Aerial Surveys of Northern Royal Albatross (*Diomedea sanfordi*) on the Chatham Islands: 2017-2018 Breeding Season

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Front cover

Northern Royal Albatross adults incubating eggs on Rangitautahi in December 2017 (top) and resulting chicks just prior to fledging, August 2018 (bottom). The images are not exactly aligned.

Photo credits: Erin Patterson (top) and Nicola Tuanui (bottom)

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Executive Summary

1. Two aerial photographic surveys were carried out on the Chatham Islands during the 2017–18 breeding season. The first, done on 4 December 2017, was aimed at counting the number of pairs of Northern Royal Albatross (*Diomedea sanfordi*) nesting on Rangitautahi and Te Awanui in the Rangitatahi (The Sisters) island group and on Motuhara (Forty-Fours). The second, flown on 23 August 2018, was designed to survey the number of Northern Royal Albatross chicks present on these islands just prior to fledging, and thereby determine nesting success for the 2017–18 season.
2. A total of 1768 photographs were received for processing (911 for December 2017, 857 for August 2018). The plateaus of all three islands were fully covered, as well as the upper parts of most cliffs. Image quality varied, with low shutter speeds compromising the quality of some wide-angle and medium-scale images, especially ones taken in August 2018. Nevertheless, at least for counting Northern Royal Albatross adults and chicks, the images were generally suitable, helped by considerable redundancy arising from repeatedly photographing the same areas during multiple circuits around the islands.
3. A total of 3919 active Northern Royal Albatross nest sites were counted from images taken in December 2017 (95% confidence limits 3794–4044): 1789 on Motuhara (95% CL 1704–1874); 1317 on Rangitautahi (95% CL 1244–1390); and 813 Te Awanui (95% CL 756–870).
4. Correspondingly, a total of 2149 albatross chicks (95 % CL 2056–2242) were counted in the August 2018 images, taken just prior to fledging: 1194 on Motuhara (95 % CL 1125–1263); 550 on Rangitautahi (95 % CL 503–597); and 405 on Te Awanui (95 % CL 365–445). Apparent nesting success overall was 54.8 % (95% CL 54.2–55.4): varying from 66.7 % on Motuhara, to 49.8 % on Te Awanui, and 41.8 % on Rangitautahi.
5. Nesting success was significantly negatively correlated with the proportion of bare ground (soil, gravel and rock) on the islands. Higher surface temperatures of bare ground can lead to the embryo death; eggs also risk being cracked or chipped.
6. Although there were some differences in the assessed stages of development of the chicks on the different islands, most notably proportionately more chicks close to fledging on Te Awanui, none of these have any obvious causal explanation.
7. Northern Royal Albatross breeds biennially. Given an estimated 4406 pairs nesting in 2016–17, and 4151 pairs nesting 2017–18, then the current upper limit for this species' population would be 8557 pairs, assuming no carry over of unsuccessful breeders from one year to the next. Conversely, assuming all failed breeders in one year attempt to re-nest the following year, then the lower limit for the albatross population is 6267 (2116 successful pairs in 2016–17, plus 4151 breeding pairs in 2017–18).
8. Compared with past estimates for the breeding population and corresponding nesting success these data suggest a slow recovery of the population from the low points recorded in the late-1980s and early-1990s, following a hurricane in 1985 that apparently destroyed much of the vegetation cover on these islands.
9. Some suggestions are made for further monitoring, including establishing more permanent sample plots on Motuhara and fixed point cameras to investigate the time-course of nest failures, especially during the incubation and chick-guarding stages. More training for DOC staff in aerial photography is also advised.

1. Introduction

Around 99% of the global population of Northern Royal Albatross or toroa (*Diomedea sanfordi*) breeds on three outlying islands in the Chatham Islands group: Motuhara (Forty-Fours), and Rangitautahi (Big Sister) and Te Awanui (Middle Sister) in the Rangitatahi (The Sisters) group. The species is a biennial breeder, with birds that successfully rear a chick in one year only returning to breed again two years later. But pairs that fail during incubation or the early nestling stage (weeks 1-6 of the ~35 week nestling period) may return to nest again the following year (Department of Conservation 2001). Annual counts of breeding birds therefore cover only around half of the total breeding population, depending on nesting success the previous season and how many of the failed breeders then return to re-nest the following year.

Based on the number of breeding pairs in a year plus the number of successful breeding pairs the previous year, Bell *et al*. (2017) estimated the current total breeding population on these islands to be 5908 pairs. In addition, a further 39 pairs, on average, have bred annually in recent years at Taiaroa Head, Otago Peninsula. Using the same formula as Bell *et al*. (2017) and annual breeding success in recent years (summarised in Cooper 2019), this gives an average breeding population at Taiaroa Head of 62 pairs, ~1% of the world's population.

Because individuals breed for the first time on average only when about 9 years old there is a substantial population of immature and sub-adult birds (Richard *et al*. 2013). Some of these visit the nesting colonies a year or more before starting to breed, to prospect for mates and nest sites. Their presence also needs to be accounted for in any census of the actual breeding population, by distinguishing them clearly from incubating and brooding birds. Together, these features all produce considerable uncertainty in population estimates.

The breeding population of toroa on Motuhara and Rangitatahi has been assessed sporadically by a combination of ground counts of nesting birds, usually done during the early incubation period (November–December), and counts of birds from aerial photographs taken around the same time (Robertson 1998; Baker *et al*. 2017). Assessments of breeding success have usually involved aerial surveys conducted in July-August, prior to the chicks fledging in September (Robertson 1998; Frost 2017a). These too have been sporadic.

An aerial photographic survey of the colonies on Rangitautahi, Te Awanui and Motuhara conducted in late November 2016, adjusted for the presence of non-breeding birds and supplemented by ground counts of nesting birds on Motuhara in early December 2016, produced an estimate of 4406—4772 nesting pairs for these islands, depending on the adjustments used (Baker *et al.* 2017; Bell *et al*. 2017). A subsequent aerial survey carried out in late-July 2017, about 6–8 weeks from the September fledging period for toroa chicks, produced an overall count of 2116 chicks (Frost 2017a).

This report covers the results of two subsequent aerial surveys of these islands carried out on 4 December 2017, when nesting toroa were in the early stages of incubation, and on 23 August 2018, a few weeks before most of their chicks were due to fledge. The December 2017 survey coincided with an on-the-ground survey of breeding seabirds on Rangitautahi and Te Awanui, during which a total of 2,255 active toroa nests were counted (Bell *et al*. 2018). This is 74–80% of the variously adjusted numbers of actively breeding pairs estimated for these two islands from the aerial survey done a year earlier (Baker *et al*. 2017). Taken together, these aerial surveys and ground counts carried out over two successive years provide a more complete view of breeding success in this biennial breeding species.

These islands are also key breeding sites for Northern Buller's mollymawk (*Thalassarche bulleri platei*) and Northern giant petrels (*Macronectes halli*). Almost all the global population of Northern Buller's mollymawk breed on Rangitautahi, Te Awanui and Motuhara (estimated population in December 2017 16,138–17,969 nesting pairs, depending on the extent of adjustment made for the presence of loafing birds). The only other breeding population of Northern Buller's mollymawk is tiny: 34 actively breeding pairs recorded on Rosemary Rock, Three Kings Islands, in November 2017 (Frost *et al*. 2018).

Ground counts of Northern Giant Petrel chicks made on Motuhara in December 2016 (Bell *et al*. 2017) and Rangitatahi in December 2017 (Bell *et al*. 2018), extrapolated to the number of breeding pairs by taking into account the number of failed nests present at the same time, gave an estimate of 2,133 breeding pairs on the Chatham Is. This is about 18% of the approximately 11,800 breeding pairs of this species globally (ACAP 2010). Baker *et al*. (2017) have already commented on the problems of censusing giant petrels from the air, given difficulties of consistently distinguishing giant petrel adults and chicks from their backgrounds on aerial photographs.

2. Methods

2.1 Study sites

Rangitatahi or The Sisters (43.5642° S, 176.8075° W) comprise three islands situated 20 km due north of Cape Pattison on Rēkohu (Chatham Main I.). The largest island, Rangitautahi or Big Sister, has a 3.8 ha undulating plateau around 60–90 m elevation surrounded by 40–60-m high vertical cliffs (total island area is around 7.3 ha; all areas measured on Google Earth). Te Awanui (Middle Sister) is a 4.8 ha island made up a 2.3-ha plateau lying about 40 m above sea level and a 0.6 ha, 65-m high, steep-sided rounded hill. A third island, unnamed, is a 6.9 ha rocky reef, lying <20 m above sea level. There are also two main, bare, rocky stacks off Rangitautahi.

The islands consist of massive limburgitic basalt with allied breccia, scoria and tuff deposits (Campbell *et al*. 1988). The soils are generally thin and support only sparse vegetation except in basins on the plateaus, where the Chatham Island button daisy (*Leptinella featherstonii*) and groundsel (*Senecio radiolatus*) are well established. The Chatham Island button daisy is a species that reputedly thrives on nutrient inputs from nesting seabirds.

