White-chinned petrel (*Procellaria aequinoctialis*) burrow density, occupancy, and population size at the Auckland Islands

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ABSTRACT: In New Zealand's subantarctic Auckland Islands, the island-wide population size of white-chinned petrels (*Procellaria aequinoctialis*) is unknown. On ten islands in the group, surveys for burrow distribution were followed by whole-island burrow counts or stratified random sampling of white-chinned petrel habitat. White-chinned petrel burrow density, burrow occupancy, and slope-corrected surface areas were used to calculate the breeding population size. Burrows were patchily distributed and most abundant in dense megaherb communities. White-chinned petrel burrow density at Adams Island was 701 burrows/ha (95% CI: 480–803 burrows/ha). Burrow occupancy was 0.59 ± 0.02 (mean ± *se*) at the start of incubation. An estimated 28,300 (10,400–44,800) white-chinned petrel pairs breed on Adams Island. Including the small colonies on Ewing, Monumental, and Enderby Islands (together *c.* 100 pairs) and the estimated 155,500 breeding pairs on Disappointment Island, the Auckland Island group has an estimated 184,000 (95% CI: 136,000–237,000) pairs of breeding white-chinned petrels.

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Introduction

Seabirds are one of the most threatened bird groups in the world, with nearly half of all species known or suspected to be declining (Croxall *et al.* 2012). Population estimates underpin species status and trend assessment, as well as management action, yet accurate and precise estimates are relatively rare for seabirds, particularly burrow-nesting seabird populations (Barbraud *et al.* 2009; Parker & Rexer-Huber 2015).

The white-chinned petrel (*Procellaria aequinoctialis*) is the largest of the burrow-nesting petrels at *c.* 50 cm from beak to tail and with a wingspan of *c.* 140 cm (Heather & Robertson 1996; Fig. 1). White-chinned petrels breed on subantarctic islands around the Southern Ocean (Brooke 2004). Their global Red List conservation status is Vulnerable (BirdLife International 2017) due to documented declines on land and at sea, and very high rates of incidental mortality in commercial fisheries (Woehler 1996; Berrow *et al.* 2000; Barbraud *et al.* 2008; Perón *et al.* 2010). White-chinned petrels remain a major component of commercial fisheries by-catch – both globally and within New Zealand's Exclusive Economic Zone – with observed captures even increasing in some regions despite general decreases in seabird captures (Bell 2014; Abraham & Thompson 2015; Rollinson *et al.* 2017). Risk assessments that rank seabirds in terms of their risk from fisheries (e.g. in New Zealand, Richard & Abraham 2013) are intended to help mitigate the effects of commercial fishing. Such models should be underpinned by detailed, reliable population data (Tuck *et al.* 2015). Adult breeding population size could substantially influence risk assessment models (Richard & Abraham 2013; Walker *et al.* 2015), yet the breeding population of white-chinned petrels is either poorly quantified or unknown in the New Zealand region.

In the Pacific sector of the Southern Ocean, white-chinned petrels breed on the New Zealand subantarctic Auckland, Antipodes, and Campbell Island groups. G.A. Taylor (2000) suggested that Auckland and Antipodes Islands may each support around 100,000 pairs, and Campbell Island around 10,000 pairs. Work at Antipodes Island in 2008–11

FIGURE 1. White-chinned petrel, Disappointment Island, Auckland Islands, January 2018. *Image: C. Miskelly.*

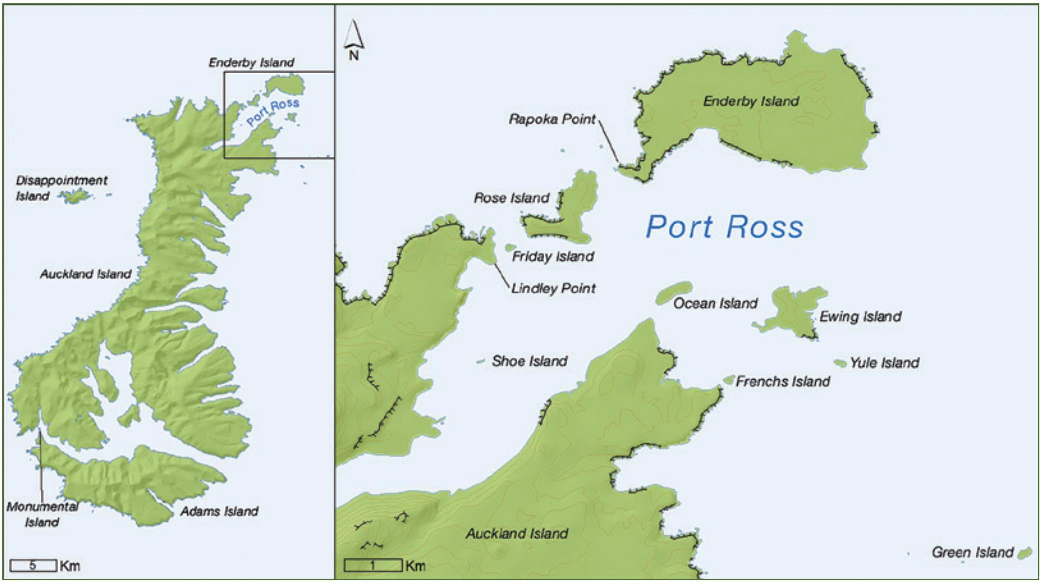

FIGURE 2. (**LEFT**) Auckland Island group in the New Zealand subantarctic, with (**RIGHT**) Port Ross islands.

