2015). Possible parameters include access to food (dependent on sea temperature, storm frequency, energetics, whether populations breed in the Tasman Sea or Pacific Ocean), predation (most introduced mammalian predators) and burrow habitat quality (particularly soil and vegetation structure and composition).

Food accessibility is the dominant marine environmental driver of grey-faced petrel populations (Buxton et al. 2014). Major changes in the marine environment are driven by both short-term (e.g. El Niño / La Niña weather patterns) and long-term (e.g. gradual changes in climate) processes, which can alter the strength and location of ocean currents and fronts, increase or decrease storm frequencies and intensities, and shift prevailing wind directions – all of which can impact on the distribution and abundance of marine prey (Grémillet & Boulinier 2009).

Predation by introduced mammalian predators is the dominant terrestrial environmental driver of grey-faced petrel populations. Feral cats (*Felis catus*) prey upon both adults attending colonies and chicks (Rayner et al. 2009), and have contributed to the decline of grey-faced petrels on Te Hauturu-o-Toi / Little Barrier Island (Veitch 2001). Mustelids and uncontrolled dogs can also kill adults and chicks (Taylor 2000), while feral pigs (*Sus scrofa*) have the potential to kill adults and dig up burrows along with the eggs and chicks they contain. Rats, particularly Norway and ship rats (*Rattus norvegicus* and *R. rattus*, respectively) are common predators of young or weak grey-faced petrel chicks (Imber et al. 2000), and have been known to severely reduce breeding success and even extirpate entire colonies.

The customary indigenous harvest of grey-faced petrel chicks is permitted in November from eight islands / island groups (Schedule Three, Wildlife Act 1953). There has been an active interest among Hauraki iwi to establish a sustainable customary harvest, which has resulted in collaboration between these iwi and Landcare Research to enable the prediction of grey-faced petrel population trends (Lyver et al. 2008). Lyver at al. (2015) found that customary approaches to harvesting grey-faced petrel chicks are likely sustainable in growing populations. However, they stressed that harvests from declining populations should not be considered sustainable, a fact which iwi take into account by placing temporary bans on harvesting when necessary (Clint Savage, DOC, pers. comm. 2014).

1.1.3 Measures of population size

Survival, breeding success, burrow density and occupancy are commonly used as indirect measures of population size in burrowing seabirds (Piatt et al. 2007). Burrow density tends to remain stable over decades, but long-term changes in this parameter can indicate changes in recruitment which, in turn, influence the size of a colony (Moller et al. 2009). By contrast, burrow occupancy tends to be more variable, reflecting intra- and inter-annual terrestrial and marine conditions. Changes in occupancy occur within seasons, when breeding attempts fail as a consequence of abandonment by parents or predation, and between seasons, as environmental conditions influence breeding success (Sutherland & Dann 2012). Consequently, burrow occupancy is commonly used to estimate the breeding population size.

Methods for estimating burrow occupancy include inspecting a burrow with a hand, stick or burrowscope (consisting of a small camera and light mounted onto the end of flexible tubing that sends a live video feed to a monitor display); excavating a burrow; and playing conspecific calls outside a burrow entrance and monitoring for a response (Rayner et al. 2007). Robust and defendable population size estimates are extremely difficult to obtain within colonies on islands (Whitehead et al. 2014) and even harder to standardise among islands (Parker & Rexer-Huber 2015), making population trend monitoring for grey-faced petrels challenging, particularly given their long breeding cycle (Jones et al. 2015b).

1.1.4 Survey methods

When using an indicator species, it is important that appropriate population and environmental parameters are monitored at the correct scale. As marine top predators, seabird populations can indicate the general health of the marine environment, particularly food availability (Piatt et al. 2007). However**,** measurable changes in the state of both the environment and indicator species must be able to be detected, as a guide, over half the generation time of the species, which for grey-faced petrel is 20 years. At the national scale, monitoring would need to occur at least three times during this period, i.e. once every 5–7 years, and population parameters would need to be measured that are both sensitive to changes in the environment during this period and yet robust enough to allow trends to be detected.

To date, grey-faced petrel burrow counts and occupancy estimates have been made using various plot survey methods, with no national or standardised methods (Parker & Rexer-Huber 2015). Plots are usually laid along transects, but there is also no standardised approach here, e.g. whether a systematic or random design should be used. Methods for estimating burrow density include counting burrows within plots of various sizes spaced along transects of different lengths or within large permanent plots; undertaking complete counts; and mapping all burrows on an island or in a particular area (Harrison 1992; Imber et al. 2003; Whitehead et al. 2014; Buxton et al. 2016). The sampling designs that are used tend to be specific to each monitored site or island, at best allowing comparisons to be made within a site or island over time. Consequently, robust estimates of grey-faced population size within and among sites and islands are highly variable, making it difficult to detect temporal trends in this long-lived bird.

Therefore, to estimate and detect long-term changes in population size at multiple sites over time, a standard national sampling design and sampling method is required that allows burrows to be counted on any island regardless of the burrow density, and that is unbiased and able to be extrapolated and applied to any population, rather than optimised for a particular island or location.

1.2 Objectives

The objectives of this pilot study were to:

1. Develop a sampling method that will detect changes in the national population of grey-faced petrel on predator-free islands off the east coast of the North Island with known populations of more than 100 pairs.
2. Pilot random and stratified random sampling methods to estimate grey-faced petrel population sizes on three predator-free islands off the east coast of the North Island with different grey-faced petrel densities.

The results of this study were intended to inform a more rigorous national sampling design and methodology for monitoring 5–21 predator-free islands with known grey-faced petrel populations of more than 100 pairs in this region during the breeding season peak (June/July) once every 5–7 years.

2. Methods

2.1 Sampling design

Plot-based burrow sampling methods assume that the burrow densities that are obtained from sampled locations reflect areas that are not sampled (Rayner et al. 2007). However, for this assumption to be valid, an appropriate statistical sampling design is required that includes random sampling to remove the effects of any confounding variables such as vegetation structure and composition, habitat modification, and introduced predator distribution.

The development of a national sampling method for grey-faced petrel populations on islands first requires a good understanding of their distribution and density. Greene et al. (2015) undertook a literature review of the historic and current distribution of grey-faced petrel breeding locations, identified the major environmental drivers of the meta-population, and summarised sampling designs; and also considered sampling designs and the use of a range of standard methods to detect trends within islands, e.g. larger plot sizes (20 × 20 m) for low-density populations of <100 pairs, medium plot sizes (2.5-m radius) for medium-density populations and small plot sizes (1-m radius) for high-density populations. This literature review showed that the distribution and density of grey-faced petrel populations change both within and between generations. Therefore, we concluded that a spatially balanced sampling approach within and among all islands using a single sampling method was preferable to stratifying by habitat or using a combination of methods.