Motuhara (Forty-Fours or Bertier) lies 42 km east of Rēkohu, at 43.9622° S, 175.8347° W). It comprises an 11.5 ha, 60-m high main island with a relatively flat 7.8 ha plateau, and four large and two smaller stacks that together cover a further 1.4 ha. In contrast to the volcanic origin of Rangitatahi, Motuhara consist of predominantly of hard, fine- to medium-grained, partly recrystallised quartzo-feldspathic sandstones or feldsarenites (Andrews *et al*. 1978). It is the most easterly exposure of Mesozoic basement rocks in the New Zealand region. The soils are patchy and generally thin, supporting a mixture of open herb-fields and low-growing shrubland dominated by the Chatham Island button daisy. Much of the vegetation cover on Motuhara (and apparently also on Rangitatahi, albeit to a lesser extent) was destroyed in a hurricane in July 1985 (Robertson 1998), and has been recovering ever since, subsequent storms notwithstanding. Currently, vegetation cover on Motuhara is generally more extensive than on Rangitatahi (Bell *et al.* 2017, 2018).

Northern royal albatross breed on the plateaus of all three islands, including a few pairs on the rounded hill on Te Awanui, where they generally nest in soil-filled fissures and depressions on more gentle slopes. The albatrosses do not nest on the cliffs or steep slopes of any of these islands.

2.2 Aerial survey

Two aerial surveys were carried out during the 2017–18 breeding season by Department of Conservation staff on the Chatham Is using a Cessna 206 and pilot hired from Air Chathams. Sara Forder and Erin Patterson undertook the 4 December 2017 survey, with Gemma Greene and Nicola Tuanui doing the 23 August 2018 survey. Two cameras were used on each flight to photograph the colonies. Basic details are given in Table 1. There are some notable differences between the flights in terms of the camera settings used, which affected the quality of the images. One of the cameras used on the December 2017 flight was set with shutter speed priority (with a shutter speed of 1/1328s being selected throughout); the other was set with aperture priority (with the ISO number set to 200 throughout, aperture set variously between F4.0 and F8.0 but predominantly F5.6 and F4.0, and shutter speeds from 1/197 to 1/4096).

In contrast, on the August 2018 flight, one camera was set in Program mode. In this mode the settings for ISO numbers, aperture and shutter speed are adjusted automatically. Because of the generally sunny conditions, this resulted in ISO settings between 100 and 320, aperture settings predominantly F5.6–8.0, and shutter speeds generally less than 1/400s, which is too slow to counter the movement of the aircraft. As a result, many individual birds were blurred, showing ghosting because of motion blur. The second camera was adjusted manually with the ISO number fixed at 3200 and the aperture set at F5.6 throughout. This allowed shutter speeds up to 1/8000 sec (86 % of images were at 1/8000 sec, 13 % at 1/1000 sec). Although such shutter speeds successfully countered the aircraft's movement, resulting in generally sharply focused images, the high ISO number meant that the images were 'grainy' when enlarged because of the increased sensitivity of the sensor to light, making it sometimes difficult to pick out fine detail.

Table 1. Summary of cameras used during aerial surveys of Northern royal albatross on Motuhara and Rangitatahi islands in December 2017 and August 2018. AE = automatic exposure lock on.

Date	Camera	Lens	Setting	Shutter speed	Images
4/12/17	Canon EOS 77D	EF-S18-135mm f/3.5-5.6 IS USM	Shutter speed priority; AE	1/1328s (100%)	423
	Canon EOS 700D	EF75-300mm f/4-5.6	Aperture priority; AE	variable 1/1328s (47%)	488
23/08/18	Canon EOS 77D	EF-S18-135mm f/3.5-5.6 IS USM	Program mode; AE	variable 1/512s (66%)	506
	Nikon D800	28-300mm f/3.5-5.6 G VR	Manual mode	variable 1/8000s (86%)	351

The aircraft flight paths were to have been tracked using a Garmin 64s GPS but for reasons that are unclear this did not work out exactly as planned. Although the December 2017 flight was closely tracked from Rēkohu/Chatham Main to Motuhara then to Rangitatahi and back to Chatham Main, the tracking appears to have broken down when circuits around the islands were being flown. The tracks had numerous discontinuities in them (Fig. 1). The breaks were undoubtedly where contact with the satellites was lost. The apparent long excursions away from the islands then back again seemed to be associated with the aircraft turning well away from the islands, presumably to avoid the umbrella of albatrosses in the air around them.

Where possible, the corrected time stamps on the December 2017 images were correlated with the contemporaneous track points, which were being recorded automatically at a variable rate (GPS64s Auto Recording Method — the average interval between successive track points with this setting was 39 sec). The number of circuits and the duration of each were calculated from the times at near-coincident track points on successive circuits. One complication was that the flight around the Rangitatahi colonies often switched from Rangitautahi to Te Awanui and back, in a figure 8 pattern. The circuit time given in Table 2 therefore encompasses both islands.

There was no recorded track of the August 2018 flight other than the land journey on Rēkohu from Matarangi to the airport. Either the GPS was inadvertently switched off or the batteries failed unnoticed just before take-off. Information on the number of circuits around the islands and the times taken to complete these was deduced from the time stamps of images taken of the same point on the islands (usually one end or the other) on successive circuits (Table 2).

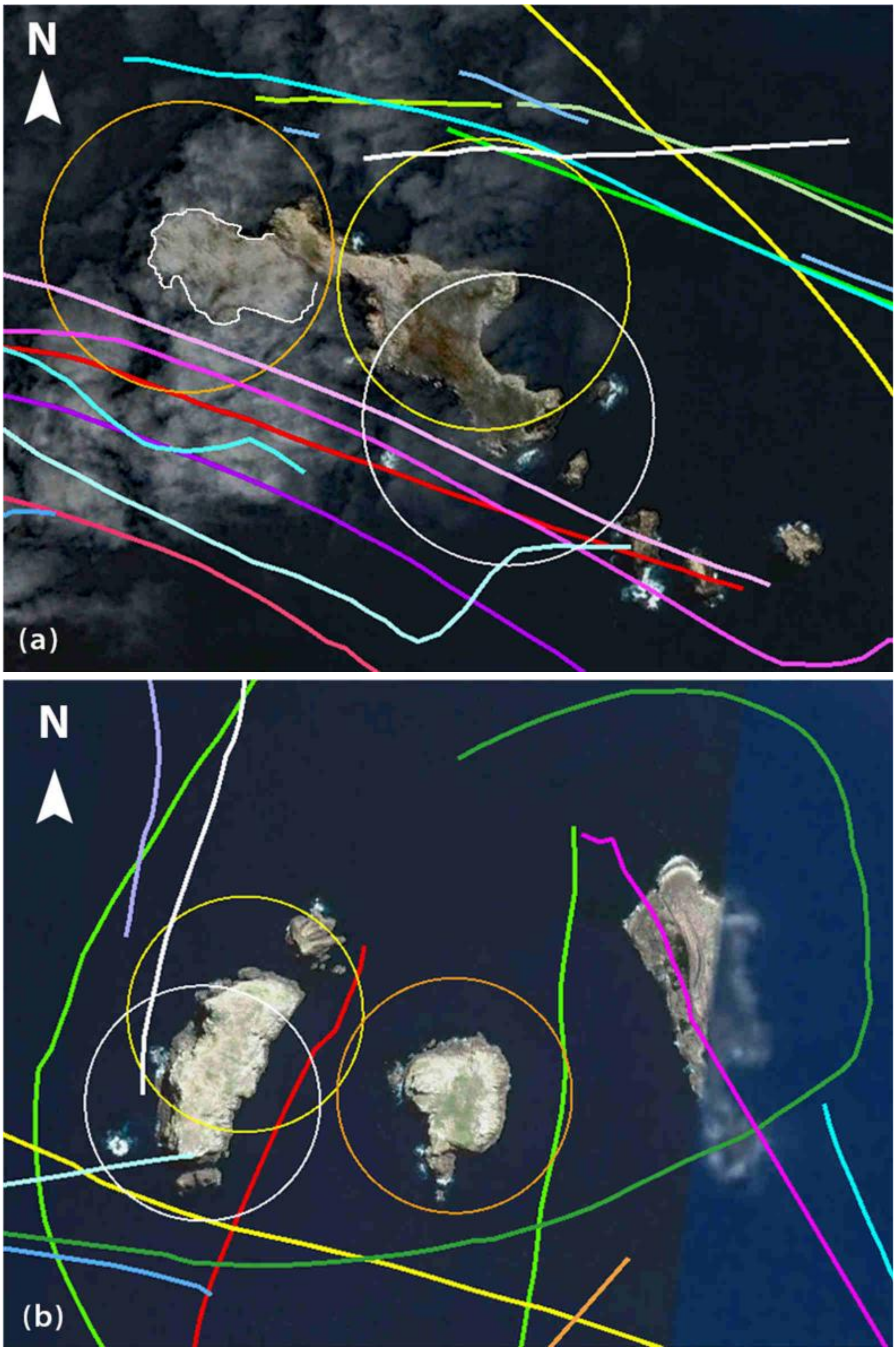

Fig. 1. Flight paths around (a) Motuhara and (b) Rangitatahi (Rangitautahi [left], Te Awanui [middle]) in December 2017, as recorded by GPS. These illustrate the broken nature of the flight-path records and, perhaps, some misregistration of positions. The different coloured flight lines have no significance other than illustrating separate sections (between breaks). The rings in each image are arbitrarily positioned circles of 250 m radius centred either on the approximate mid-points of the islands (Motuhara and Te Awanui) or towards their ends (Motuhara and Rangitautahi) to provide a measure of scale. The approximate outline of the north-east end of Motuhara, obscured by cloud, is shown in white.