gave a breeding population estimate of 40,000–45,000 pairs (D.R.T., *unpubl. data*), which is less than previously suggested (G.A. Taylor 2000). The Campbell Island group supports *c.* 22,000 breeding pairs of white-chinned petrels (Rexer-Huber 2017). In the Auckland Islands, the only work on white-chinned petrels has been at Disappointment Island (Fig. 2). To refine the 1988 assessment (100,000–500,000 breeding pairs; G.A. Taylor 1988), we conducted a systematic population size estimate in 2015 and showed that an estimated 155,500 pairs breed on Disappointment Island (Rexer-Huber *et al.* 2017). However, white-chinned petrels are known to breed in other parts of the Auckland Island group: on Adams Island, the southernmost island in the group; in small numbers on nearby Monumental Island; and on Ewing Island in Port Ross (G.A. Taylor 1988; Miskelly *et al.* 2020 – Chapter 2 in this book) (Fig. 2). There are also occasional records of burrows at other sites around Port Ross: on the main Auckland Island (referred to from here as main Auckland) and on Enderby Island (Miskelly *et al.* 2020 – Chapter 2). Main Auckland has feral cats (*Felis catus*), house mice (*Mus musculus*), and pigs (*Sus scrofa*), and very few white-chinned petrel burrows have ever been found there (Miskelly *et al.* 2020 – Chapter 2). However, areas inaccessible to pigs on main Auckland probably support some petrels.

The focus of this work was to survey for white-chinned petrels across the Auckland Island group, to estimate numbers, and to obtain an island-wide population-size estimate.

Methods

Study sites

Auckland Island white-chinned petrels breed on Disappointment Island (284 ha, 6 km off the western cliffs of the main Auckland Island), Adams Island (9,693 ha, southernmost in the group), and in very small numbers on Ewing Island (58 ha) and Monumental Island (4 ha), and have been occasionally recorded on 695 ha Enderby Island (Fig. 2). White-chinned petrels might also breed in small numbers on main Auckland Island (45,889 ha; Fig. 2).

Study design

To estimate population size in burrowing petrels, a representative sample of burrow density via

Box 1. Definitions

Burrow density	The number of burrows per unit area
Burrow detection probability	The number of burrows counted as a proportion of the number available
Burrow occupancy	Proportion of burrows that contain the species of interest, expressed as a rate
Detectability	The ease with which burrows are found (see *Burrow detection probability*)
Habitat availability	The proportion of a species' habitat available for sampling
Main laying period	When all birds except a few very late birds have laid and begun incubating
Non-habitat	Habitat not utilised by the target species
Occupant detection	The probability of correctly determining burrow contents
Observer bias	Bias resulting from differences between observers
Overflow	Movement of breeding birds from an established population to adjacent/nearby habitat
Planar area	Two-dimensional area of a landscape, as on a map (cf. *Surface area*)
Representativeness	Extent to which sampled areas are representative of the habitat to which a survey is extrapolated
Surface area	Three-dimensional surface area of a landscape (cf. *Planar area*)
Timing	Period when the survey is undertaken relative to the breeding phenology of the target species

transects or plots is corrected for burrow occupancy and extrapolated to the available area of nesting habitat (e.g. Lawton *et al.* 2006; Baker *et al.* 2008; Lavers 2015) (terms in bold type are defined in Box 1). The accuracy and precision of population estimates can be influenced by sampling design, and by other aspects of study design (timing, habitat availability, burrow detection, observer bias; reviewed in Parker & Rexer-Huber 2015).

On all islands where white-chinned petrels were studied, preliminary surveys were conducted to gauge burrow distribution and spatial extent. If possible, every burrow was counted in an island-wide burrow census; if not, white-chinned petrel habitat was sampled. Survey information was used to guide selection of a sampling design that both was representative and accounted for local constraints. Sampling design selection must balance practicality (time, effort, safety) with efforts to maximise the precision of resulting estimates (Parker & Rexer-Huber 2015). Sampling mostly followed a stratified random design in view of the challenging topography, the spatially defined extent of burrowed areas, and the observation that burrow numbers differ dramatically between areas (highly 'patchy' distribution; e.g. Buckland *et al.* 2001; Rayner *et al.* 2007a). In some cases sampling was simple random; that is, sampling units located randomly across an entire island. Although other sampling design approaches could be more efficient or minimise variance, the best candidates – systematic sampling or adaptive cluster sampling (Thompson 1991; Fewster *et al.* 2009) – did not appear practical, safe or accurate to implement in deeply incised, steep terrain. For example, count accuracy and burrow detection can suffer when trying to move along a long continuous transect in steep, jagged topography. Since the accuracy and precision of point estimates are optimised when the study design is tailored to site (Parker & Rexer-Huber 2015), aspects of the study were altered to suit local constraints (detailed by site below).