Grey-faced petrel monitoring is best carried out between June and August, during the laying, incubating and early chick-rearing stages of the breeding cycle, as the highest proportion of breeding birds and either their eggs or offspring will be present at the colony during this time. However, for logistical reasons (staff and transport availability), our pilot survey needed to be carried out late in the breeding season (September and October), and so it should be noted that occupancy estimates are expected to be underestimates.

2.2 Site selection

In New Zealand, there are approximately 200 islands larger than 1 ha in size with potential habitat for grey-faced petrel. Of these, 105 have had some data collected on either the presence of birds or population estimates since the 1970s (Greene et al. 2015). To remove the confounding effects of dominant terrestrial pressures on grey-faced petrel populations, we excluded all mainland sites and islands with introduced predators. To remove the confounding effects of different marine pressures on grey-faced petrel populations between the west and east coasts, we excluded west coast islands in the Tasman Sea. Very small island populations (<100 pairs) have a higher probability of being impacted by stochastic events, making underlying population trends difficult to detect. Therefore, we also removed these islands from sampling. This left 21 predator-free islands off the east coast of the North Island with known populations of >100 pairs.

The majority of these 21 predator-free islands are subject to rahui or temporary bans on harvesting (Lyver et al. 2008), although illegal harvesting could still be taking place. Since the levels of legal and illegal harvesting may differ within and among islands (Lyver et al. 2015), we considered stratifying our sampling according to whether the islands were accessible (and therefore more likely to be subject to illegal harvesting) or subject to legal harvesting. However, since harvesting pressure is likely to be low and variable on all islands (Lyver et al. 2015), we assumed that this was a constant pressure that occurred to a similar extent within and among islands and between years.

We selected three relatively accessible islands to pilot proposed sampling designs and methods for surveying grey-faced petrel populations: Otata Island, Burgess Island (Pokohinu) and Moutohora Island. These represented a range of island sizes, known grey-faced petrel population sizes (small, medium and large, respectively) and burrow distribution patterns (clumped on Otata Island and Burgess Island (Pokohinu), and more uniform on Moutohora Island). These islands were surveyed over 1 week each during September–October 2014. We investigated whether these islands could be stratified by habitat type but were unable to obtain vegetation and soil maps at appropriate and useful scales for all three islands.

Due to time, safety and resource constraints, we used an adaptive monitoring framework, whereby burrow occupancy and density sampling methods were modified after surveying each island to improve the detectability and encounter rate of burrows on subsequent islands. To remove sampling bias and avoid the clumping of random sample points, we used a Generalised Random Tessellation Stratified (GRTS) survey design for each island, which maintains a spatially balanced sampling design through the sequential sampling of random points but can generate an oversample, which is useful when sample points prove inaccessible for field teams. Sample points can be measured in any spatial order as long as by the end of sampling no samples have been omitted from the sequential numerical order in which they were randomly generated. The total number of sample points generated by GRTS ranged from 20 to 80 plots per island and reflected the total area (ha) of each island.

2.3 Plot size

Grey-faced petrel populations are currently monitored by estimating the number of pairs or burrows using a range of plot sizes: 1– and 2-m-radius circular plots are commonly placed along transects on islands, but 3-m-radius circular plots and 10 × 10 m square plots have also been used (Whitehead et al. 2014; Buxton et al. 2015). The larger the plot size and the greater the number of plots sampled, the higher the accuracy and precision of population size estimates. However, there is a trade-off between the two. Large plots may have a higher detection probability of burrows, but are time consuming to establish, resulting in a lower number of sample points – thus, burrow density estimates are likely to be accurate but not precise. Conversely, small plots may have a lower detection probability of burrows but allow a greater representative range of habitats to be sampled, resulting in a larger sample size – thus, burrow density estimates are likely to be precise but not accurate.

To determine the trade-off between accuracy and precision, we compared burrow density estimates using 1-, 2.5- and 5-m-radius circular plots. In addition, we used 20 × 20 m reconnaissance (RECCE) plots to estimate burrow occupancy, as these are routinely used for describing New Zealand vegetation (Hurst & Allen 2007) and so their use for meeting additional monitoring objectives at the same site could bring cost benefits. Not all plot sizes were used on all three islands, however. Rather, we modified the burrow occupancy and density sampling methods after surveying each island to improve the detectability and encounter rate of burrows.

2.4 Field survey

2.4.1 Otata Island, The Noises, inner Hauraki Gulf

Site description

Otata Island is a small (16.8 ha) privately owned island situated in The Noises island group in the inner Hauraki Gulf. The coastal fringe is dominated by pōhutukawa (*Metrosideros excelsa*) and karo (*Pittosporum crassifolium*), with māpou (*Myrsine australis*), coastal karamū (*Coprosma macrocarpa*), houpara (*Pseudopanax lessonii*) and māhoe (*Melicytus ramiflorus*) dominating the centre (Cunningham & Moors 1985). Rasp fern (*Doodia australis*) and coastal cutty grass (*Gahnia lacera*) are the predominant groundcover. Norway rats were eradicated from Otata Island and the other islands in The Noises during the 1980s (Russell 2007).

Cunningham & Moors (1985) found that Otata Island only supported two breeding populations of burrowing seabirds – the grey-faced petrel and the little blue penguin (*Eudyptula minor*) – and counted approximately 150 grey-faced petrel burrows. Both of these species were also observed on Otata Island during the present study and are known to compete for burrows in other locations where they co-exist (Taylor 2000).

Field methods

Otata Island was surveyed from 2 to 4 September 2014. The northing and easting locations of 15 random points were generated using GRTS, with an additional oversample of five alternative points when the original points were inaccessible due to safety, cultural or environmental impact concerns (Fig. 2).