Table 2. Basic features of aerial survey flights over Motuhara (Forty-Fours) and Rangitatahi (The Sisters) islands as deduced from a fragmented GPS track record (4 December 2017) and images of the islands and associated Exif data (both dates). See text for more explanation.

Date	Island	Total time (min)	Circuits	Duration (s)	
				Mean	*S.D.*
4 Dec. 2017	Motuhara	21.3	8	160	45.3
	Rangitatahi	15.2	7	106	20.8
23 Aug. 2018	Motuhara	12.0	8	83	11.7
	Rangitautahi	6.8	5	66	2.2
	Te Awanui	4.8	3	64	8.5

The most notable difference between the two flights was the quicker circuits flown in August 2018. Because of the absence of a GPS record of that track it is unclear if this was due to faster airspeed or tighter and therefore shorter circuits. Comparing the duration between timestamps of photographs taken of the same areas at either end of a circuit of Motuhara during the December 2017 and August 2018 surveys strongly suggests that air speed during the August 2018 survey was up to 60% greater than in December 2017.

Table 3. Mean aircraft altitude and airspeed determined from a fragmented GPS track recorded onboard during the aerial survey of the islands and stack of Motuhara (Forty-Fours) and Rangitatahi (The Sisters) on 4 December 2017. The distance offshore was calculated as the horizontal distance of the aircraft from each island, measured perpendicular from the track to the nearest point of an island at a series quasi-random points positioned along each track. See text for more detail.

	Altitude (m)		Airspeed (kph)			Distance offshore (m)		
Island	Mean	*S.D.*	Mean	*S.D.*	N	Mean	*SD*	N
Motuhara (main)	175	*38.7*	136	*36.6*	466	211	106.6	82
(stacks)	—not separated from above—					112	*99.0*	25
Rangitautahi	146	*7.2*	137	*24.1*	184	173	95.3	40
Te Awanui	152	*13.2*	130	*20.3*	128	203	45.6	25

2.3 Image processing

Overall, 911 images of the three islands were acquired in December 2017, with a further 857 images obtained in August 2018. In both cases, these provided complete coverage of the tops of the islands at a range of scales. The cliffs were slightly less fully covered, other than in distant views. This did not affect the counts of Northern Royal Albatross, which nest almost entirely on the islands' plateaus (some birds nest on the north-western slopes of Te Awanui, but these were covered in the photographs taken).

The Exif data for the images—date and time when each was taken, the make and model of the camera used, and the corresponding shutter speed, aperture setting, ISO number and lens focal length—were bulk extracted using Picture Information Extractor 6.99.10.61 (Picmeta Systems, http://www.picmeta.com). The time stamps on the images were corrected to make them contemporaneous with the GPS (December 2017) and with each other (August 2018, when the flight was not tracked but the GPS time display, showing 'satellite time', had been photographed at the start of the flight, before the GPS failed or was inadvertently switched off). This made it possible to correct the camera time stamps and bring them into line. As it was, these required only minor adjustment, with the camera time settings being 16 sec (Canon 77D) and 35 sec (Nikon D800) ahead of satellite time.

For the images taken in December 2017, when there was a concurrent GPS track, the differences in times between the cameras and satellite time was only determined 14 weeks later, again by photographing the GPS time display and comparing this with the cameras' time settings. These were 1 hr 34 min behind (Canon 77D) and 10 hr 14 min ahead of satellite time (Canon 700D). Although the camera times could have drifted further in the period between when the survey took place and when the time differences were measured, they were applied to the images. This brought the camera times generally into line with satellite time, judged from the broad coincidence between the position of the aircraft at that time, as determined by GPS, and the fields of view of the time-adjusted images. Such adjustments allowed photographs taken by the two cameras in each survey to be approximately correlated, making it easier to find locations shown in close-up images within wide-angle images taken with the other camera around the same time.

The images taken in both surveys covered a wide range of effective focal lengths (29–480 mm in December 2017 and 29–300 mm in August 2018[1]), with 72 % of those from December 2017 and 84 % of those from August 2018 being taken at 100–300 mm equivalent focal lengths (Fig. 2). As in the July 2017 aerial survey of Northern Royal Albatross chicks (Frost 2017a), medium-scale images (70–135 mm or 112—216 mm equivalent focal lengths) made up around two-thirds of all images.

Photographs were processed in Photoshop Elements 14 before analysis. Lighting, contrast, hue and saturation were adjusted to highlight the birds as best as possible. Photographs from the Canon EOS 77D were in RAW (CR2) format and these were either processed first in that format, using Digital Photo Professional 4.6.30.0 or, more usually, were converted to JPEG format with minimum compression and then processed. In most cases, the latter was done because of the significant increase in time needed to process images in RAW format. The same applied to the Nikon photographs, which were in NEF format.

Although many medium-scale images taken in the December 2017 and August 2018 surveys were not sharply focused when examined close up, they were generally adequate for locating and counting Northern Royal Albatrosses, but not always for determining unequivocally their status (incubating, standing on an empty nest, loafing etc.). The same was not generally true for two other species for which counts were attempted: Northern Buller's Mollymawk and Northern Giant Petrel. The close-up images (>200 mm) helped in resolving some uncertainties but coverage at this scale was patchy, so they could not be used to survey these species' populations.

[1] The focal lengths given here are 'equivalent focal lengths', to make the images of the Canon cameras, the sensors of which have a 1.6x crop factor, which produces a narrower field of view, compatible with the full-frame sensor of the Nikon D800 used in August 2018.

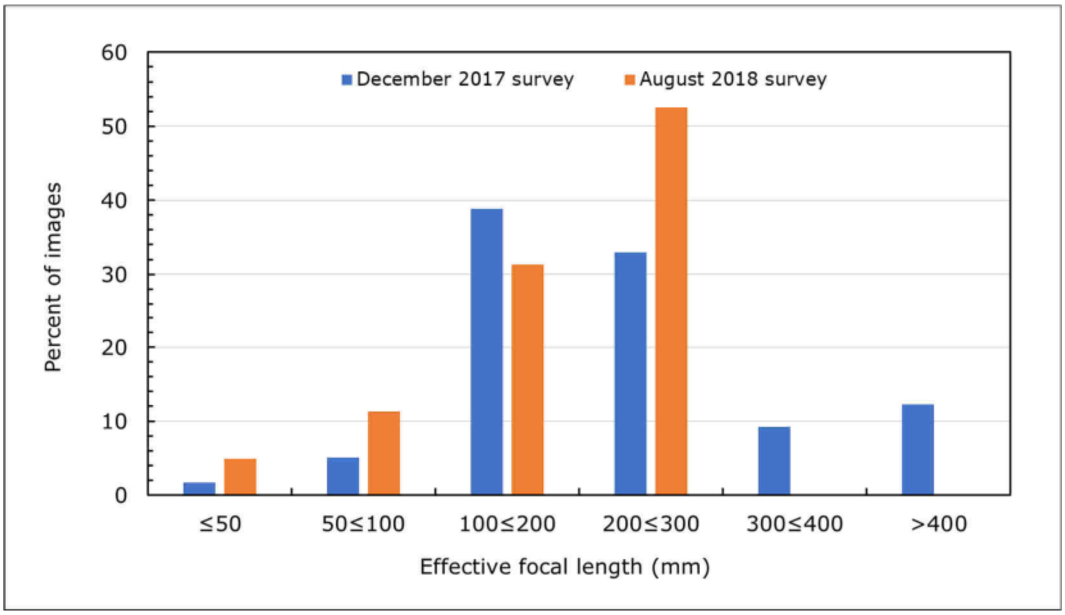

Fig. 2. Distribution of effective focal lengths at which images were taken of nesting Northern Royal Albatross (December 2017, N = 911) and their chicks (August 2018, N = 857), showing the concentration of medium-scale images. See text for further details.

To ensure no overlap or gaps in the areas analysed, suites of partly overlapping images were selected that, taken together, fully covered each island. These were not necessarily sequential images from the same photographic circuit of an island, but were chosen for their clarity. The challenge this posed was that the selected images of an area were sometimes taken at different angles and distances. This required finding enough common, identifiable features—distinctive boulders, sheets of rock, fissures, clumps of vegetation, etc.—that could be linked to mark the same boundary on both images (This also extended to images that overlapped above and below.) The outcome was a series of discrete regions on each island that, overall, ensured complete coverage without overlap or gaps (Fig. 3).

The zones mapped on Rangitautahi and Motuhara were broadly the same as those delineated in June 2017, but those used originally on Te Awanui were further divided and renumbered for 2017–18 surveys (Fig. 3b). Nesting and other individuals in December 2017, and fledglings in August 2018, were counted in ImageJ 1.52o (http://imagej.nih.gov/ij) using the programme's Multipoint tool. All counts were saved as ImageJ .roi files. Nesting success was determined as the number of chicks counted in August 2018 expressed as a percentage of the number of nesting adults counted in December 2017, both by zone and overall for each island. Confidence intervals were estimated as *2 x √count*, following Baker *et al.* (2013).