Adams Island

White-chinned petrels on Adams Island appear to be restricted to 'shelves' of habitat on the southern cliffs, and to Fairchilds Garden, a small, exposed peninsula at the north-western tip of Adams Island (Elliott *et al.* 2020 – Chapter 3 in this book) (Figs 2, 3). Preliminary surveys in 2013–14 (*c.* 300 km survey distance) and aerial survey of the entire coastline in Jan 2015 supported the observed southern shelves/Fairchilds distribution, with no sign of white-chinned petrels in other areas. Many of the southern cliff shelves are not accessible, but some were identified that could be safely accessed and surveyed on foot (Fig. 3). Nine strata were defined: seven distinct sites offering white-chinned petrel habitat that was accessible (treated as separate strata because some spatial variability was expected; Lawton *et al.* 2006; Rayner *et al.* 2007b); white-chinned petrel habitat that could not be accessed for sampling; and habitat not suitable for white-chinned petrels (based on known white-chinned petrel habitat on Adams and Disappointment Islands).

For representative sampling of each shelf-site that could be accessed, sampling plots were located using random-number tables of distances along a contour, no closer than 20 m to ensure sample independence. Small, fixed sampling plots were used instead of line-transect distance sampling (e.g. Rexer-Huber *et al.* 2017) because preliminary survey showed that transects on some shelves did not encounter sufficient burrows for distance sampling. Furthermore, small fixed-point plots were considered safer and more reliable in steep terrain, with less time spent looking for footing and more looking for burrows. The planned 30 sampling plots per shelf-site was scaled by area; that is, in particularly small or large shelf-sites the number of sampling plots was halved or doubled, respectively. Each plot for sampling burrow density was 140 cm in radius, defined and checked with a marked walking pole, giving a sampling plot of 6.16 m2. Plots were searched thoroughly for burrows, looking under vegetation. At least

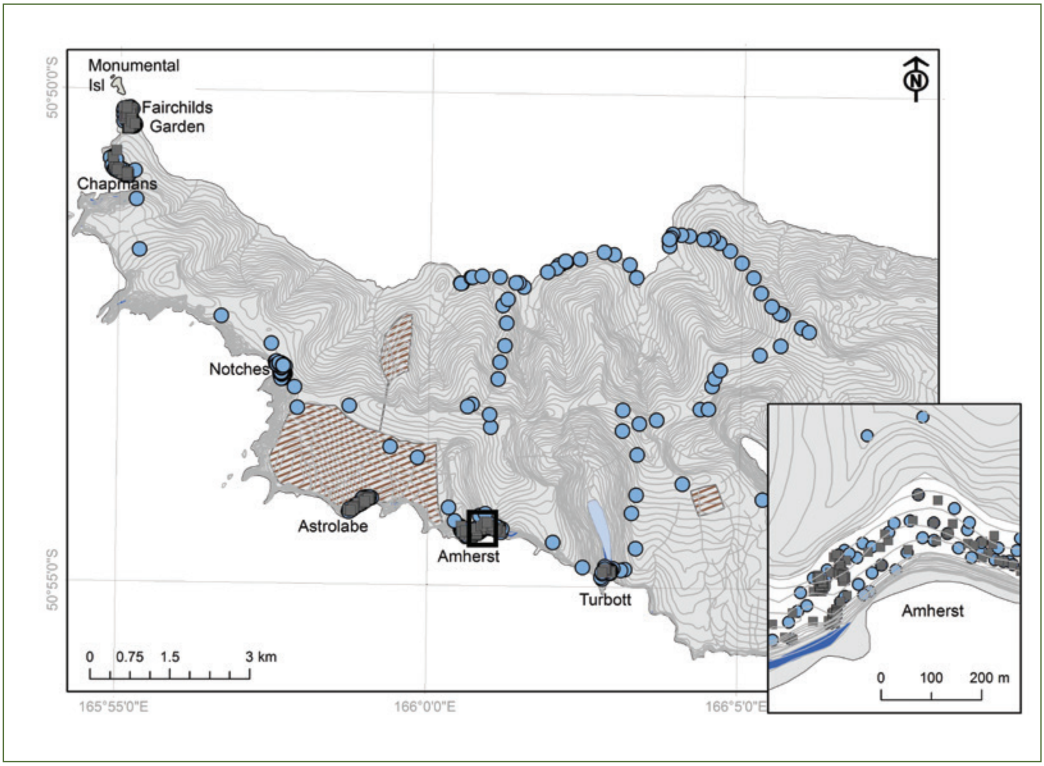

FIGURE 3. White-chinned petrel burrow distribution on Adams Island. White-chinned petrel burrows (grey squares) are shown relative to sampling effort (burrow sampling plots, blue circles) and search effort (exhaustive search blocks, brown hatched polygons). **INSET:** burrow distribution at the Amherst shelf-site, showing the extent of sampled habitat (white polygon) and of unsampled habitat (dark blue polygon). Contains data from the LINZ Data Service licensed for reuse under CC BY 4.0.

