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Tini a Tangaroa

Population trends, at-sea distribution, and breeding population size of black petrels (*Procellaria parkinsoni*) – 2018/19 operational report

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During the 2017/18 and 2018/19 breeding seasons a total of 447 study burrows were monitored within the Mt Hobson/Hirakimata study area on Great Barrier Island/Aotea. In 2017/18, 278 (62.2%) were occupied by breeding pairs, 61 (13.6%) were occupied by non-breeding birds, and 108 (24.2%) were unoccupied. In 2018/19, 289 (64.7%) were occupied by breeding pairs, 72 (16.1%) were occupied by non-breeding birds and 86 (19.2%) were unoccupied.

The 50.8% of study grid burrows occupied by breeding pairs during the 2018/19 breeding season was the lowest occupancy rate ever recorded and was 9.2% lower than the 24-year average of 60%. The 54.1% of study grid burrows occupied by breeding pairs during the 2017/18 breeding season was 5.9% lower than the 24-year average. Fledging success in 2018/19 was 74% which is higher than the 24-year average for black petrels breeding within the Mt Hobson/Hirakimata study area on Great Barrier Island/Aotea. The 62.2% fledging success recorded in the 2017/18 season was the third-lowest recorded since 1995 and was 9.9% lower than the 24-year average of 72.1%.

Global Positioning Systems (GPS) and Global Location Sensing (GLS) devices were deployed on 46 adult black petrels during incubation, yielding 29 complete foraging trips. During chick rearing, these devices were deployed on 40 individuals, yielding 32 complete chick-provisioning tracks. The results highlight that adult black petrels are highly efficient foragers that forage during both the day and night. Black petrels continue to utilise previously identified foraging hotspots at the continental shelf break off eastern Northland and East Cape, and over the eastern Chatham Rise. However, new foraging hotspots in coastal waters off the west coast of Northland, along the Norfolk and Kermadec Ridges, Hikurangi Plateau, and in pelagic waters to the north and east of the Chatham Rise were also detected. The average duration of incubation foraging trips during the 2018/19 season was 10.7 days, with an average distance travelled of 4383 km. The average duration of chick-provisioning trips during the 2017/18 season was 8.6 days, with an average distance travelled of 3633 km. Females had longer foraging trips and foraged further offshore than males. The tracking data presented here will help to improve spatially-explicit models of bycatch risk in fisheries and be used to help determine mitigation measures to help reduce the incidence of bycatch of black petrels.

During the 2018/19 breeding season, distance sampling was used to estimate burrow density and the number of breeding black petrels within 108 ha of high-grade habitat near Mt Hobson/Hirakimata. A total of 80 line transects were surveyed, and 158 black petrel burrows were detected. Of these burrows, 51.6% were being used as breeding burrows during the 2018/19 breeding season. By fitting a burrow detection function to these data, the estimated average breeding burrow density was 14.13 burrows/ha within this 108-ha area, yielding a total estimated population size of 1532 breeding pairs, or 3064 breeding birds. Distance sampling proved to be a robust and cost-effective method for estimating black petrel burrow densities and population size in rugged and heavily-vegetated terrain, and the results from the high-grade habitat show that this method may be used to estimate black petrel burrow density for remaining areas of habitat occupied by breeding black petrels on both Great Barrier Island/Aotea and Te Hauturu-O-Toi/Little Barrier Island.

1. POPULATION TRENDS OF BLACK PETRELS ON GREAT BARRIER ISLAND/ AOTEA

1.1 Introduction

Black petrels (*Procellaria parkinsoni*) are a medium-sized endemic seabird that breeds only on Te Hauturu–o–Toi/Little Barrier Island and Great Barrier Island/Aotea in the Hauraki Gulf of New Zealand. Black petrels are known by the name of tākoketai by Ngāti Rehua Ngāti Wai ki Aotea, the tangata whenua and mana whenua of Great Barrier Island/Aotea. Black petrels are ranked as Nationally Vulnerable under the New Zealand Threat Classification System and Vulnerable on the IUCN Red List of Threatened Species (Robertson et al. 2017, BirdLife International 2020). They are recognised as the seabird species that is at greatest risk of being adversely impacted by high rates of bycatch in commercial fisheries within New Zealand's Exclusive Economic Zone (Richard et al. 2017). Of the 160 observed captures of black petrel recorded between 2002 and 2018, 57.5% of captures occurred in bottom longline fisheries, 24.4% in surface longline fisheries and 18.1% in trawl fisheries (https://psc.dragonfly.co.nz/2019v1; accessed 27/03/2020). Black petrels on Great Barrier Island/Aotea are also exposed to threats on land, principally depredation by cats (*Felis catus*), rats (*Rattus sp.*), and pigs (*Sus scrofa*) (Bell 2013).

To monitor the ongoing population-level impacts of commercial fisheries on black petrels, it is necessary to quantify population parameters such as annual burrow occupancy rates, annual adult reproductive success, as well as both adult and juvenile annual survival rates to obtain accurate assessments of population trends. To this end, a long-term research project aimed at quantifying these population parameters was initiated in 1995/96 (Bell & Sim 1998). During this first season, three 40 m x 40 m study grids were set up within the largest known breeding colony on Mt Hobson/Hirakimata on Great Barrier Island/Aotea, and all burrows within the grids were marked and monitored. Additional burrows located within 10 m of the public walking tracks were also monitored. In 1998/99, the number of study grids was increased to six, and then to nine in 1999/2000 (Bell & Sim 2000a, 2000b). Over the years, additional burrows situated near the public walking tracks have continued to be added, so that by the 2018/19 season a total of 447 study burrows were being monitored (Bell et al. 2017).

During the 2017/18 and 2018/19 seasons, 447 study burrows were monitored on Great Barrier Island/Aotea. The first section of this report provides a summary of the results of this monitoring work, with updates on the trends in several population parameters including both annual burrow occupancy and annual reproductive success.

1.2 Methods

1.2.1 Field methods

A network of 447 study burrows has been established within a 35-ha study area in the vicinity of Mt Hobson/Hirakimata on Great Barrier Island/Aotea (Figure 1.1). These burrows have been progressively established over the past 24 years and include 179 burrows located within nine 40 m x 40 m study grids, plus a further 271 arbitrarily-selected burrows situated within 10 m of public walking tracks. To facilitate accurate monitoring, many of these study burrows have had study hatches installed, providing easier access to one or more chambers within the burrow.

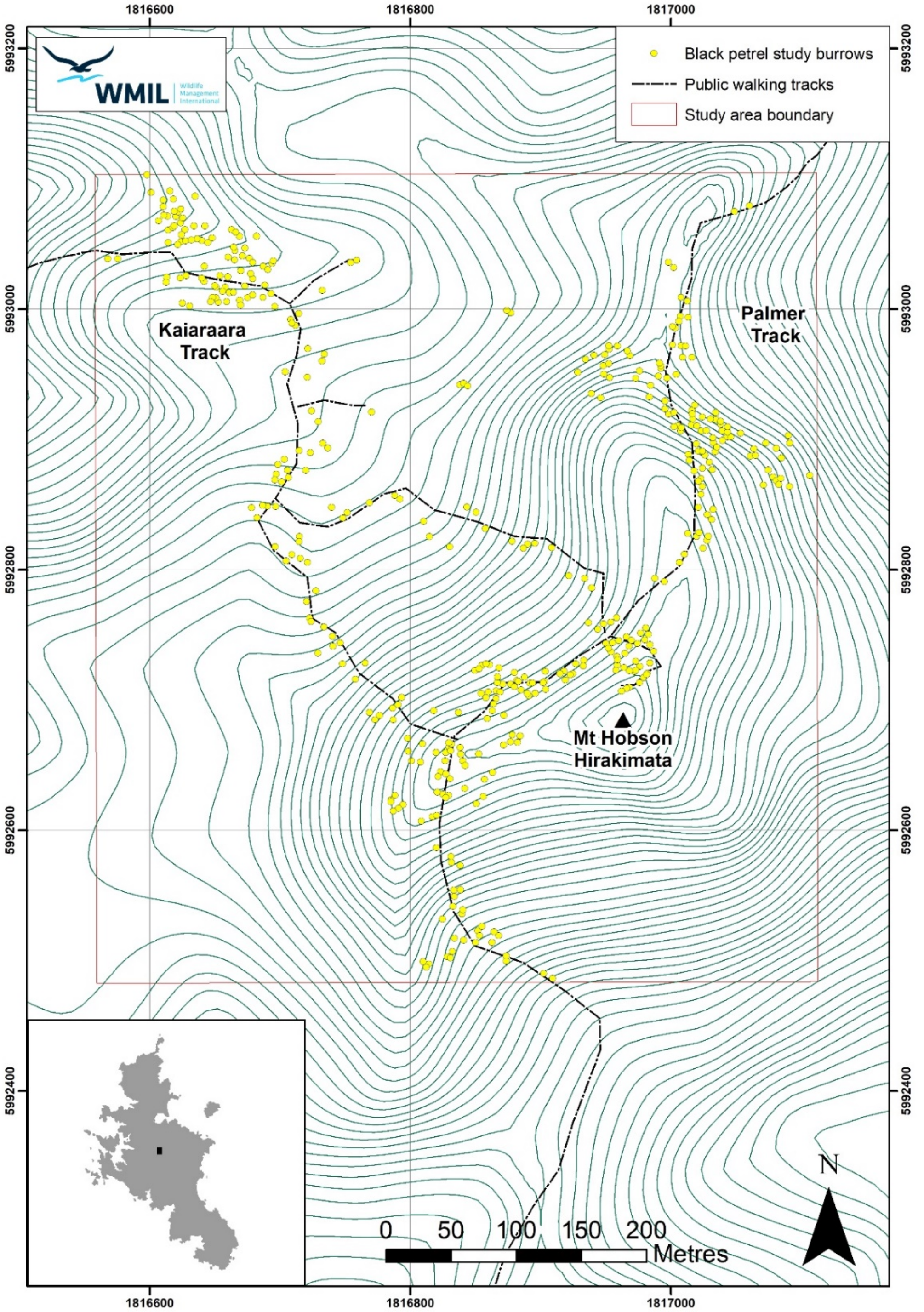

Figure 1.1: Map of the 447 black petrel study burrows that have been established in the vicinity of Mt Hobson/Hirakimata.