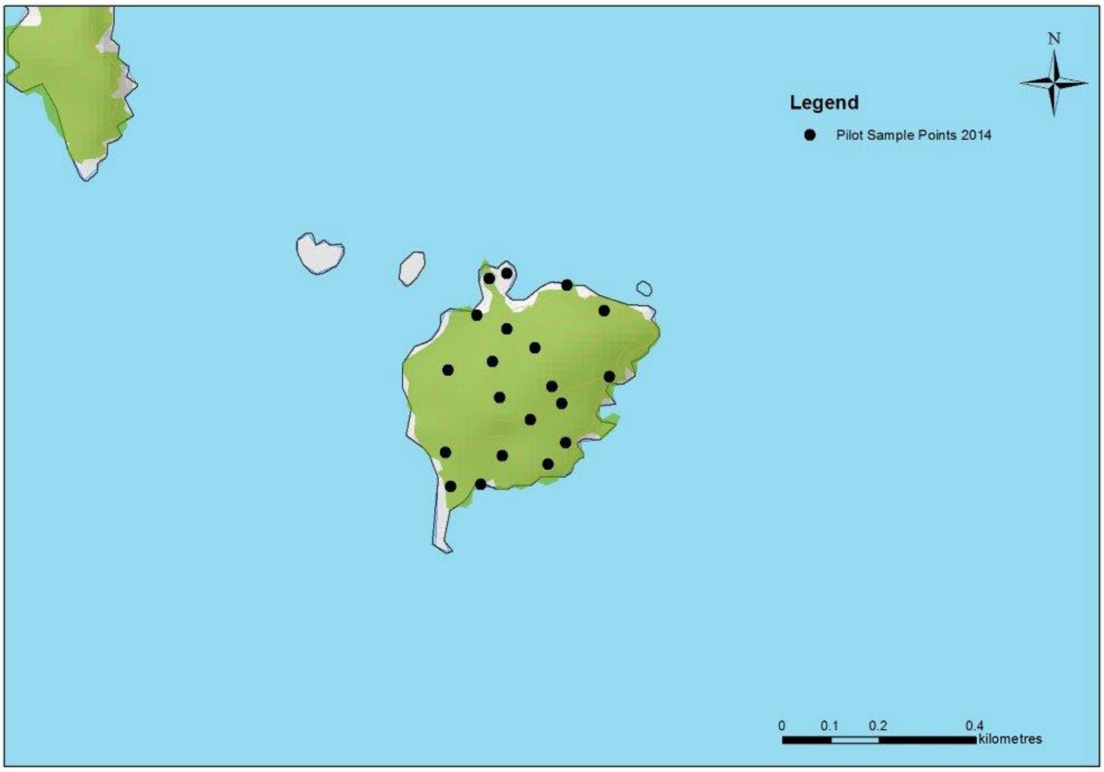

Figure 2. Otata Island sample points.

A hand-held Global Positioning System (GPS) receiver (Garmin GPSmap 62sc) was used to navigate to the sample points, which were visited in the numerical order in which they were generated. At each sample point, 1- and 2.5-m-radius circular plots were established by placing a temporary marker (e.g. a pole) at the centre of the location and looping a rope marked at 1 m and 2.5 m around it. The rope was then stretched taught to define two circles around the pole and the number of burrows found within each of the nested circular plots was tallied. Once the plot had been thoroughly searched, all plot markers were removed and observers moved to the next sample point.

A burrow was counted if it was large (approx. 30 cm circumference), and the centre of the entrance lay within the plot. Where two or more entrances led to the same nesting chamber they were counted once. If one entrance led to two or more nesting chambers then the number of chambers was counted. Burrow occupancy was determined using a LED burrow scope (Sextant Technology Ltd., Wellington, New Zealand) to determine the occupancy status (occupied, unoccupied, inaccessible or unknown) by ascertaining the presence of an egg, chick or adult. Flagging tape was removed from each burrow after it was searched. Plots were dismantled once the burrows had been counted and occupancy determined.

A 20 × 20 m square plot was also established at every fifth sample point. If any section of the plot was inaccessible, e.g. near a cliff edge, the plot was abandoned and set up at the next accessible sample point. Using a tape measure and compass, the locations of the corners of each 20 × 20 m square plot were established by measuring 14.15 m northwest, northeast, southwest and southeast from the plot centre. Each corner was then marked with flagging tape set at a readily visible height above the ground and the boundary of the plot was defined by setting up a length of rope between each of the corners. Burrows were searched for in 5-m-wide strips and, once found, were marked with flagging tape, tallied and evaluated for occupancy. No detailed vegetation assessments were undertaken, as Buxton et al. (2015) showed that micro-scale habitat preferences were not relevant when undertaking macro-scale sampling. Photographs were taken from each corner looking towards the centre of the plot to assess broad changes in vegetation structure and composition, and a photo identification number was recorded.

2.4.2 Burgess Island (Pokohinu), Mokohinau Islands, outer Hauraki Gulf

Site description

Burgess Island (Pokohinu) (56.3 ha) is situated in the Mokohinau Islands in the outer Hauraki Gulf, and is jointly managed by DOC and the Ministry of Transport. Most of the island is dominated by a mixture of knotted club rush (*Scirpus nodosus*), harakeke/flax (*Phormium tenax*), muehlenbeckia (*Muehlenbeckia complexa*) and grasses, with pōhutukawa and ngaio (*Myoporum laetum*) the only large woody plants present (Esler 1978). Feral goats (*Capra hircus*) were eradicated from the island in 1973 and kiore (Pacific rats; *Rattus exulans*) were eradicated in 1990 (Ismar et al. 2014), since when the island has been free of introduced mammals.

During the 1940s, grey-faced petrels were well distributed over the entire Mokohinau island group. Burgess Island (Pokohinu) is known to support well-established populations of a number of burrowing seabird species, including grey-faced petrels, little blue penguins, fluttering shearwaters (*Puffinus gavia*), little shearwaters (*Puffinus assimilis*), common diving petrels (*Pelecanoides urinatrix*) and white-faced storm petrels (*Pelagodroma marina*) (Gaskin & Baird 2004). However, grey-faced petrels are only likely to compete with little blue penguins for burrows on this island. Accessible seabird nesting habitat includes dense flax margins, soft ground under pōhutukawa trees and areas below rock overhangs (Gaskin & Baird 2004), while inaccessible habitat includes dense flax and taupata (*Coprosma repens*). Club rush (*Scirpus nodosus*) and buffalo grass (*Stenotaphrum secundatum*) or tussock areas were heavily burrowed and easily damaged.

Field methods

Burgess Island (Pokohinu) was surveyed from 12 to 19 September 2014. Being a larger island, it was divided into four quadrants to reduce travel time between sample points and to increase the overall number of sample points that could be surveyed to increase burrow detectability and sampling intensity (Fig. 3). These quadrants were of similar size and their boundaries were based on broad landform features such as ridges.