half of a burrow entrance had to occur within the sampling area for it to be counted. White-chinned petrel burrows are easily identifiable by their size and muddy entrance, and for typically having an entrance moat. Burrows of other species present (white-headed petrel *Pterodroma lessonii*, sooty shearwater *Ardenna grisea*, and common diving petrel *Pelecanoides urinatrix*) are markedly different from white-chinned petrel burrows, having smaller entrances and drier substrate, and lacking moats (Rexer-Huber 2017). In order to correct the planar area of the island, giving the true surface area, slope angle was measured at each plot to the nearest degree (clinometers Silva Sweden AB, Bromma, Sweden, and Suunto, Vantaa, Finland). A laser range-finder (Nikko Stirling, Shanghai, China) was used to measure the surface width of the shelf-site at every second sampling plot, to ground-truth GIS-based estimation of planar and surface shelf area. Burrow detection probability, or the number of burrows counted as a proportion of the number present, was evaluated by double-observer counts in a subset of sampling plots and in small burrow clusters (18–22 burrows), under the same field and visibility conditions as for sampling elsewhere. The first observer marked all burrows found in the plot or cluster with a small marker well inside the burrow entrance, and the second observer recorded any unmarked burrows found. Observer bias was assessed at nine sampling plots where all data were recorded independently by both observers.

Burrow occupancy

The proportion of burrows that contained a breeding pair, or burrow occupancy, was quantified from at least four burrow clusters in each of four shelf-sites on Adams Island. All burrows in the cluster were checked using an infrared burrowscope (Sextant Technologies, Wellington, New Zealand), ensuring that the burrow was inspected throughout. The key parameter was whether or not the burrow was occupied, and, if occupied, whether the bird was incubating or loafing (bird present without an egg). Burrows with loafers and empty burrows were checked for signs of a failed breeding attempt, particularly egg fragments. Some burrows that superficially appeared to be those of white-chinned petrel proved to be erosion cavities or old collapses, so these were recorded as entrance-not-burrow (ENB). K.R-H. conducted all burrowscoping to avoid introducing observer bias. White-chinned petrel burrows in the Auckland Islands are large and simple compared with those of other species, with a single entrance, tunnel, and chamber. Because of this simple structure, burrows can be inspected in full with confidence that an occupant will be detected, and so occupant detection rates were not quantified and we did not have to rely on other (non-visual) occupancy methods (e.g. playback response rates; Berrow 2000; Rexer-Huber *et al.* 2014). To avoid introducing a detection bias, a record was made in the few cases where a burrow could not be fully inspected (unscopable) and these were excluded from occupancy estimates.

Burrow density sampling at Adams Island took place during 11–30 Dec 2015, with an extra site visited on 12 Feb 2016. Burrow occupancy was estimated from at least four burrow clusters per shelf-site 9–24 Dec. If white-chinned petrel breeding phenology is similar to that at Antipodes Island (D.R.T., *unpubl. data*), Adams Island burrow occupancy was sampled at the ideal time: within a week of when the majority of eggs have been laid, when least failures have yet occurred (Parker & Rexer-Huber 2015).

Areas defined as non-habitat should be excluded from extrapolations to improve the accuracy of a resulting population estimate, but only if non-habitat does not, in fact, support breeding white-chinned petrels (Parker & Rexer-Huber 2015). To test this assumption, extensive surveys were conducted across Adams Island. Line-transect surveys and vantage-point habitat inspection in new areas were supplemented with non-habitat sampling plots (Fig. 3) searched as for other sampling plots. Exhaustive searches of three major non-habitat types were also conducted: north-facing ridges, south-facing high plateau, and south-facing clifftop slopes (67 ha, 25 ha, and 513 ha blocks, respectively; two people working in parallel *c.* 20 m apart) (Fig. 3, brown hatched polygons).

Whole-island counts

White-chinned petrels were counted on Ewing and Monumental Islands (Fig. 2). Other offshore islands that could potentially support white-chinned petrels were surveyed: Rose, Friday, Shoe, Ocean, and Frenchs Islands. Yule and Green

Islands were surveyed by binoculars from a boat within 50 m but not visited, since there is no suitable nesting habitat for white-chinned petrels (both islands are bare rock with high seas able to cover all areas). All these islands lie in the Port Ross area, roughly between Enderby and Ewing Islands, with the exception of Monumental Island which lies just off Adams Island (Fig. 2). These whole-island surveys took place in Jan or Dec 2015, and involved two to three observers covering all potential white-chinned petrel habitat in parallel line transects *c.* 20 m apart.

Analyses

Mean burrow densities from random sampling plots, and associated 95% confidence intervals, *CI*s, were calculated for each shelf-site on Adams Island. Confidence intervals were based on the normal distribution unless otherwise stated. To calculate burrow occupancy, burrows that could not be inspected in their entirety (unscopable) were first discarded. A burrow correction (b) to account for entrances that did not lead to a burrow (ENB) was calculated as:

1.1 $$b = \frac{burr_{wcp}}{\mathrm{burr}_{\mathrm{total}}}$$

where:

1.2 $$burr_{wcp} = \mathrm{burr}_{\mathrm{total}} - \mathrm{ENB}$$

and $burr_{total}$ is the total number of fully-inspected burrows. The burrow occupancy rate (c) was then calculated as:

1.3 $$c = \frac{\mathrm{burr}_{\mathrm{occ}}}{burr_{wcp}}$$

where $burr_{occ}$ is the number of burrows occupied by breeding white-chinned petrels.