During the 2017/18 field season, study burrows were monitored during three visits to the Mt Hobson/Hirakimata study area, carried out between 12 January to 9 February 2018 (trip 1); 5 March to 4 April 2018 (trip 2); and 30 April to 18 May 2018 (trip 3). These visits roughly coincided with late incubation/hatching/early chick rearing (trip 1); mid chick rearing (trip 2); and late chick rearing/fledging (trip 3) phases of the black petrel breeding season.

For the 2018/19 field season, study burrows were monitored during two visits to the Mt Hobson/Hirakimata study area, carried out between 7 January to 13 February 2019 (trip 1) and 29 April to 8 May 2019 (trip 2). These visits roughly coincided with late incubation/hatching/early chick rearing (trip 1) and late chick rearing/fledging (trip 2) phases of the black petrel breeding season. To determine the breeding status and breeding outcome for each burrow, and to record the adult occupants of each burrow, each study burrow was checked at least twice during trip 1.

During each burrow check, any resident adults were removed from the burrow, and checked for bands. If banded, the band number of each bird was recorded; otherwise the bird was banded with an individually numbered size H stainless steel band. Before being returned to the burrow, a small mark was made on each bird's forehead using white correction fluid to provide a means of visually checking whether the same bird was still occupying the burrow during subsequent checks, without having to remove the bird to read its band. The presence of an egg or chick was also recorded. After each check, a palisade of twigs was erected over the burrow entrance to provide a quick means of checking for recent activity during subsequent checks of the same burrow. During the final trip of each season, fledgling chicks found in the study burrows were extracted and banded.

During each trip, the field team spent several nights walking the public track system within the 35-ha study area, capturing any black petrels found on the ground. These birds were checked for bands, and any band numbers were recorded. If unbanded, a band was applied to the bird's leg, before being subsequently released. Before release, a small mark was made on each bird's forehead using white correction fluid to provide a means of visually checking whether a bird had already been captured, if encountered again on the same or another subsequent night.

1.2.2 Data entry and analysis

All mark-recapture and breeding status data were entered into a Microsoft Access™ database at the completion of each trip. Data analysis and visualisation was performed using Microsoft Excel™.

1.3 Results

1.3.1 Burrow occupancy and breeding success

Of the 447 study burrows monitored during the 2017/18 breeding season, 278 (62.2%) were occupied by breeding birds, 61 (13.6%) were occupied by non-breeding birds, and 108 (24.2%) were unoccupied.

Of the 447 study burrows monitored in the 2018/19 breeding season, 289 (64.7%) were occupied by breeding birds, 72 (16.1%) were occupied by non-breeding birds, and 86 (19.2%) were unoccupied.

Burrow occupancy rates in the nine study grids likely provide the most consistent and representative measure of burrow occupancy across the study area, because they are unaffected by the occasional preferential addition of active breeding burrows to the study burrow network (outside the study grids) that has occurred in previous years. For this reason, trends in burrow occupancy rates within the study grids provide the best measure of whether or not black petrel burrow occupancy is increasing or decreasing within the study area. In the 2017/18 breeding season, in the 179 study burrows within the study grids, the mean percentage of study grid burrows occupied by breeding black petrels was 54.1%, 5.9% less than the 24-year average study grid burrow occupancy rate of 60% (Figure 1.2). In the 2018/19 breeding season, this occupancy rate was even lower at 50.8%, 9.2% less than the 24-year average study grid burrow occupancy rate of 60% (Figure 1.2).

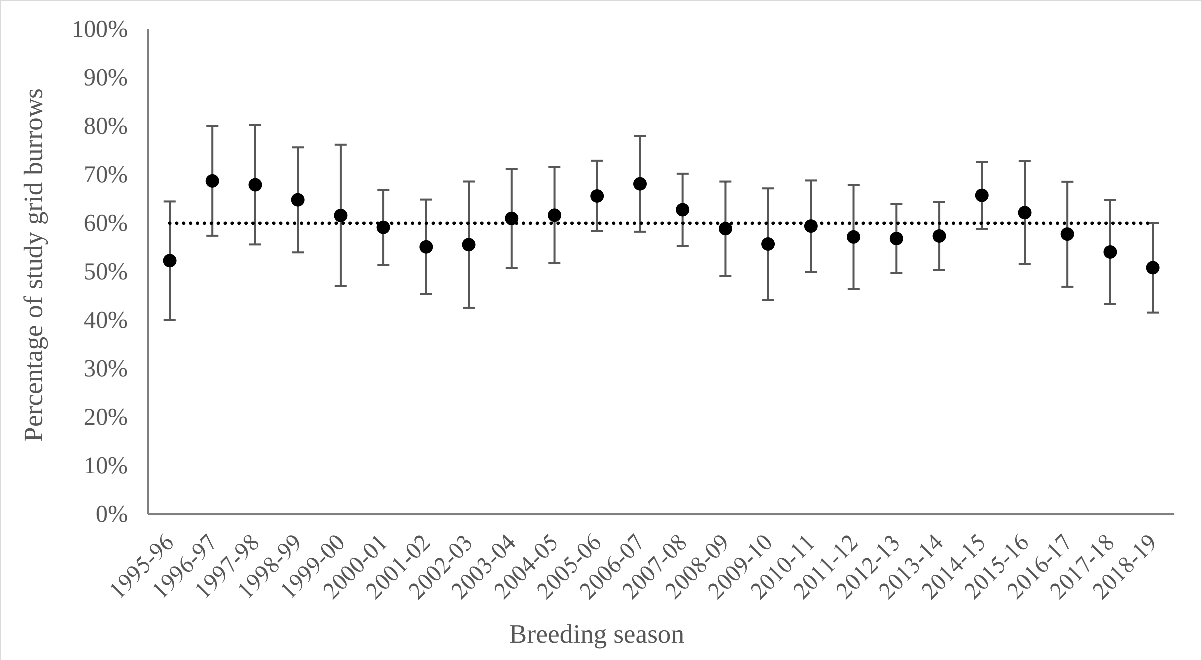

Figure 1.2: Mean percentage of study grid burrows occupied by breeding black petrels at Mt Hobson/Hirakimata on Great Barrier Island/Aotea between 1995 and 2019 (error bars represent 95% confidence intervals and dotted line represents the 24-year mean of 60%).

Of the 278 study burrows that were occupied by breeding birds during the 2017/18 breeding season, a total of 176 chicks were produced, representing a 63.3% fledging success rate. Among the 278 breeding burrows, there were 102 breeding failures representing a failure rate of 36.7%. During the 2018/19 season, 214 chicks were produced from the 289 breeding burrows, representing a 74% fledging success rate. Among the 289 breeding burrows, there were 75 breeding failures representing a failure rate of 26%. Causes of breeding failure in both seasons included eggs or chicks that disappeared from burrow, eggs being abandoned or crushed, and chicks dying.

The breeding success rate observed during the 2017/18 season (63.3%) was 8.8% less than the 24-year average of 72.1%, whereas breeding success observed during the 2018/19 season (74%) was higher than the 24-year average (Figure 1.3).

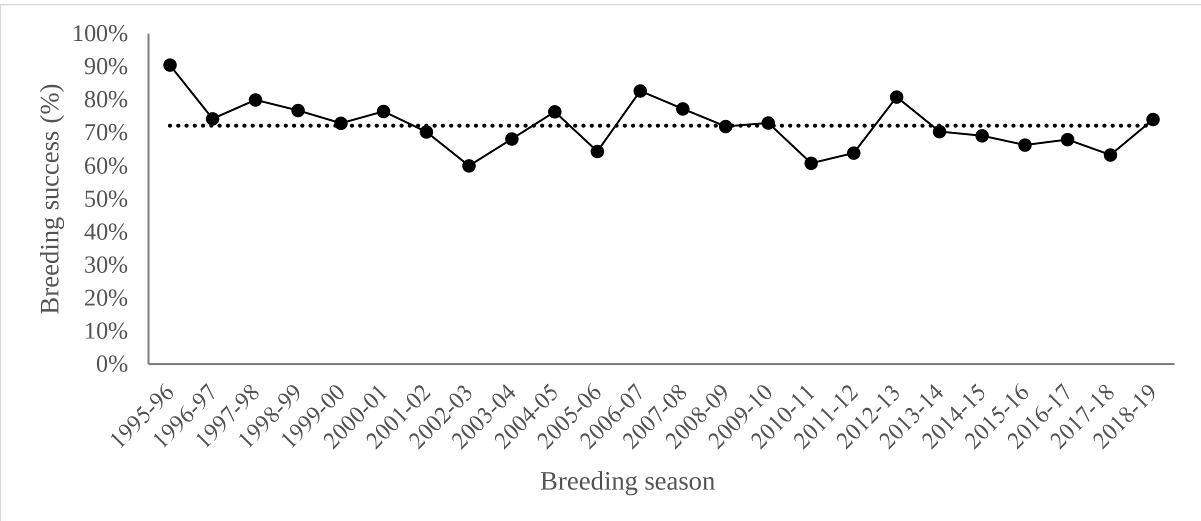

Figure 1.3: Mean breeding success (percentage of breeding burrows that fledge a chick) among black petrel study burrows at Mt Hobson/Hirakimata on Great Barrier Island/Aotea between 1995 and 2019 (the dotted line represents the 24-year mean of 72.1%).