Twenty random sample points and ten oversample points were generated for each quadrant using GRTS, and observers visited the sample points within each quadrant in numerical order. The sampling methods were the same as for Otata Island, whereby observers counted the number of burrows in 1- and 2.5-m-radius circular plots at each sample point. The 20 × 20 m square plots were also initially sampled at every fifth sampling point, as for Otata Island, but this was later changed to every tenth point, as many were abandoned due to their close proximity to dangerous terrain, e.g. cliffs. In addition, 20 × 20 m plots were not surveyed in quadrant 1 due to time constraints; however, the total number of sample points for the circular plots was consistent across quadrants (i.e. 20).

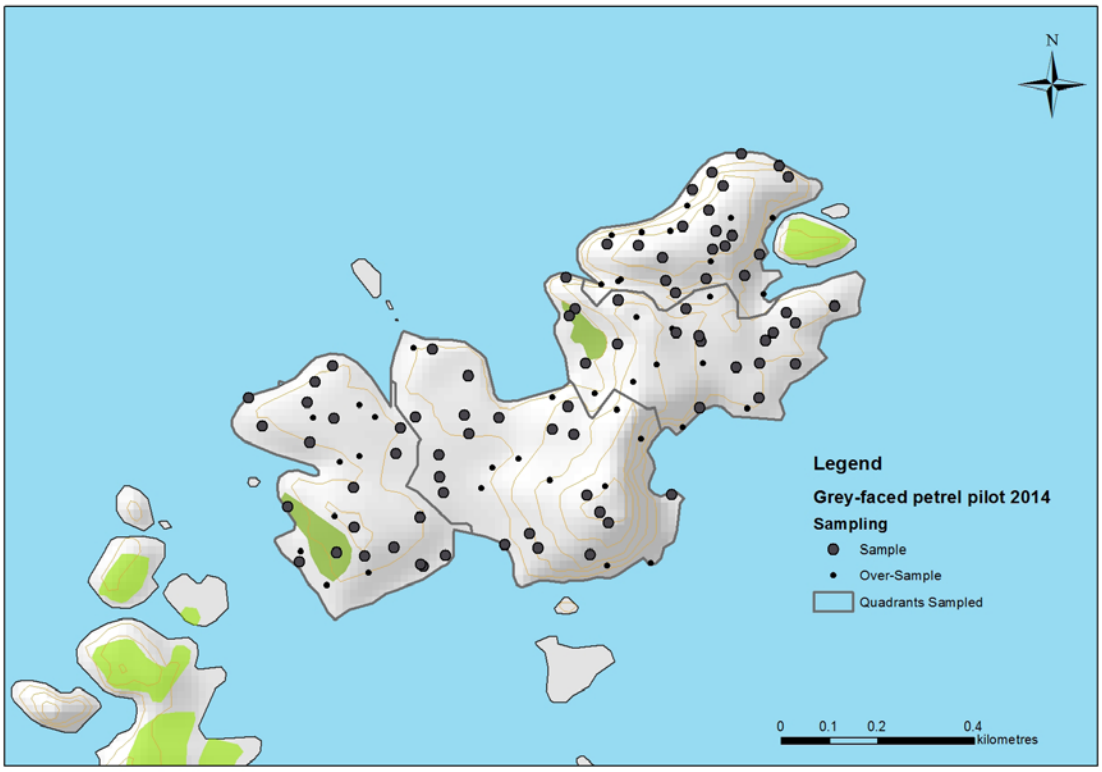

Figure 3. Burgess Island (Pokohinu) sample points and the boundaries of the four quadrants.

2.4.3 Moutohora Island, Bay of Plenty

Site description

Moutohora Island (173.8 ha; also known as Whale Island) is situated in the Bay of Plenty, 9 km off Whakatane. This island is covered in pōhutukawa- and māhoe-dominated forests, kānuka (*Kunzea ericoides*) shrublands and pasture grasses (Christensen 2012). Norway rats were introduced to Moutohora Island c. 1920, while rabbits (*Oryctolagus cuniculus*) arrived c. 1968 (Imber et al. 2000). Both species had been eradicated from the island by late 1987, following a 10-year control programme.

Moutohora Island, along with Hongiora Island, supports one of the largest populations of grey-faced petrels, with an estimated 20 000 to 50 000 breeding pairs (Taylor 2000). Breeding success was drastically reduced during rat occupation but has since increased (Imber et al. 2000). Both fluttering shearwaters and sooty shearwaters (*Puffinus griseus*) were once known to breed on the island but were exterminated by cats and rats in the mid-1900s (Christensen 2012) – there are plans to re-establish populations of these species on the island through the use of acoustic attraction and possible translocations. Therefore, little blue penguins are presently the only significant burrowing seabirds breeding on the island aside from grey-faced petrels. As on the other islands, these species are likely to compete for burrows in some areas of Moutohora Island. Moutohora Island is also one of eight permitted sites where the customary harvest of grey-faced petrel chicks by local Māori iwi in November has recently been reinstated (Jones et al. 2015a).

Field methods

Moutohora Island was surveyed from 16 to 22 October 2014. The island was divided into eight quadrants, and ten sample points and an oversample of ten points were generated for each quadrant using GRTS (Fig. 4). However, quadrants 2 and 3 were not surveyed out of respect for a request from Ngāti Awa – the local iwi and owners of Moutohora Island – not to undertake sampling within Māori cultural or archaeological zones (Christensen 2012); and quadrant 7 was not sampled due to inaccessibility. Five to six sample points in the remaining accessible quadrants were surveyed, completing surveys in 32 of the 50 accessible points.

To determine whether the use of larger circular plots would increase burrow detection rates, burrow counts and occupancy were measured in 5-m-radius circular plots. No 20 × 20 m plots were established in an attempt to maximise the number of sample points surveyed by the field team. Sample points in quadrant 1 were initially sampled in the numerical order in which they were generated, as per the requirement of the GRTS random design. However, the sample points in the remaining accessible quadrants were visited in spatial order to increase the surveying efficiency.