The planar area of unsampled, inaccessible white-chinned petrel habitat on Adams Island was quantified as polygons in ArcGIS by referencing satellite image and topographic layers (island and contours 1:50,000; sourced from the Land Information New Zealand LINZ Data Service and reused under the CC BY 4.0 licence) against available resources: aerial photos (G.B. Baker); aerial footage (H. Haazen), and vantage-point photographs (G.P., K.R-H.). The planar area of sampled habitat was quantified with the same resources and refined using the GPS tracks recorded during sampling. Examples of these planar area polygons are shown in Fig. 3 (inset; unsampled habitat bounded by dark blue polygons, and sampled habitat by white polygons). Slope-corrected surface areas were calculated from the planar map area of each shelf, site, or island *i*. The true surface area was calculated as:

2.1 $$A = \sum as_i$$

where

2.2 $$as_i = ap_i \times (sec(\emptyset_i))$$

and as_i is the slope-corrected area of each shelf-site, and $\emptyset_i$ is the mean angle of the slopes within each shelf-site. For unsampled shelf-sites, Eq. 2.2 used the mean slope from sampled shelf-sites. That is, the surface area of each unsampled shelf-site on Adams Island was calculated using the mean slope from sampled shelves ($\bar{x}$ = 36°), and areas summed to obtain the area of the unsampled habitat stratum. Note that slope corrections do not account for the surface area of cliffs (e.g. on Adams Island 400–500 m high around 21 km of southern coast) since the cliffs are mostly bare rock, unsuitable for burrowing petrels.

To estimate the number of breeding pairs, we first estimated the number of white-chinned petrel burrows in a stratum or on an island, calculated as:

3.1 $$\widehat{N}_{burr} = \widehat{D} \times A \times b$$

where $\widehat{N}_{burr}$ is the estimated number of white-chinned petrel burrows, $\widehat{D}$ is the estimated density of burrows, A is the slope-corrected surface area, and b is the burrow correction accounting for entrances that did not lead to burrows (ENB). The estimate of breeding pairs was then calculated using:

3.2 $$\widehat{N}_{pairs} = \widehat{N}_{burr} \times c$$

where $\widehat{N}_{pairs}$ is the estimated number of breeding pairs of white-chinned petrels, and c is the burrow occupancy rate. For unsampled inaccessible sites, the mean burrow density or occupancy figure was used from the closest site where it had been quantified. That is, the mean burrow density $(\widehat{D})$ and

		Fairchilds Garden		Chapmans	Amherst	Astrolabe	Notches	Turbott	Unsampled	Overall
		Upper	Lower							
Burrow density	no. of plots, *n*	12	24	37	69	36	43	20	0	241
	mean density, *n*/ha (95% *CI*)	541	1353	395	871	1083	0	812	701	701 (480–803)
Slope, area	no. of slope measures	12	24	37	68	36	43	0	0	220
	slope mean (°)	15	21	33	36	37	38	0*	*36*	33
	planar area (ha)	3.66	5.58	7.84	11.45	6.18	4.51	2.66	21.54	63.42
	surface area (ha)	3.80	5.96	9.37	14.11	8.68	5.75	2.66	24.12	74.44
Occupancy	burrows total	–	109	66	101	74	–	–	–	350
	burrows wcp	–	100	60	87	67	–	–	–	314
	burrow correct *b*	*0.9091*	0.9091	0.9091	0.8614	0.9054	––	*0.8971*	*0.8971*	0.8971
	occupancy *c*	*0.6200*	0.6200	0.6333	0.5287	0.5672	–	*0.5860*	*0.5860*	0.5860
Pairs	$\hat{N}$ burrows	2,054	8,067	3,700	12,288	9,399	–	2,160	*16,905*	54,573
	$\hat{N}$ wcp burrows	1,885	7,400	3,363	10,585	8,510	–	1,938	*15,166*	48,763
	$\hat{N}$ wcp pairs (95% *CI*)	1,169	4,588	2,130	5,597	4,826	–	1,136	*8,887*	28,333 (10,396–44,775)

occupancy (c) values across all sampled shelves on Adams Island were used as $\widehat{D}$ and c for the unsampled white-chinned petrel habitat stratum. To obtain whole-island and island-group estimates, $\widehat{N}_{pairs}$ and associated variance estimates were summed. Summing strata proved less precise but more accurate than when all strata were pooled (Rexer-Huber *et al.* 2017), and so estimates for each stratum were summed for the Adams Island breeding population estimate.

Results

Adams Island

A total of 327 sampling plots were visited across nine strata (Fig. 3). Despite substantial survey effort in non-habitat parts of Adams Island (605 ha exhaustive search and 86 sampling plots, Fig. 3, and *c*. 150–300 km of survey transects each year during 2013–18), no white-chinned petrels were found in any new parts of the island, confirming known distribution patterns and justifying the spatially restricted stratification used. About 68% of the 74 ha of white-chinned petrel habitat available was accessed and sampled (Table 1).