1.3.2 Adult and juvenile survival

A total of 615 adults and 181 fledgling chicks were captured during the 2017/18 field season. A total of 83 adults were banded during the 2017/18 field season, of which 73 were captured in the study burrows. Of the 181 fledgling chicks banded during the 2017/18 field season, 157 were banded in the study burrows. A total of 680 adults and 216 fledgling chicks were captured during the 2018/19 field season. A total of 122 adults were banded during the 2018/19 field season, of which 79 were captured in the study burrows. Of the 216 fledgling chicks banded during the 2018/19 field season, 209 were banded in the study burrows.

Of the 556 parents occupying the 278 breeding burrows during the 2017/18 breeding season, a total of 532 (95.7%) were captured and identified. Similarly, during the 2018/19 season 552 of the 578 (95.5%) parents occupying the 289 breeding burrows were captured and identified. The majority of individuals that were not identified were adults whose breeding attempts had failed either prior to, or during, the first field trip of the season and were therefore unlikely to be spending much time in their burrows during the field trips.

During the 2017/18 breeding season, a total of 531 recaptures were recorded, including 99 returned chicks (96 of which have been banded by Wildlife Management International Ltd. (WMIL) since 1995). Seventeen were chicks that had been caught for the first time since being banded as fledglings (all were banded by WMIL since 1995).

During the 2018/19 breeding season, a total of 562 recaptures were recorded, including 102 returned chicks (99 of which have been banded by WMIL since 1995). Fifteen were chicks that had been caught for the first time since being banded as fledglings (all banded by WMIL since 1995). A total of 305 returned chicks have now been recaptured at the Mt Hobson/Hirakimata colony.

1.4 Discussion

The 2017/18 breeding season was one of the least productive breeding seasons recorded on Great Barrier Island/Aotea since 1995; the 63.3% fledging success was the third lowest recorded (60% fledging success in 2002/03 and 60.8% fledging success in 2010/11).

Based on observations made by the field team, it appears that the 2017/18 low breeding success may have been caused by climate-related factors. Firstly, an unusually high number of breeding attempts failed during the incubation and early chick-rearing stages due to burrows becoming flooded during heavy rainfall events, including three ex-tropical cyclones that passed over Great Barrier Island/Aotea in February and March 2018 (NIWA 2018a, 2018b). Secondly, a higher than average number of chicks starved to death in their burrows during mid-to-late chick rearing, suggesting that some parent birds were unable to adequately provision their chicks. Unusually high air pressures at sea level in the Tasman Sea and SW Pacific prevented the usual mixing of deeper, cooler sea water with surface waters, resulting in unusually high sea surface temperatures in the SW Pacific between December 2017 and February 2018. There were three distinct peaks when sea surface temperatures were between 2 °C and 4 °C above average: mid-December 2017, late January 2018, and mid-late February 2018 and there were even some areas where sea surface temperatures were 6–7 °C above average (NIWA 2018a, 2018b). These anomalous sea surface temperatures may have altered the distribution and accessibility of the black petrels' prey, reducing the foraging efficiency of some birds. Comparison of the GPS tracking of breeding adults undertaking chick-provisioning trips during February-March 2006 with those during March-April 2018 found a significant difference between the mean trip length from the colony (two-sample t-test, $t_{48} = 2.01$, $p < 0.01$) with adults travelling an average of 3296 km in 2018 ($n = 41$, range 160–9437 km, see Appendix 6.2) and 807 km in 2006 ($n = 9$, range: 248–2396 km, Freeman et al. 2010).

The 2018/19 breeding season saw fledging success return to the mean of 74% which is higher than the 24-year average for black petrels breeding on Great Barrier Island/Aotea. However, some climate models are forecasting a prolonged period of unusually high global sea surface temperatures in forthcoming years (Sévellec & Drijfhout 2018). Should this result in higher than average summer and autumn sea surface temperatures in the Tasman Sea and SW Pacific, this could influence black petrel productivity. The effects of warming sea surface temperatures associated with climate change is an unquantified issue for black petrels and warrants more investigation. It will be crucial to continue to collect survival and productivity data from the Great Barrier Island/Aotea study site for the foreseeable future, so that the duration and magnitude of any climate impacts on the black petrel population can be measured and appropriate conservation management responses put in place, if needed.

2. GPS AND GLS TRACKING OF ADULT BLACK PETRELS

2.1 Introduction

Black petrels are recognised as the seabird species that is at the greatest risk of being adversely impacted by unsustainably high rates of bycatch in commercial fisheries both within, and beyond, New Zealand’s Exclusive Economic Zone (Richard & Abraham 2013). To adequately manage this threat, a spatially explicit model of bycatch risk is required, incorporating measures of fishing effort, fishing method, and black petrel at-sea distribution and habitat use (Richard et al. 2017). Models of the at-sea distribution of black petrels have been generated using a combination of remote tracking data and at-sea counts carried out by both fisheries observers and recreational birdwatchers (Abraham et al. 2015). However, these data don’t yet adequately describe the at-sea distribution of black petrels at all life stages, nor do they adequately describe inter-annual variation in at-sea distribution in response to changes in sea surface temperatures and other environmental variables (Richard et al. 2017).

Tracking work using both Global Location Sensor (GLS) devices and Global Positioning System (GPS) loggers has been carried out on adult black petrels during the incubation and chick-rearing periods in recent years, and this work has demonstrated that there is a great deal of individual and inter-annual variability in at-sea habitat use and foraging behaviour. Many birds concentrated their foraging efforts in the outer Hauraki Gulf and coastal waters off Northland during incubation and chick rearing, but a number of birds also ranged widely in the Tasman Sea to the west, and to waters off East Cape in the east (Bell et al. 2011, 2013).

In 2006, GPS devices were successfully deployed for the first time on nine adult black petrels that were rearing chicks on Great Barrier Island/Aotea. This work showed that birds travelled up to 1128 km from the colony during chick-provisioning trips and travelled between 248 and 2396 km per trip, spending a significant amount of time foraging in the vicinity of the continental shelf off the northeast coast of the northern North Island (Freeman et al. 2010).

A number of GLS devices have also been deployed on adult birds migrating to wintering grounds in the eastern Pacific, with the tracking data showing that these birds spent a great deal of time within a relatively small area of the eastern Pacific, off the coasts of Ecuador and the Galapagos Islands (Bell et al. 2011).

In this section of the report, the results of tracking black petrels during three different stages of their annual life cycle are presented. In March-April 2018, the focus was on tracking a sample of breeding adults undertaking chick-provisioning trips. In January-February 2019, breeding adults were tracked during the incubation stage when they were undertaking foraging trips in between bouts of incubation. Thirdly, GLS devices were deployed on a sample of breeding adults undertaking their annual migration between New Zealand the eastern Pacific between the 2017/18 and 2018/19 breeding seasons.

2.2 Methods

2.2.1 Field methods

Breeding adults were caught in their burrows between 5 March and 3 April 2018 (chick rearing) and 7 January and 11 February 2019 (incubation). Birds were intercepted in their burrows by fitting a one-way flap, or "burrowgate", to the burrow entrance. A total of 28 (chick rearing) and 40 (incubation) of the 4470 study burrows currently being monitored on Mt Hobson/Hirakimata were targeted for this tracking work (see Appendices 6.1 and 6.2).

During chick rearing, adult birds would typically make brief visits to their breeding burrows at night to feed their chick, before departing again shortly afterwards. When a burrowgate was fitted to a burrow, any visiting adults would be detained in their burrows and would be processed the following day. The burrowgate would then be removed to allow the bird to depart the following night. All burrows which had burrowgates deployed were checked daily, both to intercept and process incoming birds to allow them to depart, and to intercept the bird again during its next visit to retrieve its tracking devices. During incubation, the deployment of a burrowgate on a burrow allowed the partner of an incubating bird to enter the burrow at changeover but would prevent any bird from leaving the burrow. These burrows were similarly checked daily and when both partners were found in the same burrow, the departing bird (which had been pre-identified from its unique band number) was fitted with the devices. On three occasions, the identity of departing bird could not be determined, so devices were fitted to both birds, with the remaining bird having its devices removed the following day.

All birds intercepted were fitted with a GiPSy 5™ GPS device (manufactured by TechnoSmart™ Europe) and an Intigeo-C330™ GLS device (manufactured by Migrate Technology™). The GPS devices were programmed to record a position every 5 minutes. The GLS devices were programmed to record saltwater immersion every 30 seconds and then these data were "binned" every five minutes to give a count of between 0 and 10 corresponding to the number of 30-second intervals that were "wet" (defined as a conductivity score of > 63, the "wet count"). For example, if the bird stayed on the water for the entire five minutes, the wet count was 10. If the logger was wet for only 30 seconds the recorded wet count was one.

All GiPSy 5™ GPS devices were enclosed and sealed in heat-shrunk plastic sleeving to protect the devices from saltwater damage. The GPS devices were attached to the dorsal mantle feathers of each bird using 4–6 lengths of marine Tesa™ tape and super glue. GLS devices were attached to each bird's metal leg band using two small, plastic cable ties. The combined weight of all devices was between 14 and 18 g (including heat-shrunk plastic, tape, and cable ties) and did not exceed 3% of the bird's body weight (Phillips et al. 2003).