Nesting Buller's Mollymawk were identified and counted on Rangitautahi and Te Awanui, but not on Motuhara as this proved impractical because of poorly resolved images of areas with the highest concentrations of nesting birds. The number of birds nesting within five 10 x 10 m marked quadrats were counted instead. These quadrats had been set up in 2007 and 2008 (Fraser *et al.* 2010), and have been counted and reported separately since then (Bell *et al.* 2017). Giant Petrels proved even more difficult to recognise and count consistently, particularly in the December 2017 images, where adults and chicks were concealed among rocks. Counts of this species should therefore be treated as highly uncertain.

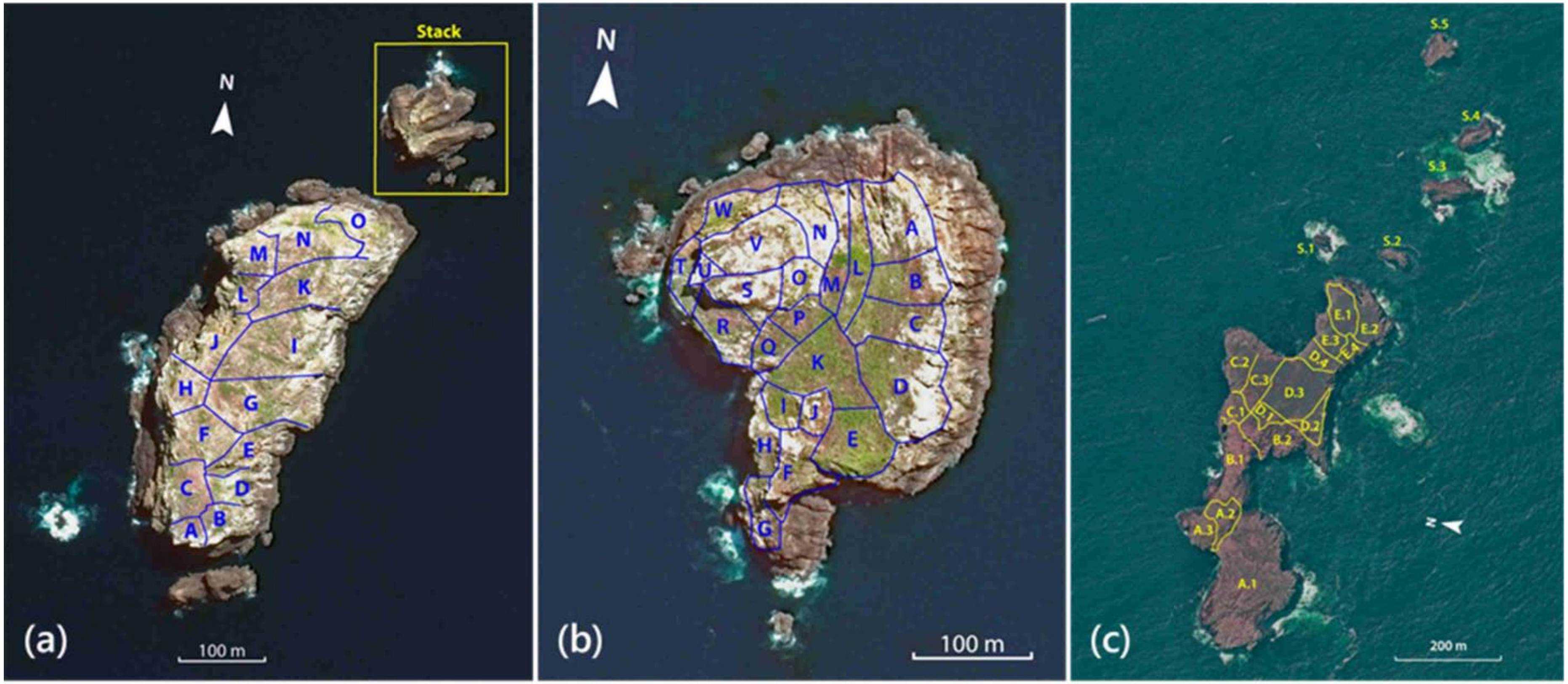

Fig. 3. Demarcated zones for counting Norther Royal Albatross adults and chicks on (a) Rangitautahi, (b) Te Awanui, and (c) Motuhara. For more detail, see text. Note the differences in scale.

Because the same counting zones were used when analysing the December 2017 and August 2018 images, this made it possible to compare the nesting success of Northern Royal Albatross among areas with different types of landcover. Land cover was determined from a selection of non-overlapping close-up images from each zone analysed in ImageJ. Each image was overlain with 100 x 100 pixel grid, positioned with a random offset, and the intersections of the grid examined at full resolution to determine the landcover at each point. Land cover was assigned to one of four groups (Fig. 4): **bush** (woody vegetation judged to more than about 15–20 cm high, mainly Chatham Island Button Daisy *Leptinella featherstonii*); **herb** (low-growing vegetation such as moss, grass and low-growing herbaceous flowering plants *e.g.,* groundsel *Senecio radiolatus*); **soil** (areas of bare soil, including those covered with small pebbles; and **rock** (sheets of bare rock or large boulders). Points that fell on a bird were discarded. The distance between successive points is estimated to have been around 1.2–1.4 m. This systematic sampling procedure with a random start allowed each zone to be categorised by the proportions of each land-cover type, later reduced to the proportion of the land surface that was vegetated (bush and herb) and the proportion that was bare (soil and rock).

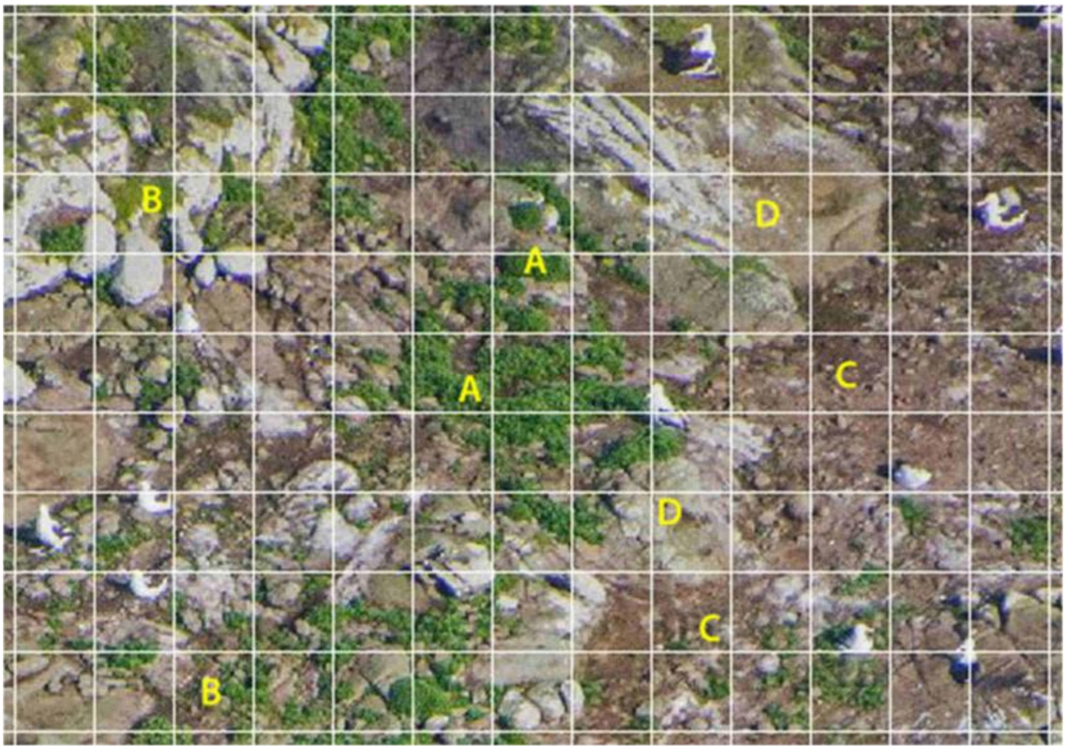

Fig. 4. Approach taken to sampling landcover on close-up photographs by categorising the cover at each point of intersection on a 100 x 100 pixel grid overlain on the image. Landcover was classed either as 'bush' (A), 'herb' (B), 'bare soil', which included pebbly soil (C), and 'bare rock', including both sheets of rock and boulders (D). See text for further explanation.

The albatross chicks in August 2018 covered a range of developmental stages. To establish if there were any significant differences in the distribution of these stages among the islands, the chicks present in a series of non-overlapping close-up images of the three colonies were assessed and categorised into six age classes. These classes are illustrated in Annex 1, along with the approximate age of the chicks based on the known age of a chick videoed at different developmental stages at Taiaroa Head, Dunedin, the same year. See Annex 1 for further details.