White-chinned petrel burrows occurred at a density of 701 ± 112 burrows/ha in sampled habitat (mean ± *se*; n = 241 plots). Densities did not vary significantly between shelf-sites where petrels were found (Kruskal-Wallis, χ^2_4 = 6.54, P = 0.16), with densities ranging from 395 ± 277 burrows/ha (n = 37) to 1,353 ± 422 burrows/ha (n = 24) on each different occupied shelf (Table 1). One shelf classed as habitat (that is, with habitat features similar to known white-chinned petrel habitat elsewhere) did not contain any white-chinned petrel burrows (Notches; Table 1; Fig. 3), but is included in the overall density estimate for sampled sites that is applied to unsampled white-chinned petrel habitat.

Burrow distribution within a shelf-site was patchy, with burrows highly clustered and non-uniform across the shelf. As many as seven burrows were found in a 6.16 m^2 sampling plot, but only *c*. 20% (mean; range 8–42%) of plots contained burrows. Burrow detection probability was assessed in 11 plots and burrow clusters via double-observer counts of all burrows within each plot or cluster. Forty-three burrows were found in the areas used for burrow detection tests and no extra, unmarked burrows were found. Slope was measured at 220 sites, with a mean of 36° (range 2–65°) on shelves and 33° across all white-chinned petrel shelf-sites sampled. Slope correction of planar map area gave a total of 74 ha of white-chinned petrel habitat; a 15% increase on the planar map area measured (63.4 ha) (Fig. 3; Table 1). Between-observer tests at nine sampling plots showed that observers did not differ in burrow numbers detected or variables recorded.

Burrow contents were inspected in 351 burrows across four shelf-sites, with only one burrow discarded as unscopable (0.3%). Similarly, only 3% of white-chinned petrel burrows on Disappointment Island could not be checked in entirety (Rexer-Huber *et al.* 2017), and 5–7% on Antipodes Island were unscopable (D.R.T., *unpubl. data*). White-chinned petrel burrows comprised 314 of the burrows checked, while 36 had an entrance that did not lead to a burrow (ENB), being washed out or collapsed. The burrow correction b (proportion of the total inspected that were burrows, not ENB) was 0.8971 ± 0.013 (mean ± *se*) and did not differ between shelves (χ^2_3 = 2.04, P = 0.56; range 0.8614–0.9174) (Table 1). Occupancy c across all shelves was 0.59 ± 0.02 and also did not differ between shelf-sites (χ^2_3= 2.30, P = 0.51; 0.5287–0.6333) (Table 1). There was no between-year variation in occupancy (Fisher's exact test; P = 0.75): at Fairchilds Garden, occupancy was 0.69 in 2013–14, 0.62 in 2015–16, and 0.60 in 2018–19.

TABLE 1 (OPPOSITE). White-chinned petrel breeding population size by shelf-site on Adams Island in December 2015. Key parameters are grouped for burrow density, slope correction, and burrow status and occupancy rates. *Italicised figures* are inferred from other site(s), and a dash (–) indicates a value not calculated or measured. Burrows total = the total number of burrows inspected; burrows wcp = the number of inspected burrows minus ENB (the number of entrances that did not lead to a burrow); burrow correct b = correction for the proportion of burrows total that were white-chinned petrel burrows, not ENB; occupancy c = proportion of white-chinned petrel burrows containing a bird on an egg; $\widehat{N}$ burrows = estimated number of burrows (burrow density by slope-corrected surface area); $\widehat{N}$ wcp burrows = estimated number of white-chinned petrel burrows ($\widehat{N}$ burrows by burrow correct); $\widehat{N}$ wcp pairs = estimated number of breeding pairs of white-chinned petrels ($\widehat{N}$ wcp burrows by occupancy); * = the burrowed area is flat so the slope is taken as 0°.

Adams Island had an estimated 48,800 white-chinned petrel burrows within its 74 ha of habitat, using density estimated by stratum and burrow corrections to account for entrances that did not lead to burrows. Correcting the number of burrows for occupancy, an estimated 28,300 (95% *CI*: 10,400–44,800) white-chinned petrel pairs were breeding on Adams Island in Dec 2015 during early incubation.

Auckland Island group

The Ewing Island white-chinned petrel colony is very small, and so every burrow was counted in Dec 2015. That census of 58 burrows was corrected by the overall burrow status and occupancy estimates (b = 0.8971 and c = 0.5860, respectively) for the Auckland Islands 2015-16 season, giving an estimated 30 breeding pairs on Ewing Island. On Monumental Island, we counted 114 burrows in Jan 2015, with an estimated 60 pairs of white-chinned petrels breeding on the island. More recent counts at Ewing and Monumental islands were comparable (95 and 90 burrows, respectively, in early 2018; C. Miskelly & A. Tennyson, *pers. comm.*), adding seven pairs to the island's estimate if burrow occupancy is assumed to have stayed the same. Three white-chinned petrel burrows have been found on main Auckland (Dec 2013 at Lindley Point, K.R-H.). On occasion, 1–3 white-chinned petrel burrows have been found on Enderby Island, first in 2016 (C. Muller, *pers. comm.*), then again in 2018 on the south and north-west coasts (January; C. Miskelly & A. Tennyson, *pers. comm.*) and at Rapoka Point (November; G.C.P., K.R-H.). Exhaustive counts to find all burrows were not possible on those occasions and so numbers at the main Auckland and Enderby sites remain unclear. White-chinned petrels were not found on Rose, Friday, Shoe, Ocean, Frenchs, Yule, or Green Islands.