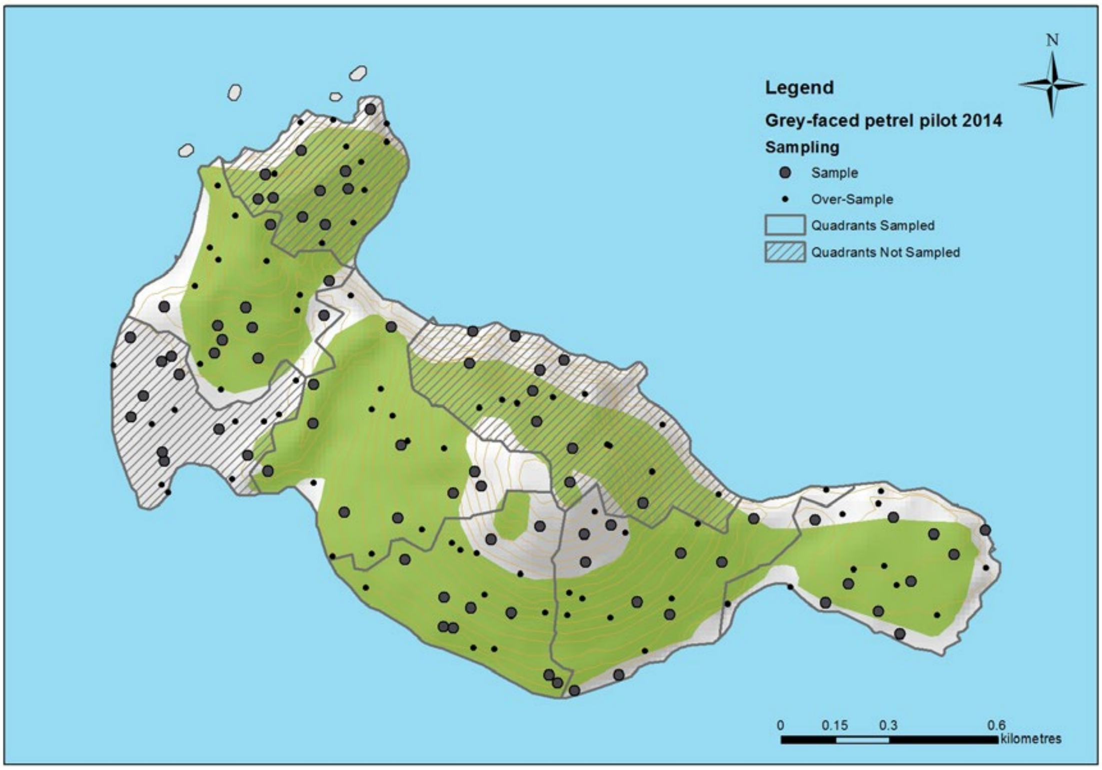

Figure 4. Potential sample points in the eight quadrants on Moutohora Island. Three quadrants (hatched) were unable to be sampled because they included cultural and archaeological zones (Christensen 2012) or were inaccessible.

2.5 Statistical analysis

Burrow occupancy was estimated by averaging the proportion of occupied burrows found in each plot, excluding burrows whose occupancy status could not be determined. Where quadrants were used, variance estimates for occupancy were calculated by summing binomial variance estimates within quadrants, then taking sums of the quadrant results weighted by the square of the area of the quadrant. All estimates and 95% confidence intervals (CIs) were calculated using the Survey package (Lumley 2004) in R 2.15.3 (R Core Team 2013).

3. Results

The total numbers of 1-, 2.5- and 5-m-radius circular plots, and 20 × 20 m square plots that were targeted and actually sampled on each island are summarised in Tables 1 & 2.

Table 1. Total numbers of target and actual sample points measured for each plot size on each island.

ISLAND	1-m-RADIUS PLOTS (BURROW COUNT)		2.5-m-RADIUS PLOTS (BURROW COUNT)		5-m-RADIUS PLOTS (BURROW COUNT AND OCCUPANCY)		20 x 20 m PLOTS (BURROW COUNT AND OCCUPANCY)	
	TARGET	ACTUAL	TARGET	ACTUAL	TARGET	ACTUAL	TARGET	ACTUAL
Otata*	20	15 (75%)	20	15 (75%)	NA	NA	4	4 (100%)
Burgess (Pokohinu)*	80	67 (84%)	80	67 (84%)	NA	NA	16	8 (50%)
Moutohora†	NA	NA	NA	NA	50	32 (64%)	NA	NA

* Area of the entire island.

† Area of the five quadrants that could be surveyed.

Table 2. Densities of target and actual sample points measured for the total available area surveyed on each island.

ISLAND	AREA SURVEYED (ha)	NUMBER OF SAMPLE POINTS ALLOCATED	DENSITY OF SAMPLE POINTS ALLOCATED (NUMBER/ha)	NUMBER OF SAMPLE POINTS MEASURED	DENSITY OF SAMPLE POINTS MEASURED (NUMBER/ha)
Otata	16.8	20	1.19	15	0.89
Burgess (Pokohinu)	56.3	80	1.42	67	1.19
Moutohora*	173.8	80	0.46	NA	NA
Moutohora†	117.8	50	0.42	32	0.27

* Area of the eight quadrants over the entire island.

† Area of the five quadrants that could be surveyed.

3.1 Otata Island

No grey-faced petrel burrows were detected in any of the 1- and 2.5-m-radius plots at the 15 sampling locations on Otata Island, but the survey team did observe at least 50 burrows while walking between sample points and 127 grey-faced petrel burrows were found during a census that was carried out just prior to the pilot (Fig. 5).