3. Results

3.1 December 2017 survey

In early December 2017, across all three islands, a total of 3919 nest sites (95% confidence limits 3794–4044) were apparently occupied by nesting Northern Royal Albatross (Table 4). Of these, 3897 sites were occupied by single nesting birds, all assumed to be incubating eggs, and 22 in which the presumed incubating bird was accompanied by a partner. The largest number of apparently occupied sites (= nesting pairs) was on Motuhara (1789, 95% CL 1704–1874), with 1317 pairs on Rangitautahi (95% CL 1244–1390) and 813 pairs on Te Awanui (95% CL 756–870). Beyond that, there were four duos (pairs of apparently non-nesting birds), mostly on Motuhara, and 91 single birds classed as 'loafers' (but which could have included some birds moving to or from active nest sites elsewhere). These were 1.2–3.2 % of the nesting total. Thirty carcasses were also counted, more than half of them on Motuhara (Table 4).

Table 4. Counts from aerial photographs of apparently occupied Northern Royal Albatross nest sites (AOS) present on 4 December 2017.

Island	Nesting individual	Pair at nest	Duo (not nesting)	'Loafer' or flying	Carcass	AOS	AOS 95% confidence limits
Rangitautahi	1314	3	0	24	8	1317	1244–1390
Te Awanui	811	2	1	10	5	813	756–870
Motuhara	1772	17	3	58	17	1789	1704–1874
Total	3897	22	4	92	30	3919	3794–4044

3.2 August 2018 survey

A total of 2149 chicks (95 % CL 2056–2242) were counted across all three islands, with most (56 %) occurring on Motuhara (Table 5). These were accompanied by 65 adults, mostly on Motuhara and Rangitautahi. Forty-three reasonably recent carcasses were also seen, with their numbers distributed among the islands in broadly similar fashion to that of the chicks (X^2 Goodness-of-fit = 0.895, p = 0.6391, ɑ= 0.05, not significant).

Table 5. Counts of numbers of Northern Royal Albatross chicks and adults in the Chatham Is colonies on 23 August 2018, along with the number of carcasses of recently-dead chicks.

Island	Chicks	Chick carcasses	Adults	Chicks 95 % CL
Rangitautahi	550	13	21	503–597
Te Awanui	405	6	3	365–445
Motuhara	1194	24	41	1125–1263
Total	2149	43	65	2056–2242

Apparent nesting success overall was 54.8 % (95 % CL 54.2–55.4, Table 6), being highest on Motuhara (66.7 %), lower on Te Awanui (49.8 %), and lowest on Rangitautahi (41.8 %). These figures each assume that the chicks present at this stage all fledge successful. Judging from the number of relatively recent carcasses present, amounting to 2 % of the population at the time, it seems likely that actual nesting success could be 1-3% lower by the time all chicks have fledged.

Table 6. Apparent nesting success of Northern Royal Albatross in the Chatham Is during the 2017–18 nesting season, calculated as the number of chicks present in August 2018, just prior to fledging, expressed as a percentage of the number of apparently active nests recorded in December 2017.

Island	Active nests Dec 2017	Chicks Aug 2018	Apparent nesting success (%)	95% confidence limits on nesting success
Rangitautahi	1317	550	41.8	40.4–42.9
Te Awanui	813	405	49.8	48.3–51.1
Motuhara	1789	1194	66.7	66.0–67.4
Total	3919	2149	54.8	54.2–55.4

Egg laying in Northern Royal Albatross is broadly synchronous, with most eggs being laid within a month, late October to late November (Sugishita 2013). Nevertheless, although considerably more than 80 % chicks were fully feathered or judged to be about to fledge (94.6 % on Te Awanui), there were a notable number of younger chicks (Table 7). There were not distributed independently across the islands. Among the more significant departures from independence were more pre-fledging chicks and fewer feathered downy chicks than expected on Te Awanui; more large downy chicks than expected on Rangitautahi; and fewer pre-fledging chicks than expected on Motuhara (overall $X^2 = 72.677$, $p < 0.0001$, $\alpha = 0.05$, df = 6).

Landcover on the three islands also differed significantly (Table 8: $X^2 = 401.43$, df = 6, $\alpha = 0.05$, $p < 0.00001$). Rangitautahi had significantly less bush cover and more exposed rock than expected if cover types were independently distributed; Te Awanui had significantly less bush and herb cover and more soil and rock than expected; and Motuhara had significantly greater bush and herb cover, and less soil and rock cover than expected.

These differences appear to have influenced nesting success, which was correlated negatively with the proportion of bare ground (soil, gravel and rock) present in each census zone on the islands (Fig. 4; $r = 0.612$, df = 40, $p < 0.001$). Any census zone that had < 10 nests in it was treated as an outlier and excluded from this regression, on the grounds that with such a small number of nests stochastic events could potentially override any influence of substrate. Nevertheless, even if these outliers were included, a statistically significant negative relationship still existed between nesting success and the proportion of bare ground ($r = 0.502$, df = 47, $p < 0.001$).

Table 7. Numbers of Northern Royal Albatross chicks in different developmental stages, as derived from an analysis of samples of non-overlapping close-up images of the three colonies taken on 23 August 2018. Illustrations of these age classes, along with the approximate age of the chicks in each, are given in Annex 1.

Island		Large downy	Feathered with down	Fully feathered	Pre-fledging	Total classified	Not classified	Adults
Rangitautahi	N	20	63	372	61	516	34	21
	%	*3.9*	*12.2*	*72.1*	*11.8*	*100*		
Te Awanui	N	5	16	303	66	390	15	3
	%	*1.3*	*4.1*	*77.7*	*16.9*	*100*		
Motuhara	N	15	119	889	65	1088	106	41
	%	*1.4*	*10.9*	*81.7*	*6.0*	*100*		
Total	N	40	198	1564	192	1994	155	65
	%	*2.0*	*9.9*	*78.4*	*9.6*	*100*		

Table 8. Occurrence of different land covers on islands with Northern Royal Albatross colonies, August 2018. Just over 13,700 points were sampled systematically at the intersections of 100 x 100 pixel grids, placed over each photograph with a random offset.

Island	Sample points (*percentage)*					Surfaces	
	Bush	Herbs	Soil	Rocks	Total	Vegetated (%)	Bare (%)
Rangitautahi	257	586	354	1214	2411	843	1568
	10.7	*24.3*	*14.7*	*50.4*		*35.0*	*65.0*
Te Awanui	550	750	697	1773	3770	1300	2470
	14.6	*19.9*	*18.5*	*47.0*		*34.5*	*65.5*
Motuhara	1793	1918	937	2874	7522	3711	3811
	23.8	*25.5*	*12.5*	*38.2*		*49.3*	*50.7*

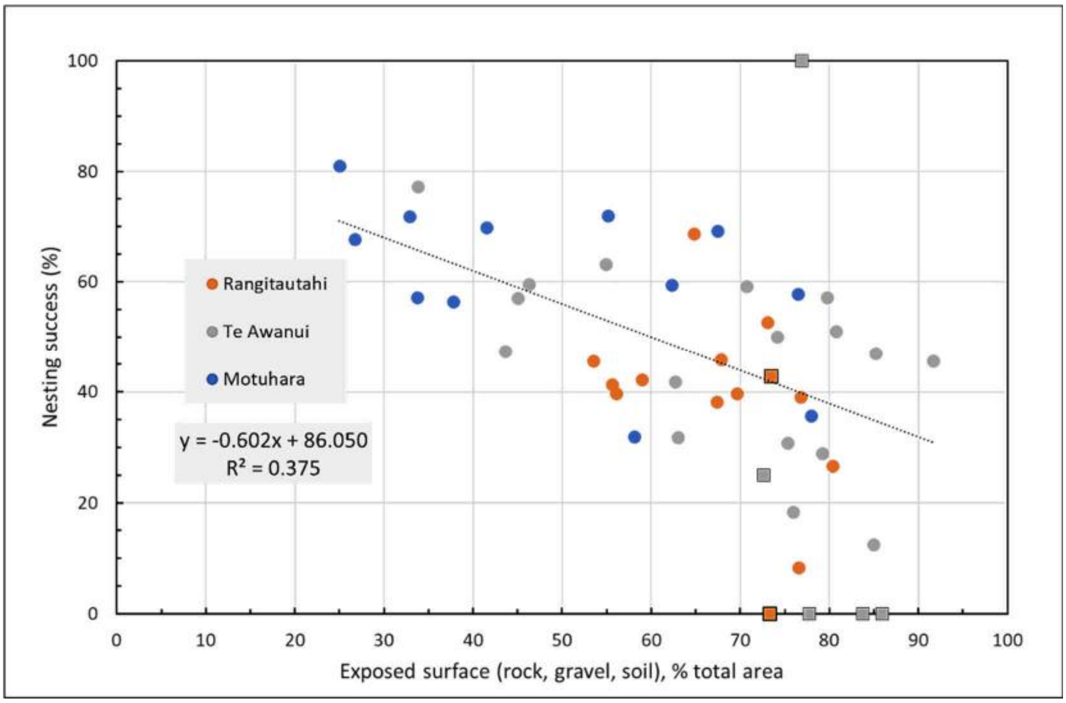

Fig. 4. Northern Royal Albatross nesting success declined with increasing exposure of the nesting areas, as measured by systematic sampling of a grid of sample points placed over a nesting area. All the data points for the three islands are shown separately but the regression line is based on those data points in areas in which there were more than 10 nests in December 2017. The excluded points (7), based on fewer than 10 nests in an area, are shown as square symbols.