Taken together with the 155,500 (125,600–192,500) breeding pairs at Disappointment Island (Rexer-Huber *et al.* 2017), these estimates suggest that the Auckland Islands support a breeding population of 184,000 (136,000–237,000) white-chinned petrels.

Discussion

This study presents the first systematic, quantitative estimates of the number of white-chinned petrels breeding on the Auckland Island group as a whole. The estimate of 184,000 (136,000–237,000) white-chinned petrel pairs breeding in the Auckland Islands is substantially larger than the 100,000 proposed by G.A. Taylor (2000). This study, taken together with those on Campbell and Antipodes Islands (Rexer-Huber 2017; D.R.T., *unpubl. data*), suggests that the New Zealand subantarctic islands support around 249,000 (178,000–326,000) breeding white-chinned petrel pairs.

Disappointment and Adams Islands are the main islands supporting white-chinned petrels in the Auckland Island group. Burrows occur at high densities at some sites: 701 burrows/ha in white-chinned petrel habitat on Adams Island, similar to the 654 burrows/ha on Disappointment. Similar densities on islands as different as Adams and Disappointment are somewhat surprising, since it is reasonable to expect density estimated at an island-wide level (e.g. Disappointment Island) to be lower than estimates specifically targeting petrel habitat or colonies (e.g. Adams Island; also see Ryan *et al.* 2012; Waugh *et al.* 2015; but see Francis & Bell 2010). Even if only burrows with breeding activity are compared (381 active burrows/ha Adams Island, 394 active burrows/ha Disappointment Island), these burrow densities are an order of magnitude greater than most island-wide estimates for white-chinned petrels: up to 26 active burrows/ha on Îles Kerguelen (Barbraud *et al.* 2009), 30–34 active burrows/ha on Antipodes Island in white-chinned petrel habitat (D.R.T., *unpubl. data*), and 63 active burrows/ha on South Georgia (Martin *et al.* 2009). It is tempting to link the relatively high density of active white-chinned petrel burrows on Disappointment and Adams Islands with the islands' complete lack of introduced mammalian predators. By contrast, most of the seabird populations mentioned above have a lower density of active burrows in the presence of predators in varying combinations: Antipodes Island had mice at the time of work there; Îles Kerguelen have a range of species, including feral cats and ship rats (*Rattus rattus*); and South Georgia had Norway rats (*R. norvegicus*) and mice prior to 2015 (DIISE 2015; TIBD 2018).

White-chinned petrels can coexist to some extent with mammalian predators, but such predators have impacts on population productivity and persistence (Jouventin *et al.* 2003; Dilley *et al.* 2017).

Patchy burrow distribution is typical of many loosely colonial burrowing seabirds (e.g. Ryan *et al.* 2012). The variability in burrow densities between shelf-sites on Adams Island (395–1,083 burrows/ha) was not statistically significant but reflected the highly patchy burrow distribution seen at all islands and sites. Burrows are notably patchy even within a given white-chinned petrel shelf on Adams Island, despite clear habitat availability constraints. White-chinned petrel burrows on Adams were found primarily among megaherbs, *Veronica elliptica* and *Poa foliosa*, and rarely in low open vegetation or in the *Cassinia*/*Myrsine*/snow tussock scrub community, as on Disappointment Island (Rexer-Huber *et al.* 2017). No burrows were found in forest (dominated by the small trees rātā *Metrosideros umbellata* and inaka *Dracophyllum longifolium* and *D. cockayneanum*) or fellfield habitat on any of the islands surveyed. The megaherb–burrow association may be the consequence of petrels burrowing in the area, introducing nutrients and modifying the vegetation communities, as documented in other seabirds (e.g. Bancroft *et al.* 2005). Alternatively, the megaherb–burrow association could be due to substrate stability; the root system of *Anisotome* megaherbs spreads both deep and wide (authors, *pers. obs.*), interlinking between plants to provide a 'scaffold' that may help support the very large burrows dug by white-chinned petrels.

To deal with burrow distribution patchiness, survey coverage was planned to be both broad and representative. More than two-thirds of the habitat that supports white-chinned petrels on Adams Island was sampled, and other islands (Monumental, Ewing) were counted in their entirety. Stratifying the survey effort into biologically relevant zones reduced bias in the resulting population estimates. Although stratifying Adams Island by shelf-site increased the variance around the estimate compared with that from pooled unstratified data (variance 37% of estimate, *cf.* 13% of estimate, respectively), this variance is more likely to overlap the true population size. The variance in the breeding population estimates is expected to be mainly due to the encounter rate variance, as it was at Disappointment Island, where the variance followed an over-dispersed Poisson distribution (Rexer-Huber *et al.* 2017). This suggests, not unreasonably, a somewhat aggregated rather than a truly random distribution of burrows, which could be addressed by improving replication (more transects or plots, or transects run several times; Burnham *et al.* 1980).