Each bird was weighed before being fitted with GPS and GLS devices and weighed again when the devices were retrieved to obtain information on body condition and to assess the impact of carrying the devices. Three flank or breast feathers were also collected from each bird, to enable each bird's sex to be determined from DNA testing. Attachment of both the GPS and GLS devices took less than 13 minutes on average (range: 9–21 minutes).

In addition to the GPS and GLS tracking carried out during the incubation and chick rearing stages, a total of 55 GLS devices were deployed on breeding adults in March-April 2018 and were retrieved again in January-February 2019 once these birds had completed their annual migration to the eastern Pacific and back. These GLS devices were programmed to record ambient light levels every five minutes (used for geolocation) as well as temperature, conductivity, and wet/dry data.

On 12-13 March 2018, ex-tropical cyclone Hola passed over Great Barrier Island/Aotea, dropping over 100 mm of rain on the island within a 24-hr period (NIWA 2018b). Because it is not safe to handle birds in such wet conditions, the burrowgates were removed from the 28 study burrows on the nights of both 12 and 13 March 2018 to allow the adult birds to freely come and go from their burrows. The burrowgates were subsequently re-installed on 14 March 2018, however a number of device-carrying birds had returned to feed their chicks during this two-day period and had departed again, resulting in the subsequent retrieval of several GPS devices that contained tracks for two consecutive foraging trips.

2.2.2 Data entry and analysis

The GPS device data were first cleaned to remove any clear outlying points that resulted from a poor satellite fix or a device malfunction. Any data recorded by the devices both pre-deployment and post-removal were also removed. Wet count data collected from the GLS devices were classified into one of three behaviour types, using a classification method previously used to determine the at-sea behaviour of flesh-footed shearwaters (*Puffinus carneipes*) from tracking data (Kirk et al. 2017, Crowe 2018). Flight was classified as positions with a wet count of zero or one (mostly dry), resting positions had a wet count of nine or ten (mostly wet), and foraging behaviour was classified as positions with an intermediate wet count of between two and eight inclusive. Each GPS location was then paired with the corresponding behaviour type in Microsoft Excel by matching the time/date stamps recorded by each device. This method was used for the analysis of tracking data collected during incubation, but not for chick rearing. During chick rearing, saltwater immersion data were collected over a different timeframe due to having 'geolocation mode' enabled to record black petrel migration during the non-breeding season. Pairing the saltwater immersion data with the corresponding GPS data collected during chick rearing was therefore not possible, and so GPS data for chick rearing is presented autonomously with no behavioural analysis.

The geolocation files were processed in R 3.6.0 (R Core Team, 2019), initially using the FLightR (Rakhimberdiev et al. 2017) and GeoLight (Lisovski & Hahn 2013) packages. FLightR was originally chosen because the light curve-based algorithm produces less bias in location than the threshold method does (Rakhimberdiev et al. 2016). However, after discussion with co-authors and external clients, the probGLS package (Merkel et al. 2016) was chosen for the final estimation of location data. Although the method uses light thresholds for the estimation of latitude and longitude, probGLS accounts for introduced bias by using a probabilistic sampling method and by adding in sea surface temperature data (SST) to improve location accuracy (Merkel et al. 2016).

Beginning with the drift-adjusted '.lux' files, twilight times were calculated using the twilightCalc function from the GeoLight package, with the light threshold level set to 10. The 2018 and 2019 high resolution sea surface temperature data, ice extent, and land mask raster layers were compared with the logger recorded temperature data in the '.deg' file.

A boundary box was defined to encompass the expected migration area for black petrels (latitude -70° S to latitude 25° N, longitude 145° E to longitude -70° W). A mask was used to prevent location estimates on land. Location estimates were calculated using the prob_algorithm in the probGLS package (Merkel 2019). This function takes a long list of user defined parameters. Key inputs were set as follows:

- The tagging location was the breeding colony on Mt Hobson/Hirakimata, on Great Barrier Island/Aotea (175.413° E, 36.181° S).
- The tagging and retrieval dates, which were recorded for all individuals.
- The wet/dry resolution was set to 30 (the resolution of the Intigeo-C330 GLS model).
- Days around spring and autumn equinoxes were set to 30 either side, to account for error in latitudinal estimates.
- Wet speed included mean speed of 1m/s, SD of 1.3, maximum speed 5m/s.
- Dry speed included mean speed of 10m/s, SD of 5, maximum speed of 50m/s. The mean movement parameters were derived from a published distribution of flight speeds recorded by GPS-tracked black petrels (Freeman et al. 2010) breeding at the same colony.

From each logger the 'most probable' estimates of latitude and longitude were extracted from paired twilight events. These were paired with an estimate of uncertainty around each location. The uncertainty was calculated by taking the 95% confidence interval for 'all possible' locations derived by the model at each time stamp. For each migration track, the date, time, most probable latitude and longitude, and respective upper and lower confidence intervals were exported, along with a measure of uncertainty for each location (a product of the difference between upper and lower credible intervals for both coordinates). Positional data were further filtered to remove coordinates where the latitudinal uncertainty was greater than 20°. This threshold was determined by plotting latitudinal uncertainty against date, which showed that latitudes recorded during the equinoxes often had an uncertainty greater than 20° (when day length is uniform across the globe, latitudinal estimates may have a larger error). The data were also filtered to remove a very small number of erroneous locations recorded at latitudes greater than 14° N. These single erroneous location estimates occurred in 14 out of 46 migration tracks.

Spatial analyses were carried out using QGIS version 2.18. To generate the kernel density maps from the GPS data, a smoothing parameter (radius) of 100 km was used and applied to a 2 km x 2 km grid over the entire extent of the tracking data.

2.3 Results

2.3.1 Incubation 2019

A total of 46 adult black petrels (30 females, 16 males) from 40 different burrows were GPS tracked in January and February 2019. Nine individuals had their devices removed before they departed Great Barrier Island/Aotea because they reached the 3% device-to-body weight threshold, or they were the partner of a departing bird (as described in the methods section above). Two individuals with devices attached didn't return during to Great Barrier Island/Aotea in January-February 2019, and these devices were not retrieved; one individual has since been recaptured at the colony (30 December 2019) but the GPS device had been lost at sea during the moult period. This means that a total of 35 of the 37 GPS devices deployed on departing black petrels were subsequently retrieved. The remaining two devices will have been shed by the birds during the subsequent moult.

Of the 35 devices retrieved, 26 had successfully recorded tracks, and these tracks yielded a total of 29 foraging trips completed between 8 January and 11 February 2019. Of these, all but one had corresponding saltwater immersion data from the GLS devices. There were some complications with these GPS devices switching off before some of the birds had departed Great Barrier Island/Aotea. This is most likely due to these devices failing to obtain a GPS fix while the bird remained in the burrow. A summary of all deployments is presented in Appendix 6.1.

The devices did not appear to affect the foraging behaviour or body condition, with the mean weight gain of tracked birds being 11.3 g (range: -120 g to +160 g) or 1.7% (range: -17.1% to +24.2%) of their pre-attachment body weight while carrying the devices. In comparison, control birds (n = 33) had a mean weight gain of -40.3 g (range: -140 g to +110 g) or -4.9% (range: -16.3% to +16.4%) of their original body weight. There was a significant difference between the mean weight gain between tracked birds and control birds (two-sample t-test, $t_{65} = 3.62$, $p < 0.001$) with the control birds losing more weight. However, black petrel weights change greatly throughout the breeding season and these weight differences between tracked and non-tracked birds may relate to time of capture (i.e., stage of breeding: after incubating or guarding a chick for a number of days in the burrow or just after returning to the colony with a full belly) rather than body condition itself.

Chicks from burrows with either one or both parents tracked had a 75% (n = 40) chance of surviving to fledging whereas chicks from burrows with no tracking manipulation (control) had a 74% (n = 250) chance of surviving to fledging. No significant difference was found in fledging success rates between tracked and non-tracked burrows (Pearson Chi-Square, $\chi_1 = 0.167$, $p = 0.683$); showing there was no effect of tracking on subsequent breeding success.

Of the 29 foraging trips, 26 were complete tracks and three were only partial tracks. The three partial tracks (birds 28390, 33540, 42947; see Appendix 6.3) were still relatively long tracks, so it was likely that the batteries had run down before the birds returned to Great Barrier Island/Aotea.

The classification method used here to determine behaviour type is very simple, however visual inspection of Figure 2.1 demonstrates that using these thresholds of saltwater immersion can effectively distinguish between flying, resting (or rafting), and foraging. When each track is broken down in this way, most birds appear to depart Great Barrier Island/Aotea and undertake a direct and rapid flight to a specific (perhaps known) location where they then spend several days flying around at a slower pace foraging and spending time resting or rafting on the water surface. They may visit several other locations to forage and rest before undertaking a similarly rapid and direct flight back to Great Barrier Island/Aotea.