3.3 Other species

Northern Buller's Mollymawk

Near-complete counts of nesting and other Northern Buller's Mollymawk were made from aerial photographs taken of Rangitautahi and Te Awanui on 4 December 2017, when birds were incubating eggs. A total of 1540 apparently occupied nests were counted on Rangitautahi (95% CL: 1462–1618), with a further 442 apparently occupied sites on Te Awanui (95% CL: 400–484). On both islands, around 98 % were of single birds at a nest (Table 9). These may be slight undercounts because the sets of images did not always extend to the base of the cliffs around the islands, other than in distant views. Where they did, it was possible to see some apparently nesting mollymawks in low-down caves and hollows, so some nesting birds may have been missed in those parts of the islands with incomplete photographic coverage of the cliffs.

The quality of the images of Motuhara was inadequate for clearly identifying and counting nesting mollymawks. This difficulty was compounded by the greater number of nesting birds and the often more rugged landscapes in which the birds were nesting. Attempts to count birds in those areas where they could be clearly seen were eventually abandoned because of the lack on any suitable landmarks that could be used to demarcate areas and which would be easily identifiable in images taken in subsequent years. Counts of birds in undefined, unreplicable areas would be essentially meaningless.

Instead of attempting to count every nesting mollymawk on Motuhara, attention turned to locating and counting the number of birds nesting in five randomly positioned 10 x 10 m quadrats set up in 2007 and 2008 (Fraser *et al.* 2010), and which had been censused since (Bell *et al.* 2017). The corners of these quadrats had been marked originally with orange-painted boulders. Most of these were still visible 10 years later, but in a couple of cases the colour had either disappeared or was greatly reduced, or was possibly obscured by surrounding vegetation. The position of these missing corner markers was estimated by examining 2–3 close-up photographs of the quadrats concerned. Boundary lines were drawn on the images between the existing visible corner markers, and the other boundary lines extrapolated to form a loose parallelogram (taking account of distortion due to angle and distance from which the photographs were taken). The projected lines converged on areas in which the missing marker was thought to lie or once have been. In two out of three cases, the estimated position of the missing marker lay in a well-vegetated area. The other one fell among rocks from which the paint is thought to have been worn off or been completely obscured.

One of these grids is shown in Fig. 5, with the position of missing marker thought to lie somewhere close to the top righthand corner of the grid. The approximate positions of these quadrats are given in Table 9. They were determined from Google Earth, despite the thin cloud cover over the western end of the island where the quadrats are located (Fig. 6). The number of pairs of mollymawks nesting in each quadrat averaged 59.2 (S.D. 4.3, range 55–64), equivalent to a density of 5920 pairs ha^{-1} (Table 9).

Table 9. Counts from aerial photographs taken on 4 December 2017 of the number of apparently occupied Northern Buller's Mollymawk nests (AOS) on Rangitautahi and Te Awanui, and on five marked 10 x 10 m quadrats set up in 2007 and 2008 on Motuhara (Fraser *et al*. 2010).

Island	Nesting individual	Pair at nest	Duo (not nesting)	Loafer or flying	Apparently occupied sites	AOS 95% confidence limits
Rangitautahi	1504	36	8	245	1540	1462–1618
Te Awanui	433	9	0	16	442	400–484
Motuhara[1]						
1. -43.9621, -175.8384	54	1	0	1	55	40–70
2. -43.9618, -175.8376	54	1	0	2	55	40–70
3. -43.9614, -175.8381	59	5	0	1	64	48–80
4. -43.9616, -175.8351	54	5	0	2	59	44–74
5. -43.9614, -175.8350	62	1	1	1	63	47–79

[1] 10 x 10 m quadrats and approximate geographic location. Quadrats numbers and positions are shown in Fig. 6.

Fig 5. Northern Buller's Mollymawk nesting inside Grid No.1. Cyan dots mark nesting individuals, squares indicate a duo at a nest, and triangles mark individuals not clearly associated with a nest ('loafers'). The grid was established in 2007 and marked with orange-painted boulders, one of which is clearly seen at the bottom-left of the grid. Two other corner markers are just visible in close-up, but the fourth marker (top-right) is not visible. Its position was inferred by extrapolation and interpolation from the existing markers and projected boundaries.

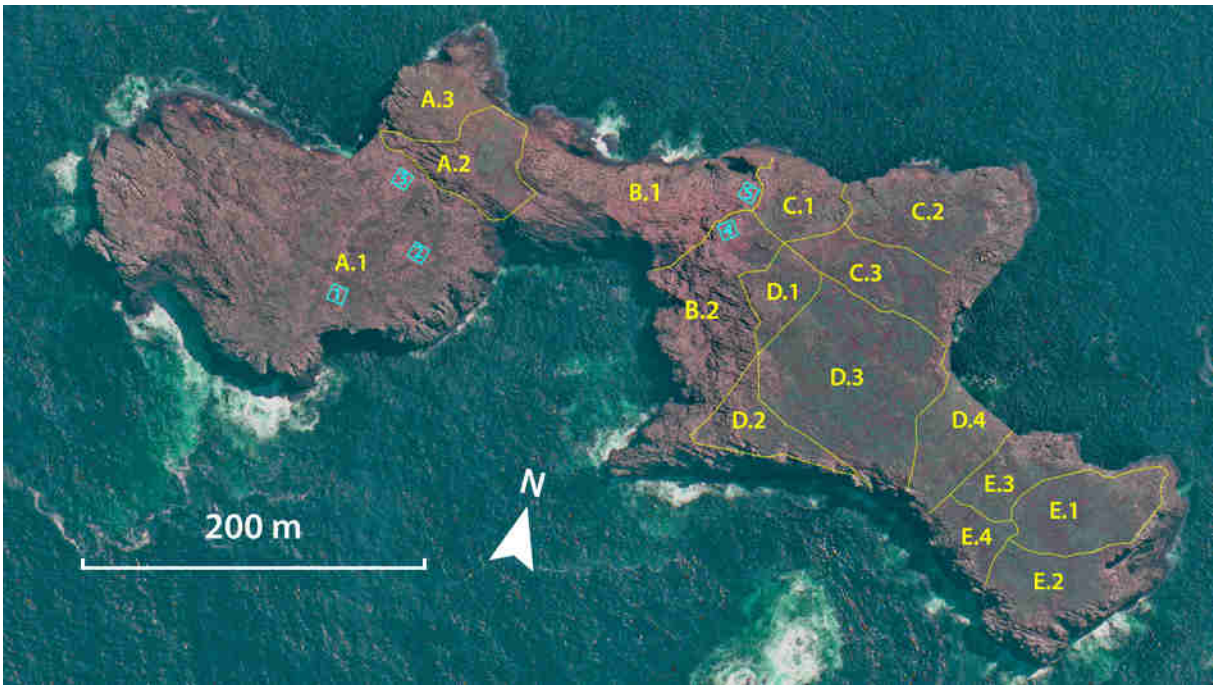

Fig. 6. Motuhara, showing the locations of five 10 x 10 m quadrats (numbered cyan squares), established in 2007 and 2008, in which the number of nesting Northern Buller's Mollymawk were censused.

Northern Giant Petrel

Northern Giant Petrel proved to be almost impossible to detect and count with any certainty. The birds nest preferentially among boulders and in shallow fissures on Rangitautahi, among boulders and under overhangs on Te Awanui, and among boulders and in rocky areas covered with *Leptinella featherstonii* on Motuhara. The volcanic breccia, greywacke and partly recrystallised quartzofeldspathic sandstones (feldsaranite) of which these islands are variously composed make it difficult to distinguish the grey chicks from their backgrounds. This is particularly so on Motuhara, where the predominant geology is grey sheets and boulders of feldsaranite (Andrews *et al*. 1978), making it particularly difficult to pick out the similarly-coloured downy chicks, especially as some of the boulders are the same size as chicks. The problem was compounded by the generally low resolution of the photographs taken on both occasions, particularly when magnified. Baker et al. (2017) commented on the same difficulty. Overall, adults were more prominent and detectable in August 2018, when the birds were aggregating before breeding, although it is not clear what proportion of these were upcoming breeders.

Overall, in August 2018, 2852 adult Northern Giant Petrels were counted across all three islands (2527 on Motuhara, 241 on Te Awanui and 84 on Rangitautahi: Table 10). The level of uncertainty is still judged to be high. The figures are reported here nonetheless, largely for the record. Beyond that, it seems impractical to use aerial survey as the means of monitoring this species on these islands.

Table 10. Counts of Northern Giant Petrel on Rangitatahi and Motuhara island groups made from aerial photographs taken on 4 December 2017 and 23 August 2018. The large uncertainty associated with these counts is stressed, even beyond that reflected in the estimated 95% confidence limits.