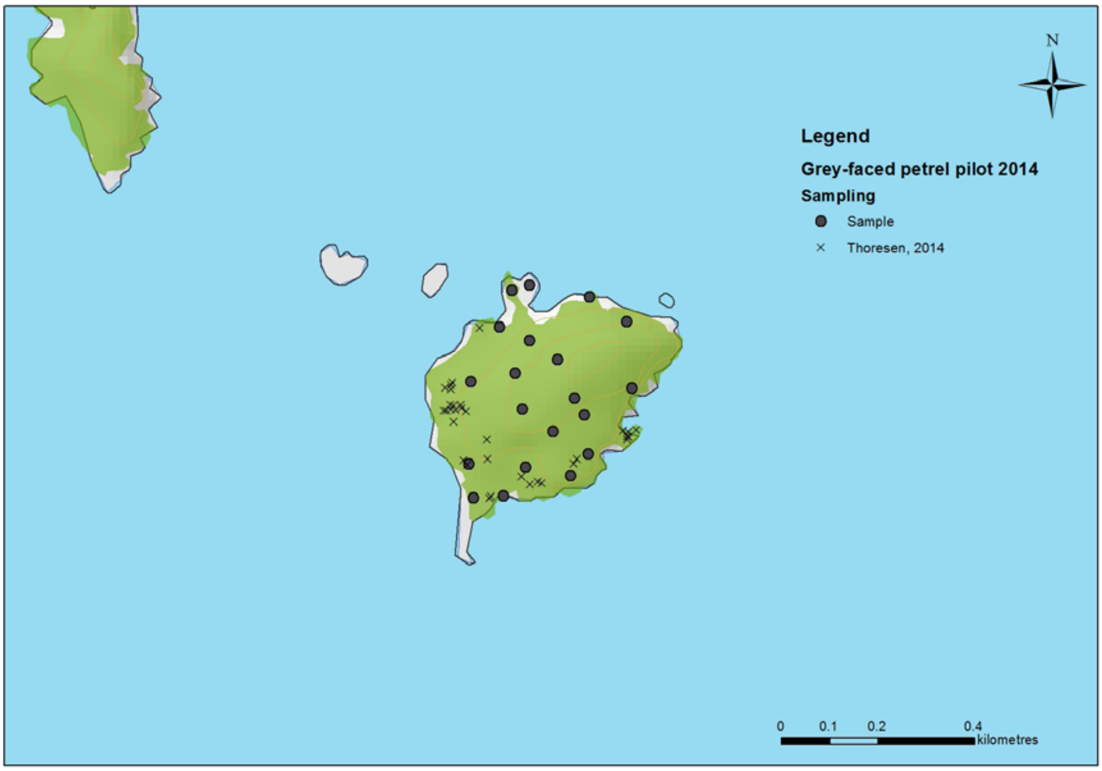

Figure 5. Grey-faced petrel (*Pterodroma gouldi*) burrow distribution on Otata Island in 2014

3.2 Burgess Island (Pokohinu)

Burrows were detected in four of the 1-m-radius plots (6.0%) and 12 of the 2.5-m-radius plots (17.9%) (Fig. 6), giving total estimates for the island of 8500 ± 4300 and 10 000 ± 3000 burrows, respectively (Table 3). Burrows were also detected in two of the eight 20 × 20 m occupancy plots (25%), giving an island-wide estimate of 2000 ± 1700 burrows (Table 4). However, since the sample size was low, this result should be interpreted with caution and it was not possible to estimate burrow occupancy. The 95% CIs were much wider for the burrow density estimates from the 1- and 2.5-m-radius plots than from the 20 × 20 m square plots.

Table 3. Grey-faced petrel (*Pterodroma gouldi*) burrow density estimates on Burgess Island (Pokohinu) based on 1- and 2.5-m-radius plot surveys.

QUADRANT		1-m-RADIUS PLOTS		2.5-m-RADIUS PLOTS	
NUMBER	AREA (m^2)	DENSITY (NUMBER/m^2)	TOTAL (n ± SE)	DENSITY (NUMBER/m^2)	TOTAL (n ± SE)
1	69 682	0.0579	4000 ± 2700	0.0648	4500 ± 1900
2	137 696	0.0199	2700 ± 2000	0.0223	3100 ± –*
3	114 833	0.0159	1800 ± –*	0.0127	1500 ± 1800
4	177 348	0	0	0.0051	900 ± 1000
TOTAL	499 559		8500 ± 4300		10 000 ± 3000

* Standard error estimates are not available because the counts were identical in each of two replicates (2.5-m-radius plots, Quadrant 2) or there was only one replicate (1-m-radius plots, quadrant 3).

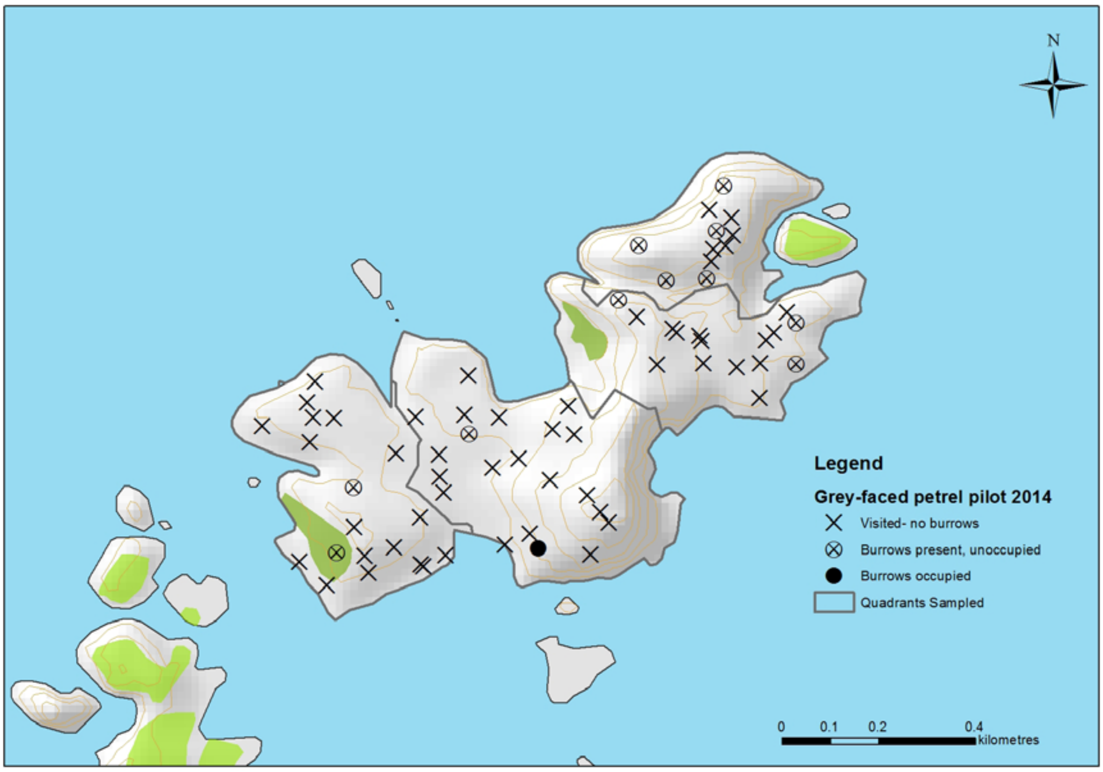

Figure 6. Grey-faced petrel (*Pterodroma gouldi*) burrow distribution on Moutohora Island in 2014.

Table 4. Grey-faced petrel (*Pterodroma gouldi*) burrow density and occupancy estimates on Burgess Island (Pokohinu) based on 20 x 20 m plot surveys.

QUADRANT		20 x 20 m-RADIUS PLOTS		BURROW OCCUPANCY (%)
NUMBER	AREA (m^2)	DENSITY (NUMBER/m^2)	TOTAL (n ± SE)	
1	69682	0	0	NA
2	137696	0	0	NA
3	114833	0.0038	400 ± 600	0
4	177348	0.0917	1600 ±1600	9.1
TOTAL	499559		2000 ± 1700	NA

3.3 Moutohora Island

Grey-faced petrel burrows were detected in 28 of the 5-m-radius plots (89.5%) on Moutohora Island (Fig. 7), giving estimates of 155300 ± 25900 burrows and 49300 ± 6700 occupied burrows for the 72% of the island that was surveyed (Table 5).