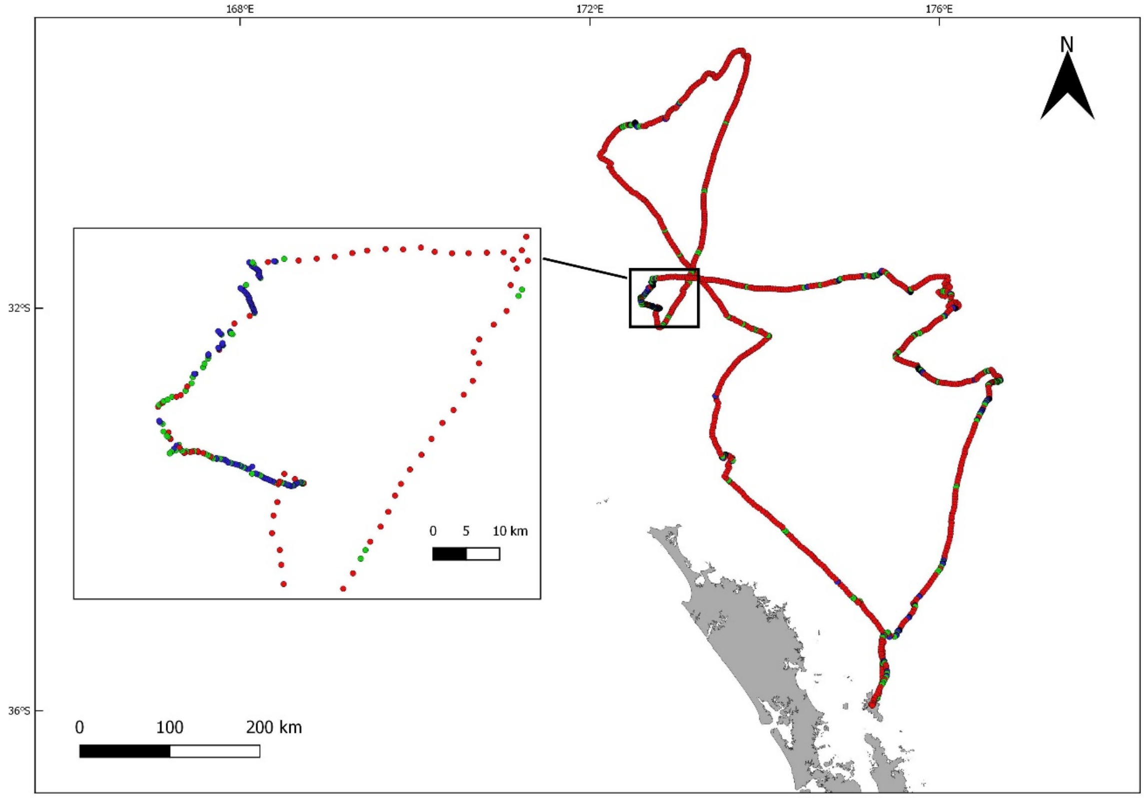

Figure 2.1: One example of a black petrel foraging trip from Great Barrier Island/Aotea with each GPS point classified as one of the three behaviour types: flight (red); rest (blue); or forage (green). Note that where there are clusters of points, there is some overlap of different behaviour types.

Foraging trips during incubation varied greatly in all respects. Trips were 10.7 days on average (± 5.7 days, n = 29, range 2–26 days; Figure 2.2, Appendix 6.1). For birds with complete tracks, the average trip distance was 4383 km (± 2527 km, n = 26, range 522–10275 km); an average of 438 km travelled per bird per day (± 127 km, n = 26, range 237–790 km). The mean maximum range from Great Barrier Island/Aotea was 1029 km (± 718 km, n = 29, range 99–2872 km; Figure 2.3).

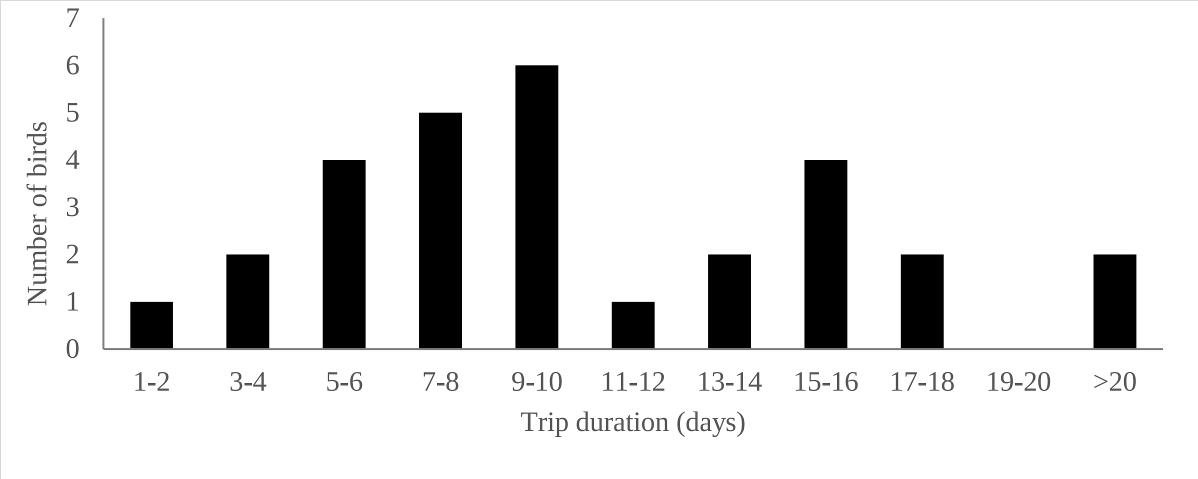

Figure 2.2: Number of days of each foraging trip for black petrels tracked during incubation from Great Barrier Island/Aotea in 2019.

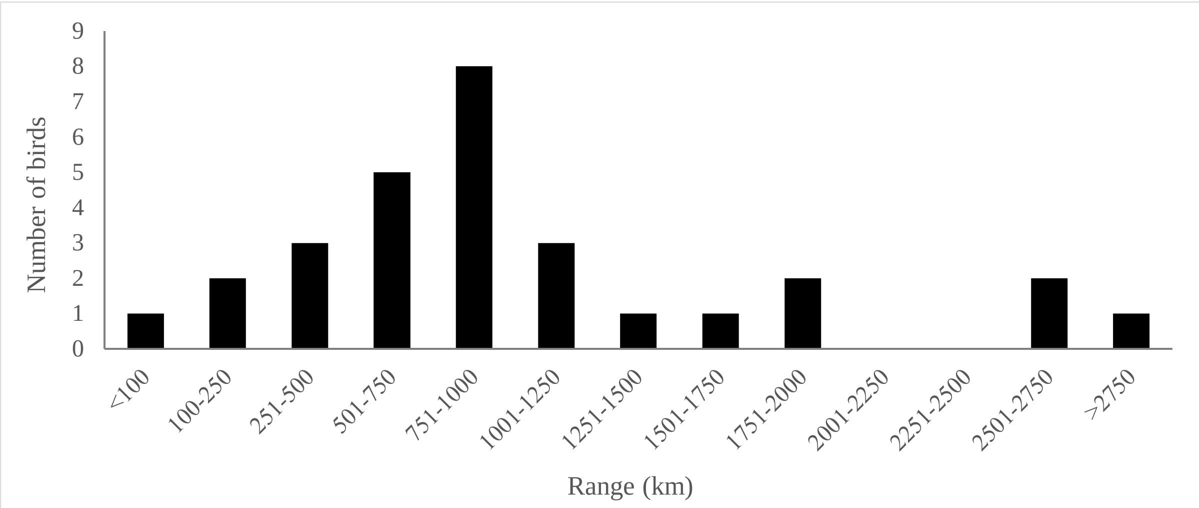

Figure 2.3: Maximum range for each foraging trip by black petrels tracked during incubation from Great Barrier Island/Aotea in 2019.

Birds foraged to both the west and east of northern New Zealand (Figures 2.4 and 2.5). By pairing saltwater immersion data with relevant GPS points and then mapping the resulting distribution of foraging locations using kernel density analysis, twelve foraging “hotspots” were identified for black petrels during incubation stage (Table 2.1, Figure 2.4). Six of these foraging “hotspots” fall inside the New Zealand EEZ and the other six fall outside the New Zealand EEZ (Table 2.1, Figure 2.4). Of the twelve hotspots identified, three were identical to “hotspots” identified during chick rearing in 2018 and an additional two were very similar (McArthur et al. 2018).

Table 2.1: Details of the twelve black petrel incubation foraging “hotspots”, identified by pairing saltwater immersion data with GPS data and then plotted using kernel density analysis.