	December 2017			August 2018	
Island	AOS	AOS 95% CL	Total	Adult	Adult 95% CL
Rangitautahi	40	27–53	49	84	66–102
Te Awanui	29	18–40	36	241	225–257
Motuhara	602	553–651	1132	2527	2426–2628
Total	671	619–723	1217	2852	2751–2953

Discussion

Counts from aerial photographs taken in early December 2017 show a total of 3919 pairs of Northern Royal Albatross were apparently breeding in the Chatham Is during the 2017–18 breeding season (95% CL 3794–4044). Of these, 1789 pairs (45.6 %) were located on Motuhara, with 1317 pairs (33.6%) on Rangitautahi (33.6%) and 813 pairs (20.7 %) Te Awanui. Ground counts carried out on Rangitautahi and Te Awanui at the same time found 1286 nests with eggs, 105 failed nests and 38 empty nests on Rangitautahi, and 806 nests with eggs, 58 failed nests, and 95 empty nests on Te Awanui (Bell *et al.* 2018). The 95 % confidence limits for the aerial survey counts encompass the ground counts of nests with eggs. Given that failed nests have also been active at some stage in the early season, they should be added to the ground counts of nests with eggs to give a minimum number of active nests. For Rangitautahi and Te Awanui these amount to 1391 and 864 nests respectively, or 6 % greater than the aerial survey counts. No comparable ground count was made on Motuhara during the 2017–18 breeding season, but if the aerial survey count was similarly underestimated, the actual breeding population on Motuhara in 2017-18 could have been around 1896 pairs.

Northern Royal Albatross breed biennially, with pairs successfully rearing a chick in one year, or which fail late in the season, only returning to breed again two years later. Birds that fail during incubation or the early nestling stage, while still guarding the chick, may attempt to re-nest the following year, but what proportion of the initial number of breeding birds in any one season this represents is not known (Department of Conservation 2001). It almost certainly varies, depending on the season in question, and the timing of failures. The total breeding population of Norther Royal Albatross on these islands is therefore not simply the sum of the number of breeding pairs counted early in two successive seasons, but it does establish an upper bound for the population. Taking the aerial survey counts for 2016–17, adjusted in line with a ground count on Motuhara that year (4406 pairs: Baker *et al.* 2017) and 2017–18 (also adjusted, as outlined above, 4151 pairs), then the upper limit for the population would be 8557 pairs.

Following Bell *et al.* (2017), and taking the number of breeding pairs in 2017–18 plus the number of successful breeding pairs the previous season (2116: Frost 2017a), the lower limit for the current breeding population of Northern Royal Albatross is 6267 pairs. This is the lower limit because not all birds that failed prior to fledging in 2016–17 would have re-nested in 2017–18. The actual breeding population is therefore likely to lie between 6267 and 8557 pairs. Clearly, more information is needed on the timing of nest failures during at least the early part of the breeding season, so that the proportion of birds that re-nest the following year can be reasonably estimated. Given the remoteness of these islands and the impracticalities of any prolonged on-the-ground research activity, such monitoring might best be done remotely using well-secured, fixed-point cameras.

Nesting success overall can be roughly estimated as the number of chicks counted just prior to fledging as a percentage of the number of active nests counted in the same areas near the start of incubation. For the 2017–18 season, 2149 chicks (95% CL 2056–2242) were counted across all three islands: 1194 on Motuhara; 550 on Rangitautahi, and 405 on Te Awanui. Taking the aerial survey counts of adults and chicks at face value, overall nesting success was therefore around 54.8 % (95% CL 54.2–55.4): 66.7% on Motuhara; 41.8% on Rangitautahi and 49.8% on Te Awanui. Both nesting (breeding) success and the number of chicks presumed to have fledged in 2017–18 can be compared with figures from earlier years (Figs 7, 8).

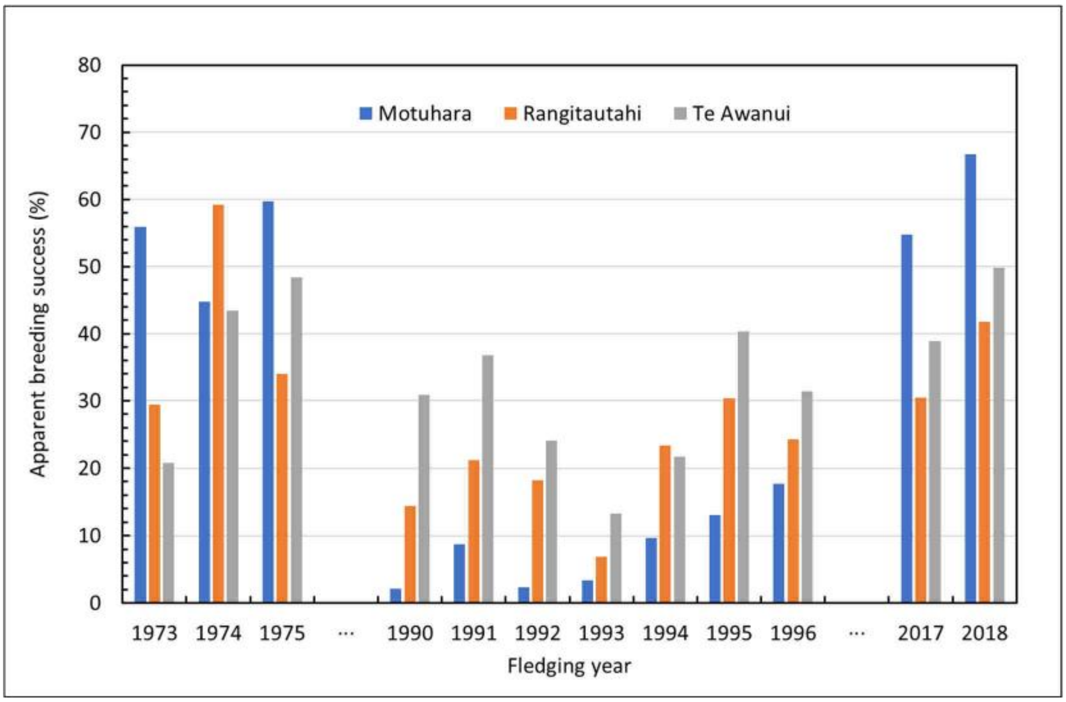

Fig. 7. Changes in apparent breeding success of Northern Royal Albatross on the Chatham Is during the mid-1970s, early 1990s, and in 2017 and 2018. Data for the first two periods extracted from Robertson (1998). Data for the last two years from Frost (2017a) and this study. Low breeding success in the 1990s appears to have been due to the lingering effects of the destruction of much of the islands' vegetation, especially Motuhara, by a hurricane in 1985.

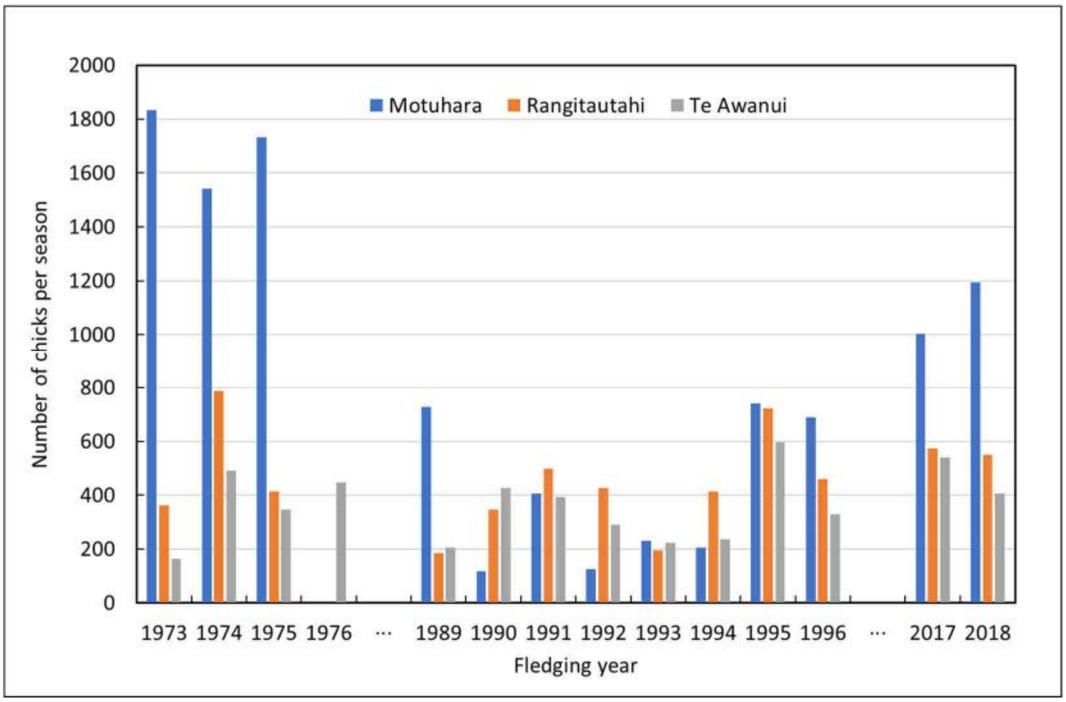

Fig. 8. Variations in Northern Royal Albatross chick production on the Chatham Is during three time periods: 1973–1976, 1989–1996, and 2017-2018. Data for 1973–1976 and 1989–1996 extracted from Robertson (1998). More recent data from Frost (2017a) and this study. See Fig. 7 and text for further explanation.