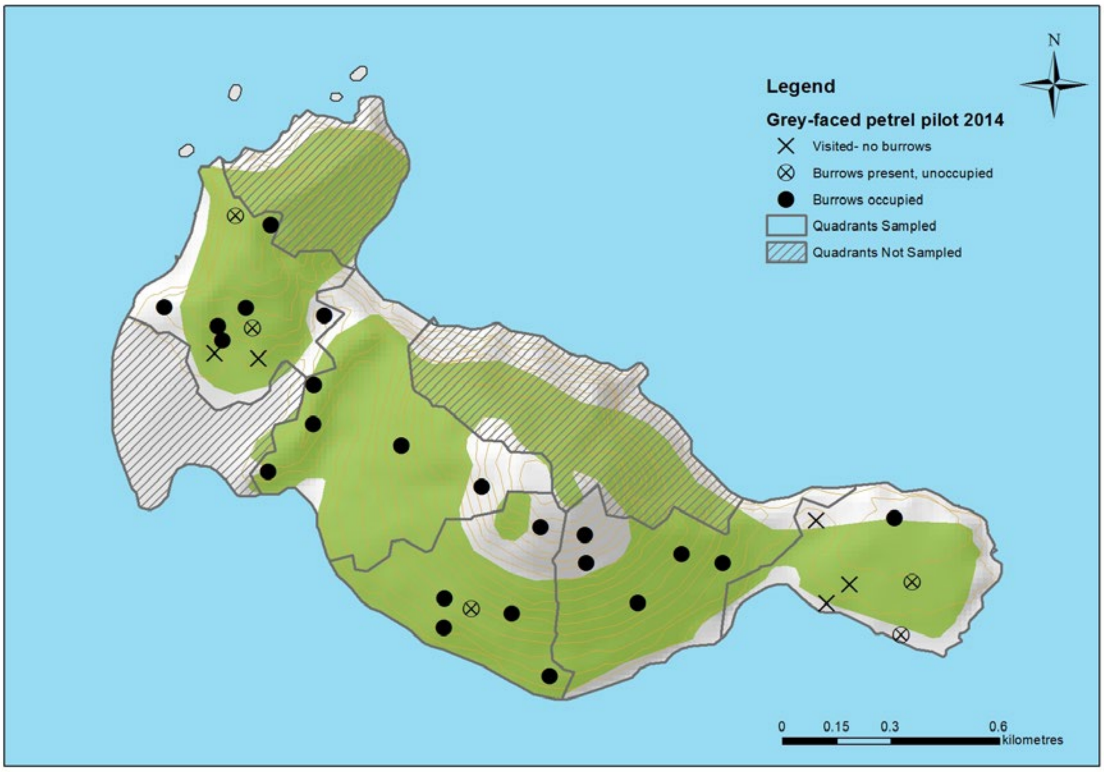

Figure 7. Grey-faced petrel (*Pterodroma gouldi*) burrow distribution on Moutohora Island in 2014.

Table 5. Grey-faced petrel (*Pterodroma gouldi*) burrow density and occupancy estimates for Moutohora Island.

QUADRANT		BURROWS		OCCUPIED BURROWS	
NUMBER	AREA (m^2)	DENSITY (NUMBER/m^2)	TOTAL (n ± SE)	DENSITY (NUMBER/m^2)	TOTAL (n ± SE)
1	284 593	0.1248	35 500 ± 8500	0.0458	13 000 ± 4000
4	220 140	0.0357	7800 ± 2400	0.0184	4000 ± 6100
5	374 895	0.2063	77 300 ± 23 300	0.0637	23 900 ± 2500
6	147 110	0.1910	28 100 ± 6000	0.0509	7500 ± 3500
8	208 417	0.0318	6600 ± 3500	0.0042	900 ±900
SUBTOTAL	1 235 155 (72%)		155 300 ± 25 900		49 300 ± 6700
2	152 290	*Cultural zone – no access permitted*			
3	60 532	*Cultural zone – no access permitted*			
7	265 175	*Inaccessible*			
SUBTOTAL	477 997 (28%)				
TOTAL	**1 713 152**				

4. Discussion

The purpose of this pilot study was to determine which sampling designs and monitoring methods are most suitable for robustly estimating the number and occupancy of grey-faced petrel burrows on islands off the east coast of the North Island of New Zealand with different population sizes and burrow density patterns. The ability to monitor changes in the state of the national population of grey-faced petrel will not only allow us to infer changes in the broader marine environment, but will also contribute to reporting towards DOC's measure 5.1.2 'Demography of widespread animal species' under indicator 5.1 'Ecosystem composition' (Lee et al. 2005). To be of use, any sampling design and method would need to be able to generate estimates for up to 21 predator-free islands, some of which have very small and spatially dispersed populations.

The three islands that were assessed in this pilot had been predator free for over 20 years or had never had predators present. The 15 spatially balanced randomly located sample points that were used on the first (and smallest) island, Otata Island, yielded zero burrow detectability. Therefore, an adaptive monitoring framework approach was adopted to pilot different sampling designs on the subsequent two islands (Burgess Island (Pokohinu) and Moutohora Island), which have much larger grey-faced petrel populations with very different spatial patterns of burrow density, likely as a result of their different habitat types, predator histories, durations of petrel occupancy and the presence of other seabird species.

4.1 Plot size

No burrows were detected in any of the 1- or 2.5-m-radius plots surveyed on Otata Island. However, observations of burrows whilst walking around the island and counts of burrows during a census that was carried out just prior to the pilot (J. Thoresen, unpubl. data), indicate that this population has remained relatively stable since 1985 (Cunningham & Moors 1985). Therefore, the use of small plots clearly underestimated the number of burrows on this island, which is home to a small, clumped population of grey-faced petrels, highlighting the importance of conducting surveys that are suitable for detecting changes in the distribution and abundance of small populations to meet DOC's widespread indicator species objective.

On Burgess Island (Pokohinu), few 20 × 20 m plots could be safely established for occupancy estimates, with several needing to be abandoned. The number of burrows that were detected in 1- and 2.5-m-radius plots was also low. There was little difference in burrow estimates based on the two plot sizes (8500 ± 4300 v. 10 000 ± 3000 burrows for 1- and 2.5-m-radius plots, respectively), suggesting that either could be used.