Location / Bathymetric feature	Label on Figure 2.4	Longitude	Latitude	Same foraging location identified during chick rearing? (Reference to location in Figure 2.10)
Within New Zealand EEZ				
Great Barrier Island/Aotea stretching southeast, east, and northeast	1	176.194	-35.685	Yes (1)
Northeast of Three Kings Islands, along Three Kings Ridge	2	172.249	-33.801	Yes (2)
Bay of Plenty, 50 km offshore	3	177.067	-37.367	Similar (1)
15–80 km off the coast of East Cape	4	179.045	-37.843	Similar (3)
Hikurangi Plateau	5	-178.400	-38.989	No
On edge of Kermadec Ridge and Kermadec Trench	6	-179.661	-36.649	No
Outside New Zealand EEZ				
200km Southwest of Lord Howe Island on Dampier Ridge	7	157.300	-32.772	No
Lord Howe Rise	8	165.566	-35.844	No
New Caledonia Trough	9	166.323	-29.464	No
West Norfolk Ridge	10	167.344	-31.326	Yes (9)
Hikurangi Plateau	11	-175.332	-38.560	No
Hikurangi Plateau	12	-172.835	-38.015	No

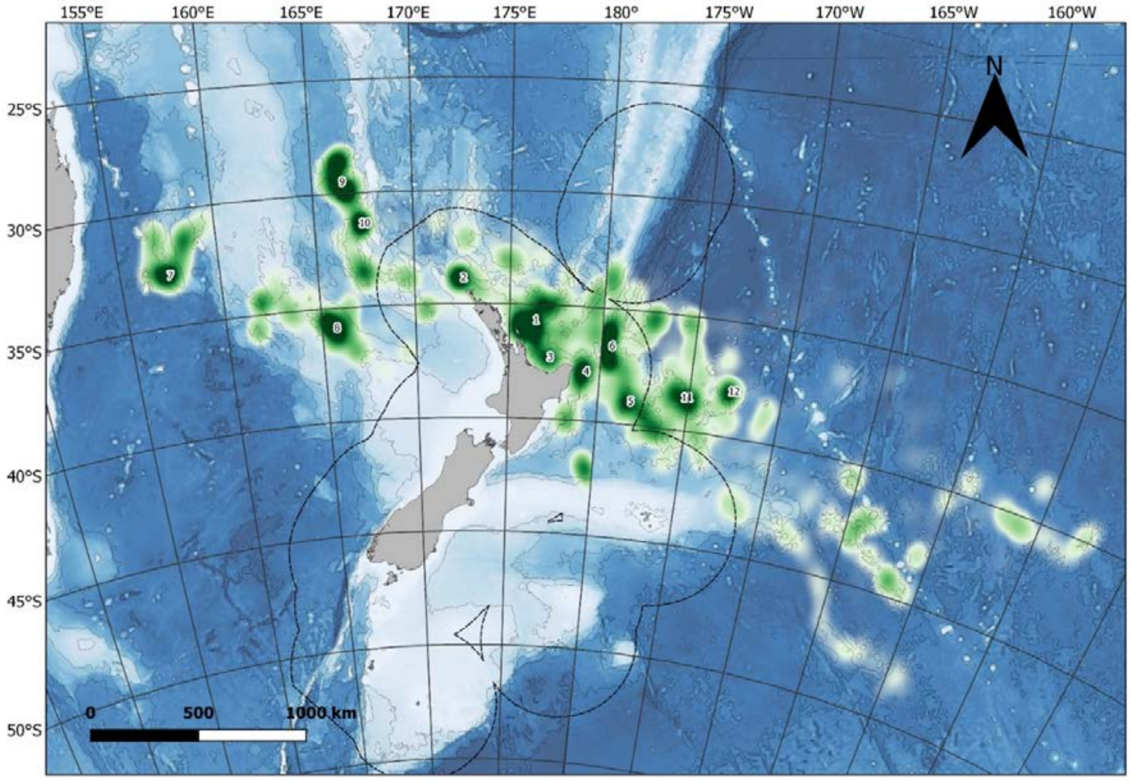

Figure 2.4: Kernel density map of all black petrel foraging trips during incubation. Numbered foraging “hotspots” are given in Table 2.1. Darker areas represent greater concentrations of foraging activity. The black dashed line represents the EEZ boundary.

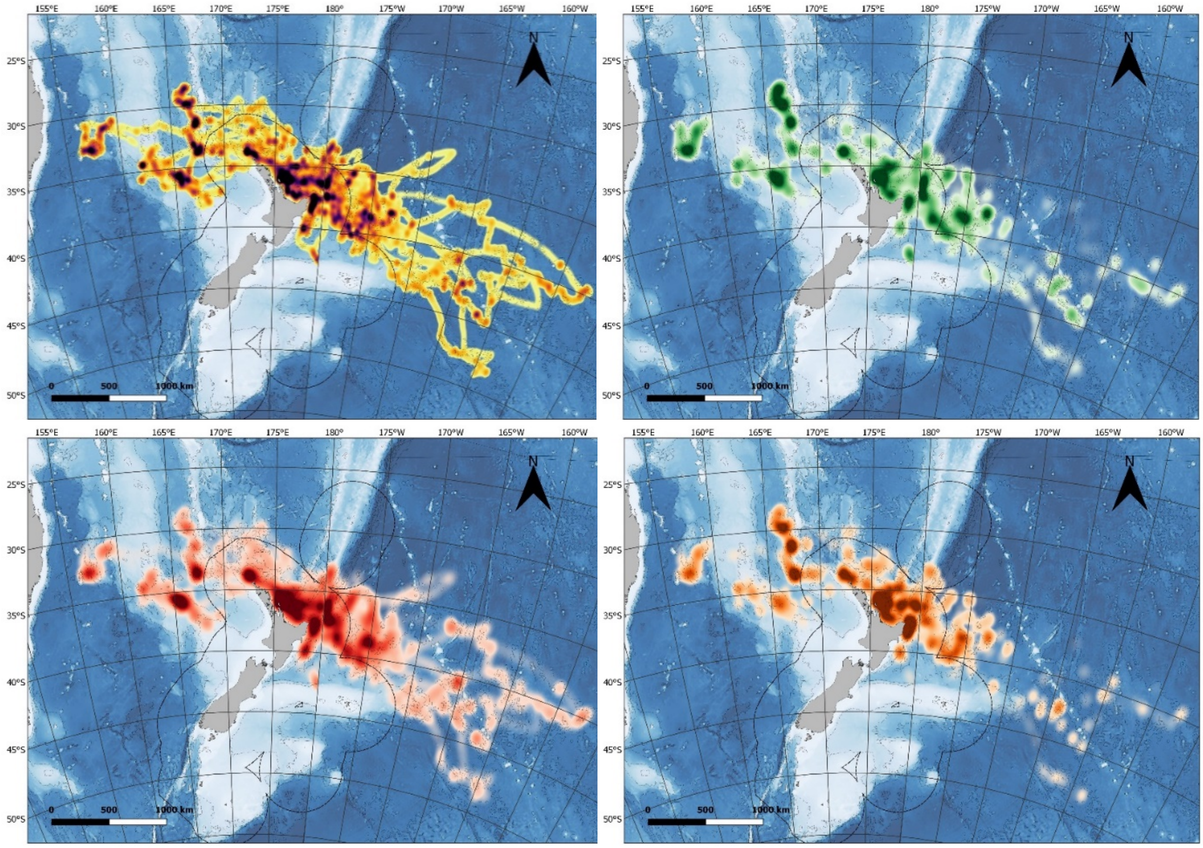

Figure 2.5: Kernel density maps of black petrel at-sea distribution and behaviour during incubation. Clockwise from top left: All behaviours combined (yellow), foraging (green), rest/rafting (orange), and flight (red). Darker areas represent greater concentrations for each relative behaviour type. The black dashed line represents the EEZ outer boundary.

Overall, these tracked black petrels spent the majority of their time (56%) during these foraging trips in flight, but there was a large amount of variation between individual trips (± 13% SD, *n* = 26, range 23–78%). These black petrels also spent 29% of their time resting or rafting on the sea surface, but again this also varied greatly between individual trips (± 13% SD, *n* = 26, range 12–66%). The remaining 15% of the time was spent foraging and there was relatively low variation between individuals (± 3% SD, *n* = 26, range 10–21%). There was no significant relationship between individual foraging effort (time) and change in body weight; $R^2 = 0.05$, $F_{1,20} = 1.08$, $p = 0.31$ (Figure 2.6, Appendix 6.1).

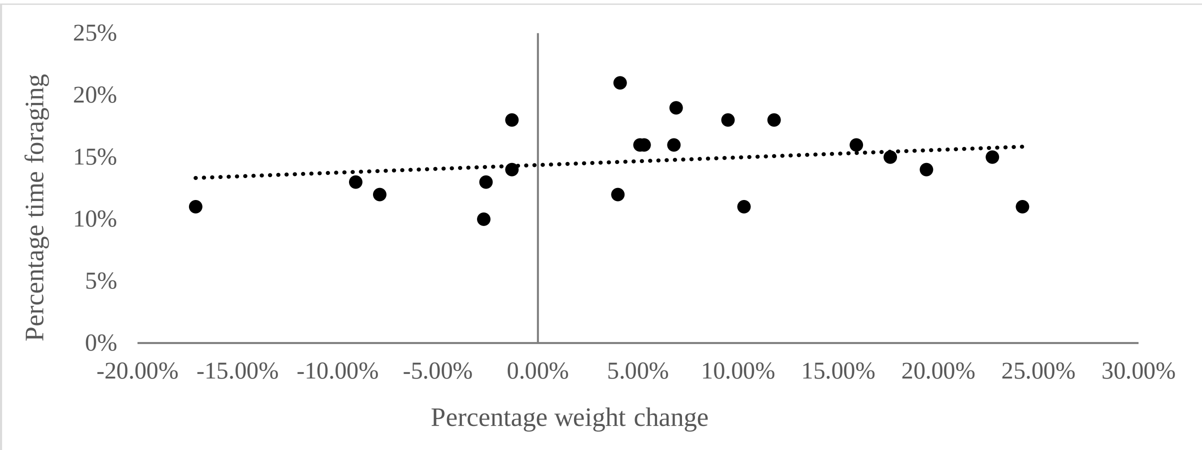

Figure 2.6: Relationship between individual foraging effort and change in body weight for black petrels from Great Barrier Island/Aotea in 2019.

When the combined total proportion of time spent engaging in each behaviour type was plotted against time of day, these black petrels exhibited some interesting circadiel patterns in behaviours (Figure 2.7). Black petrels spend proportionately more of their night-time hours (20:00–06:00) engaging in flying behaviour, while the inverse relationship is observed for resting/rafting with proportionately more time spent engaging in this behaviour during the day (07:00–19:00) (Figure 2.7). Foraging behaviour tends to peak between 06:00 and19:00 indicating that black petrels tend to spend more of their daytime hours foraging than during the night (Figure 2.7).