Burrow occupancy was broadly consistent across sites within an island. The only site with notably lower burrow occupancy was a shelf on Adams Island (53%, *cf.* other sites that ranged between 57% and 63%). More slips and cave-ins were seen at that site, with disturbance potentially leading to more burrow desertions and a correspondingly lower occupancy rate. Caved-in burrows were accounted for in occupancy sampling (included in the burrow correction *b*). Occupancy was stable across the three study years but differed between islands, with higher occupancy rates at Disappointment (73%; Rexer-Huber *et al.* 2017) than at Adams (59%). These white-chinned petrel burrow occupancy rates of 59–73% are similar to occupancy on Kerguelen and on Crozet (60–70% of burrows occupied; Barbraud *et al.* 2008, 2009), and also similar to that of the closely related spectacled petrels (*Procellaria conspicillata*) on Inaccessible Island (81% of burrows occupied; Ryan & Ronconi 2011). However, Auckland Island occupancy rates are much higher than for Antipodes Island white-chinned petrels at the same time of year (22–30%; D.R.T., *unpubl. data*). Occupancy rates are also higher than for Antipodes Island grey petrels (*P. cinerea*) (20–31%; D.R.T., *unpubl. data*) and Westland petrels (*P. westlandica*) on the west coast of New Zealand's South Island (43%; Waugh *et al.* 2015).

White-chinned petrels breed in small numbers at other sites in the Auckland Islands, on Enderby Island and possibly on main Auckland (Miskelly *et al.* 2020 – Chapter 2). Since a small colony breeds on Ewing Island in the northern Port Ross area of the Auckland Island group, other Port Ross islands were surveyed to find out whether white-chinned petrels breed nearby. None of the additional Port Ross islands surveyed (Rose, Friday, Shoe, Ocean, Frenchs, Yule, and Green Islands) had any sign of white-chinned petrels. Main Auckland has feral cats, mice, and pigs, and Enderby Island had mice and was extensively modified by feral pigs, feral cattle (*Bos taurus*), and rabbits (*Oryctolagus cuniculus*) before they died out or were eradicated (R.H. Taylor 1968; Torr 2002; Russell *et al.* 2020 – Chapter 6 in this book). There are very few records of white-chinned petrel burrows being found on either island (three records on Enderby, one on main Auckland; Miskelly *et al.* 2020 – Chapter 2). However, neither has had focused search effort, and small numbers of white-chinned petrels likely persist in areas of main Auckland inaccessible to pigs. On this basis, the main Auckland and Enderby Islands may together support hundreds to perhaps several thousand burrows. Using the extent of pig-free habitat on main Auckland (likely limited to shelves on the north-western coastal cliffs), our work here illustrates how white-chinned petrel distribution could potentially be inferred from aerial and satellite images, with local density and occupancy data now available to obtain a rough idea of white-chinned petrel numbers in unsurveyed sites.

Broadly, point estimates of population size provide only a snapshot of numbers, and need repeating to assess population trends. The value of the point estimates reported here is that they provide best efforts to account for spatial variability in the distribution of petrels. These data enable future estimates to balance the need for accurate, precise estimates with manageable effort. For example, the spatial coverage of the data here enables identification of low-, medium- and high-density indicator sites within an island for long-term monitoring (e.g. Adams or Disappointment Islands), and provides data for power calculation to check that estimates from selected sites would have the power to detect change.

Summary

Taken together, the subantarctic Auckland Island group supports an estimated 184,000 breeding pairs of white-chinned petrels. Importantly, these quantitative population estimates contribute to work evaluating the effects of current levels of fisheries by-catch on white-chinned petrels; for example, informing models of fisheries by-catch risk for white-chinned petrels (Richard & Abraham 2013). The estimates have been incorporated into updates of white-chinned petrel conservation status (BirdLife International 2017; Robertson *et al.* 2017). The New Zealand regional threat status was changed from At Risk – Declining to Not Threatened (stable or increasing) in 2016 (Robertson *et al.* 2013, 2017). This acknowledges that white-chinned petrels are abundant, but involves the assumption that trends are stable or increasing. Since trends remain entirely unknown, a precautionary approach would suggest that New Zealand populations continue to be treated as At Risk until trend estimates are available. This work provides a baseline to build on for future trend calculations. The breeding populations of white-chinned petrels on the Auckland Island archipelago is smaller than on the much larger Îles Kerguelen and South Georgia, where estimates are of 234,000 (186,000–297,000) and 773,000 (592,000–1,187,000) active burrows respectively (Barbraud *et al.* 2009; Martin *et al.* 2009). Nonetheless, the islands' very high densities of active burrows are striking, suggesting that predator-free islands in the New Zealand subantarctic are key sites for white-chinned petrels globally.

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White-chinned petrel, Ewing Island, January 2018.
Image: Colin Miskelly.