Moutohora Island supports a much larger population of grey-faced petrels than the other two pilot islands and burrows are more evenly dispersed. However, we believed that the use of larger survey plots would still be of value to improve the encounter rate and spatial coverage of the sample points. Therefore, 5-m-radius plots were sampled on this island. Since more time was required to sample these plots, this approach was traded-off against not sampling any larger 20 × 20 m plots. The island-wide burrow estimate that was obtained from these plots (155 300 ± 25 900) was within the range of other recent estimates. In 1982 there were 3000 grey-faced petrel burrows on Moutohora Island, prior to the eradication of Norway rats and rabbits; and 2000 burrows in 1985 and 820 in 1986 (Harrison 1992). Following the eradication of Norway rats and rabbits, in 1991 1036 grey-faced petrel burrows were estimated to be present on the island (Harrison 1992; Imber et al. 2003); however, this number subsequently increased to 99 000–119 000 burrows in 1998–2000 based on sampling 2-m-radius (n = 40–172) and 10 × 10 m plots along transects that were located within 16 quadrants stratified by landform (Imber et al. 2003). Whitehead et al. (2014) estimated that Moutohora Island supported 69 330 (95% CI: 10 590–128 300) breeding pairs over the 2006, 2007, 2008 and 2010 breeding seasons; and also estimated

52 ± 35% burrow occupancy over the entire island based on estimates from 27 randomly located 10 × 10 m permanent plots that were surveyed between July and November. On Moutohora Island the use of 20 × 20 m plots was discontinued as they were found to be inefficient on the other islands surveyed.

To obtain a national occupancy estimate for grey-faced petrel as a widespread indicator species, variable occupancy rates would need to be accounted for (Whitehead et al. 2014). Imber et al. (2003) considered the occupancy rate of grey-faced petrel burrows to be the proportion of burrows in which an egg was laid, but also reported the occupancy rate based on the proportion of burrows with a fledgling and the known percentage of breeding failures. However, because any future monitoring of grey-faced petrel as a widespread indicator species will coincide with the incubation period (June–September), it may be important to distinguish between inactive and active but unoccupied burrows.

An inactive burrow is a burrow that is empty (i.e. without an adult, chick or egg). However, an unoccupied burrow would be considered to be active where there were obvious signs of recent activity including smell, droppings, feathers, recent digging and eggshell. This distinction may be particularly important where monitoring is carried out early in the incubation period and near the hatching period to account for any females that have not returned to the colony to lay, as well as early breeding failures and the subsequent removal of the egg or chick from the burrow – parents will often roll the egg out of the burrow following breeding failure during incubation. Chicks will also often move towards the front of the burrow if they have gone a long period of time without food and may die in the burrow entrance or a short distance away, in which case the burrow would appear unoccupied even though breeding had been attempted. The survey teams encountered a number of burrows like this, where breeding had presumably failed during incubation or in the early chick-rearing period. Thus, consideration of the number of active burrows when determining occupancy may lead to a more accurate estimate of an island's population size.

4.2 Stratification

Burgess Island (Pokohinu) and Moutohora Island were stratified into quadrants based on geographic landform (mostly major ridges), which increased the number of sample points that needed to be visited by the field teams but reduced the travel time between them. It was also hoped that this approach would reduce variability by increasing the detection probability of burrows. The scale of this stratification provided a good balance between the requirements for plot randomisation, the efficiency with which field teams could travel between multiple sample points and potential environmental impacts (e.g. trampling of burrows). Stratification based on landform warrants further investigation as topography can be a predictor of burrow density (Whitehead et al. 2014; Buxton et al. 2015). For instance, since grey-faced petrel burrows tend to occur on ridges, quadrants may be best defined by valleys (Taylor 2000, 2013) – or, alternatively, valleys could be excluded from future sampling designs if they include no or negligible grey-faced petrel populations. These landform features can be readily identified from aerial photographs, topographic maps and satellite imagery, making stratification much easier across many different islands than would be the case for habitat or other vegetation features.

Use of a simple random stratified spatially balanced sample design also permits flexibility in the order in which sample points are visited by the field team. Sample points within a quadrant may sometimes be visited and measured in spatial order (i.e. proximity) rather than numerical order, but only if the field team is confident that they can visit and survey all of the sample points. Therefore, this may be more appropriate for quadrants where there is a high certainty of completion, such as those that are visited early in a survey or are located on favourable terrain. For example, on Moutuhora Island, the field team spent the first 2 days surveying sample points in the first quadrant but this could have been reduced to 1 day if they had been visited in spatial rather than numerical order. However, when there is less certainty that all of the sample points can be accessed and measured (e.g. those monitored nearer the end of a survey trip), they should be surveyed in numerical order to ensure that the sample points within incomplete quadrants remain spatially balanced.

To prevent under- or over-sampling quadrants between years, the numerical order in which the quadrants are completed could be changed between surveys. Furthermore, if only a selection of quadrants can be sampled in any given year on an island, the random or systematic allocation of quadrants sampled in each subsequent year of sampling will ensure that comparisons can be made between years. This design can allow the number of survey points to be increased or decreased depending on the size of the island being surveyed and possibly the density of the burrows. Such scaling up or down the number of sample points while still allowing burrow number and occupancy estimates to be compared between sample years and among islands would be advantageous for a monitoring programme that could include up to 21 islands.

Our findings indicate that a spatially balanced sampling design should be used to monitor grey-faced petrel populations, whereby the numbers of burrows are counted and assessed for occupancy in randomly allocated 5-m-radius plots. To develop a multi-island programme, further work is needed to evaluate the applicability of the methods used on Moutohora Island to islands of different sizes with different seabird population densities, and to investigate ways of improving stratified sampling based on landform features.

5. Recommendations

Based on the findings of this study, we recommend that:

- Grey-faced petrel populations are monitored using a simple random sampling design in which the sample points are also spatially balanced to avoid any clumping.
- Monitoring is carried out during incubation (between June and August).
- Burrow counts and occupancy estimates are made using 5-m-radius plots.
- A density of 3–4 sample points per hectare is aimed for.
- Islands are stratified into quadrants based on landform to increase the efficiency of plot surveys and the number of sample points.
- Sample points are monitored in spatial order when there is a high certainty of completion, e.g. at the beginning of a survey period; otherwise, they should be sampled in numerical order to ensure a spatially balanced design.
- Inactive and active but unoccupied burrows should be distinguished between.

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