Low nesting success and the correspondingly low number of chicks fledged annually in the late 1980s–early 1990s appears to have been a consequence of the hurricane in 1985, which destroying much of the vegetation on these islands, particularly on Motuhara (Robertson 1998). The results of this study show clearly the influence of landcover on nesting success and therefore chick numbers, with nesting success being significantly negatively correlated with the proportion of bare soil in the nesting areas. Bare ground leads to high surface temperatures and embryo death. The eggs also risk being cracked or chipped during incubation (Robertson 1998).

Most chicks in the colonies were at a similar stage of development, being fully feathered with some looking likely to fledge with a week or so (termed pre-fledging here), especially on Te Awanui. Nevertheless, there were some significant differences among the islands in the proportion of chicks in earlier stages of development, with fewer feathered downy chicks than expected on Te Awanui (unsurprising, given that most chicks there were close to fledging), more large downy chicks than expected on Rangitautahi, and fewer pre-fledging chicks than expected on Motuhara if chick development was independent of site. This pattern also differed from that recorded in 2017, when there were significantly more feathered downy chicks and fewer well-feathered chicks than expected on Motuhara, relative to the other two islands. The reasons for these differences are not known. They may simply be stochastic.

Little can be deduced from the counts of Northern Buller's Mollymawk. The species was reasonably successfully counted only on Rangitautahi and Te Awanui. The number of apparently active nests counted on aerial photographs taken in early December 2017 was close to, but slightly less than the number of incubating birds counted on the ground by Bell *et al.* (2018) in the same period. Counts from aerial photographs were 96 % and 91 % respectively of the number counted on the ground on Rangitautahi (1598 birds incubating eggs vs 1540 apparently occupied nests counted from aerial photographs) and Te Awanui (488 vs 442). The ground counts were within the 95 % confidence limits of the aerial survey counts. At least for Rangitautahi and Te Awanui, annual aerial surveys of Northern Buller's Mollymawk during the early incubation period would seem to be a cost-effective approach to monitoring this species, particularly if supplemented periodically by ground counts

It proved too difficult to get reliable figures for Buller's Mollymawk on Motuhara, partly because clearer images are needed of the dense nesting colonies there. In addition, photographs need to be taken from a higher angle, to make it easier to distinguish individual birds and determine their status. Some success was achieved in finding and delineating the five 10 x 10 m quadrats set up in 2007 and 2008, and counting the number of mollymawks nesting in each. These numbers can be compared with those obtained when the quadrats were first set up (Fraser *et al.* 2010) and later surveyed by Bell *et al.* (2017) in December 2016 (Table 11).

In the period 2007–09, each quadrat had an average of around 44 nesting pairs of mollymawks. In 2016, the average was 51 pairs, which rose to around 59 pairs in 2017 (Table 10). But the 2017 survey was based on locating, delineating and counting these quadrats on aerial photographs, so the figures obtained are less certain and may even be slight overestimates. Nevertheless, the approach shows promise as a means of cost-effectively monitoring Northern Buller's Mollymawk on Motuhara. Re-painting the original corner markers to make them clearly visible from the air is needed, however. Setting up more survey quadrats across a wider area would also help greatly in establishing a monitoring scheme for this species, especially if supplemented periodically by more detailed on-the-ground surveys.

Table 11. Counts through time in the numbers of Northern Buller's Mollymawk nesting in five 10 x 10 m quadrats established on Motuhara. The numbers refer solely to birds known or judged to be incubating eggs. All numbers are based on ground counts except for 2017, when the number of nesting birds was counted on aerial photographs. See text for more information. Data from Fraser *et al.* (2010), Bell *et al.* (2017) and this study (data for 2017).

Quadrat No.	2007	2008	2009	2016	2017
1	47	43	39	51	55
2	54	42	44	52	55
3	53	43	37	41	64
4	–[1]	44	41	55	59
5	–[1]	48	42	56	63
Average (S.D.)	51.3 (3.8)	44.0 (2.3)	40.6 (2.7)	51.0 (6.0)	59.2 (4.3)

[1] Quadrat only established in 2008.

An attempt was made to extrapolate the 2017 density of nesting pairs in these quadrats across the western plateau of Motuhara, encompassing areas A1–A3, except the 'bowling green' (much of A.2), B1 and a quarter of B2 (see Fig. 6). The estimated combined area of these zones, calculated from Google Earth, is 4.1 ha. At a density of 5920 pairs ha^{-1}, this translates to 24,272 pairs, much higher than previously recorded for the whole of Motuhara: 15,667 occupied nests counted from aerial photographs in November 2016 (Baker *et al.* 2017); 13,407 nests with eggs, counted 2 weeks later in early December 2016 (Bell *et al.* 2017). It therefore seems impractical to extrapolate from counts of only a few randomly placed quadrats to a much larger area, at least not without some stratification of the sampling plots. Whether extrapolation could be improved by more intensive sampling, ideally stratified by nest density, has yet to be tested.

Any measures such as marking and maintaining more permanent sample plots or placing fix-point cameras to improve the monitoring and interpretation of the albatross and mollymawk populations and their changes on Motuhara will require the approval and cooperation of the island's owners. Initial, informal discussions on this seem promising (Mike Bell, *personal communication*).

Perhaps more could be done to improve the quality and interpretability of the aerial photographs themselves. A set of guidelines for photographing seabird colonies was produced before the surveys (Frost 2017b) but it is unclear if it was used. Ideally, photographs should be taken at a shutter speed of no less than 1/1000–1/1500 s. This means using the Shutter Priority setting to allow the shutter speed to be selected manually. With this setting the aperture setting (F-stop) needed to produce an optimum exposure is selected automatically. High shutter speeds generally result automatically in wide aperture setting (low F-stop value), which in turn reduces the depth of field. But because of the distance at which the photographs are being taken, this is seldom a problem. Even at an F-stop of 3.5 and a focal length of 135 mm, the depth of field focused on a subject 250 m away is 120–1700 m, which is generally quite adequate.

Automatic aperture settings are also affected by the ISO setting, high ISO numbers allowing narrower apertures (higher F-stop number) because the intensity or brightness of the image is increased at high ISO numbers by digitally amplifying differences in reflectance from the ground. The downside is that such images are generally grainy, which is a disadvantage when there is a need to enlarge the image to explore some fine detail, such as whether an object is the top of a head of an otherwise obscured bird, or simply a rock. To get shutter speeds of 1/1000–1/1500 s usually requires an ISO number in the range 1200–1600. Higher shutter speeds require selecting a higher ISO number, which produces grainy images. For example, the many close-up photographs taken at 1/8000 s during the August 2018 survey were taken with the ISO number set at 3200 throughout, resulting in sharply focused but graining images in which fine points of detail were often difficult to discern particularly in images that were visually cluttered anyway by a mosaic of soil, rocks, vegetation, and partly visible birds. Future surveys would be best served by setting the ISO number to 1600, which would still allow shutter speeds 1/1000 s or more, while producing a bright but less grainy image.

Using a digital camera's automatic mode should be avoided. This setting compromises image quality because the camera and lens cannot detect that the photograph is being taken in motion. Consequently, the shutter speeds are too low to compensate for this, as seen in the many wide-angle and medium-scale photographs taken at 1/512 s or less during the August 2018 survey. This produced images in which most chicks were blurred when even moderately magnified, which was necessary to do to distinguish well-grown chicks ('pre-fledging') from the few adults present (presumably coming to feed chicks), or when trying to classify chicks into different development classes.

Finally, it can be a disadvantage to photograph in bright light unless allowance is made by narrowing the aperture (setting a higher F-stop value). White chicks and even adults photographed in bright light can result in their details being 'burnt out', *i.e.*, pure white with no contrast present between adjacent pixels across the burnt out part of the image so that no detail can be discerned. Burn-out is particularly prevalent in images in which there is a strong contrast between a relatively dark background, which often causes automatic aperture settings to widen to compensate, and very pale or white objects embedded in it, such as albatross adults and chicks, or guano-stained, chick-sized rocks. In such circumstances, it can be difficult to distinguish chicks from pale, similar-sized rocks if both are overexposed. Whereas a slightly underexposed image can always be brightened up, at least enough to pick out details, there is little that can be done to correct for overexposure, especially if the details are burnt out. Personnel assigned to do the surveys would benefit from doing some short local flights beforehand and then examining the results, so that they become familiar with the opportunities and limitations of aerial photographs as a population survey tool.

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Annex 1

Northern Royal Albatross plumage classes used to classify chicks on Rangitatahi and Motuhara, August 2018, based on photographs of the known-age female chick, *Amira*, reared at Taiaroa Head in 2018. Hatched on 22 January 2018, she fledged on 7 September 2018 when 229 days old (32.7 weeks old). The photographs were acquired at weekly intervals from www.doc.govt.nz/royalcam.

Small downy

Aged 17 weeks or less. No visible feathers at this stage. Looks like a ball of white fluff.

Large downy

17–20 weeks old. Wing feathers just beginning to emerge at 20 weeks.

Residual down

21–25 weeks old. Wing and back feathers visible but covered in down.

Near fully feathered

25–31 weeks old. Nearly fully feathered but with down still present on neck, belly and, occasionally, some on coverts.

Pre-fledging

>31 weeks old. No down visible; distinguished from adult by posture (often sitting on tarsi), dirty belly, and pale (ivory-coloured) bill.

Adult

'Clean' appearance; upright posture; pink bill