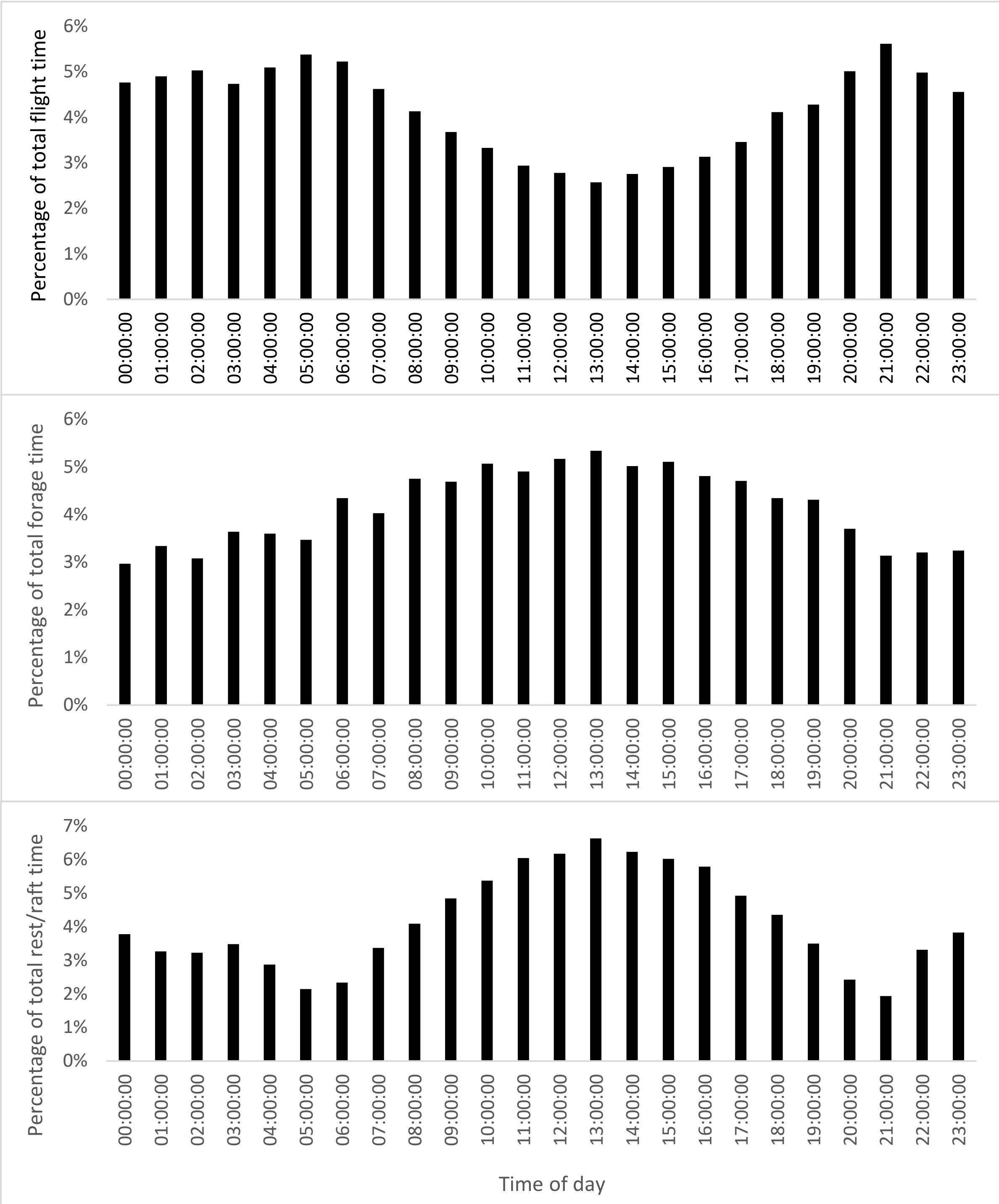

Figure 2.7: Bar graphs showing the distribution of each black petrel behaviour type throughout the day for all GPS points combined. Behaviour type from top to bottom: flight, forage, and rest/raft.

2.3.2 Chick rearing 2018

A total of 40 adult black petrels (22 males, 18 females) were GPS tracked in March and April 2018. These 40 birds included both the male and female birds from 12 breeding pairs, and either the male or female bird from a further 16 breeding pairs. A summary of the deployments is given in Appendix 6.2.

The devices did not appear to affect the foraging behaviour or body condition, with the mean weight gain of tracked birds being 52.3 g (range: -75 g to +220 g) or 8.1% (range: -10.1% to +32.8%) of their pre-attachment body weight while carrying the devices. In comparison, control birds (n = 66) had a mean weight gain of 17.0 g (range: -160 g to +140 g) or 1.6% (range: -25.0% to +16.3%) of their original body weight. There was a significant difference between the mean weight gain between tracked birds and control birds (two-sample t-test, $t_{120} = 3.09$, $p < 0.002$) with the control birds gaining less weight between captures. However, as stated earlier, these weight differences between tracked and non-tracked birds may relate to time of capture rather than body condition itself.

Chicks from burrows with either one or both parents tracked (n = 28) had an 82.1% chance of surviving to fledging whereas chicks from burrows with neither parent tracked (control burrows) (n = 251) had a 61.4% chance of surviving to fledging. No significant difference was found between tracked and non-tracked burrows (Pearson Chi-Square, $\chi^2 = 2.975$, $p = 0.085$) showing there was no effect of tracking on breeding success.

Four of the 41 tracks retrieved were discarded from our analyses below, because they were believed to represent a non-natural behaviour in response to the burrowgates. All discarded tracks were short (< 470 km) one day trips following a foraging trip of longer duration and distance. The authors suspect these trips were a result of birds returning to their burrow and being deterred from entering their burrow due to the presence of the burrowgate. They then returned to sea for an additional day before returning the following night and entering the burrow. Because there was an apparent manipulation of behaviour, these four trips were not included in any of the analyses or results presented here. Of the 37 remaining tracks, 32 were complete tracks and five were partial tracks (Appendices 6.2 and 6.4). Partial tracks resulted from either the battery losing its charge partway through a chick-rearing foraging trip, or due to a failure of the GPS unit.

Foraging trip durations varied greatly between individual birds but were 8.2 days on average for returned birds (± 5.4 days SD, *n* = 37, range: 2–22 days; Figure 2.8). For birds with complete tracks, the average trip distance was 3633 km (± 2437 km SD, *n* = 32, range: 825–9437 km); an average of 498 km travelled per bird per day (± 138 km SD, *n* = 32, range: 305–1050 km). The average maximum distance travelled from Great Barrier Island/Aotea was 846 km (± 679 km SD, *n* = 32, range: 151–2902 km; Figure 2.9).

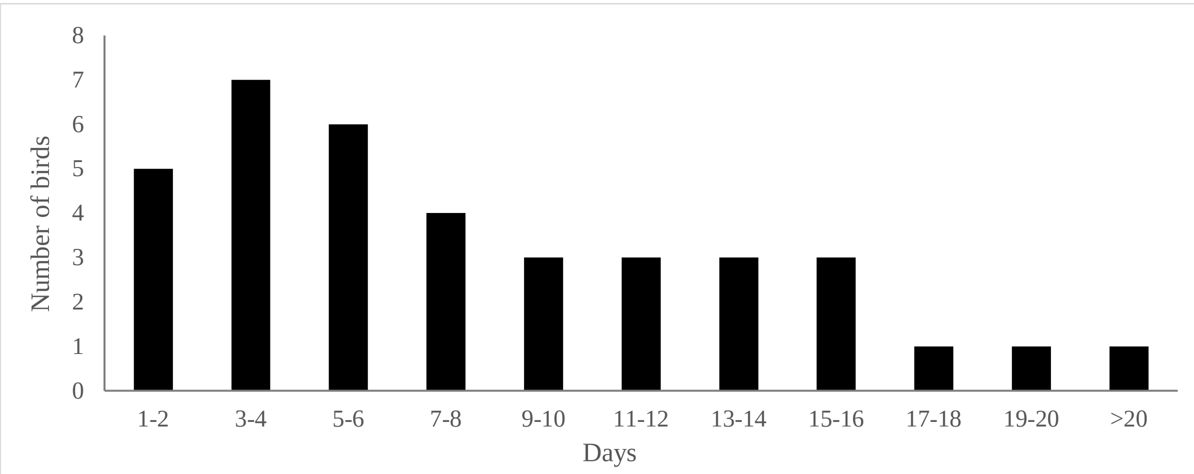

Figure 2.8: Number of days of each foraging trip for black petrels tracked during chick rearing from Great Barrier Island/Aotea in 2018.

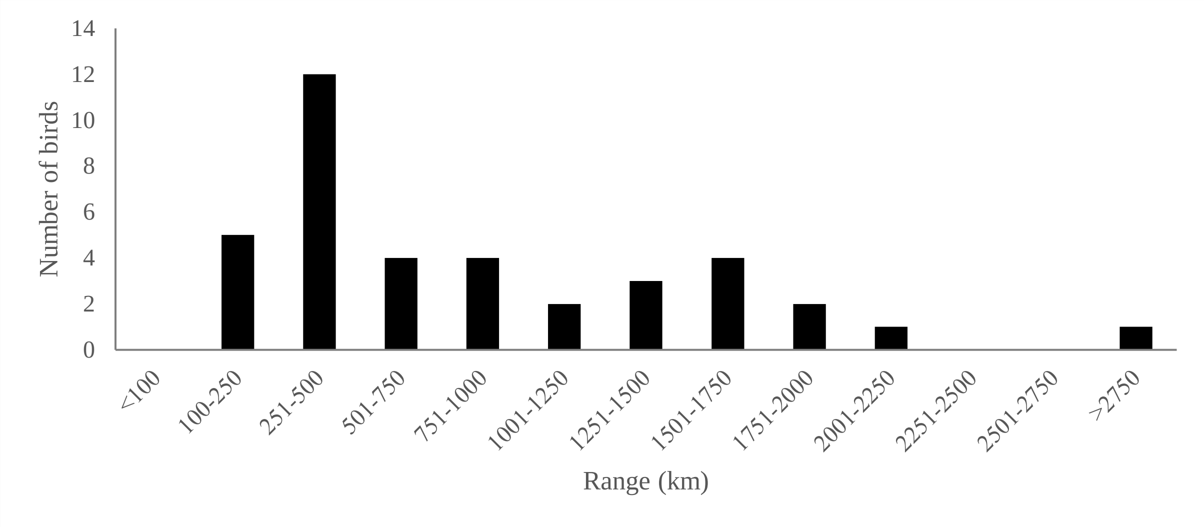

Figure 2.9: Maximum range for each foraging trip by black petrels tracked during chick rearing from Great Barrier Island/Aotea in 2018.

Birds foraged to both the west and east of northern New Zealand (Figure 2.9, Appendix 6.4). Using kernel density analysis (with smoothing radius of 100 km applied to a 2 km grid over the entire extent of the tracking data), nine activity "hotspots" were identified (Figure 2.10). Seven of these "hotspots" were within the New Zealand EEZ and the remaining two were outside the New Zealand EEZ. Of the nine hotspots identified, three were identical to "hotspots" identified during incubation in 2019 and an additional two were very similar (Table 2.2).

Table 2.2: Details of the nine activity "hotspots" for black petrels during chick rearing 2018. "Hotspots" were identified by mapping all points for all chick-provisioning trips using kernel density analysis.

Location / Bathymetric feature	Label (Figure 2.10)	Longitude	Latitude	Same foraging location identified during incubation? (see Figure 2.4)
Within New Zealand EEZ				
Great Barrier Island/Aotea stretching southeast, east and northeast	1	175.844	-35.965	Yes (1)
Northeast of Three Kings Islands, along Three Kings Ridge	2	172.251	-33.877	Yes (2)
South of East Cape, on the shelf break between Mahia Peninsula and Gisborne	3	178.467	-38.893	Similar (4)
Between Kaipara and Manukau Harbour mouths, up to 50 km offshore	4	174.087	-36.930	No
50-100 km offshore from Hokianga Harbour along shelf break	5	172.542	-35.558	No
South of Kermadec Islands along Kermadec Ridge	6	-178.971	-32.102	No
Approximately 200 km northeast of Chatham Island on the northern edge of the Chatham Rise.	7	-175.155	-42.240	No
Outside New Zealand EEZ				
North-East end of Chatham Rise	8	-170.099	-41.105	No
West Norfolk Ridge	9	167.888	-31.861	Yes (10)

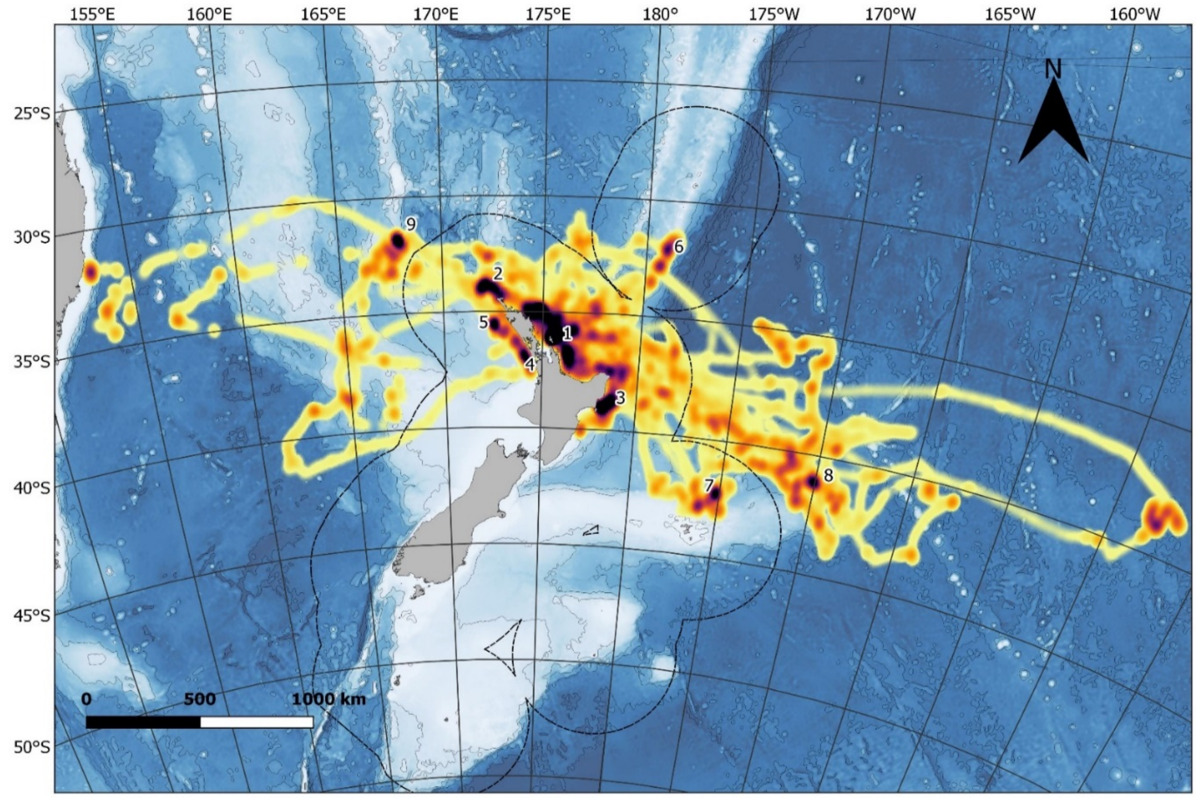

Figure 2.10: Kernel density map of all black petrel chick-provisioning trips from Great Barrier Island/Aotea recorded in March-April 2018. Darker areas represent greater concentrations of black petrel activity and details of "hotspots" are provided in Table 2.2. The black dashed line represents the EEZ outer boundary.

Four black petrels were tracked during two consecutive chick-provisioning trips (Figure 2.11). The results for these trips suggest that black petrels exercise a dual foraging strategy whereby the birds alternate between short trips and long trips, but this needs to be investigated further using cameras at burrows, radio frequency identification (RFID) tags on parent birds, and additional tracking.

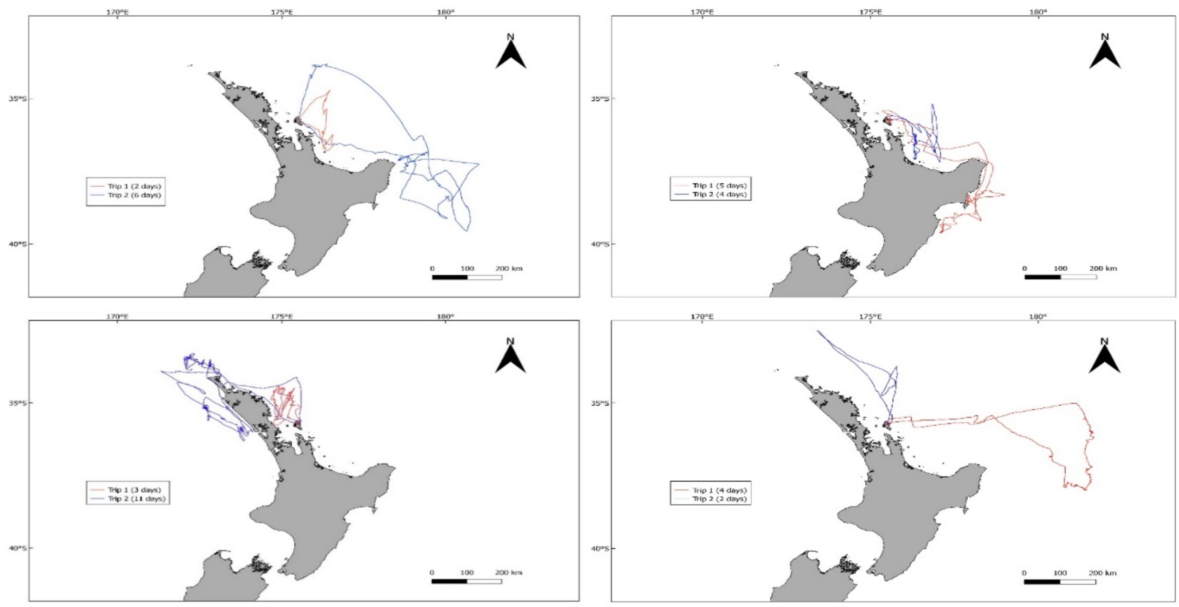

Figure 2.11: GPS tracks from two consecutive chick-provisioning trips carried out by each of four adult black petrels breeding on Great Barrier Island/Aotea in March-April 2018.

During incubation, females made significantly longer trips than males in all respects (Table 2.3). There was a significant difference between mean trip length and duration between females and males during incubation; females travelled further (two-sample t-test, $t_{22} = 3.14$, $p < 0.01$; Table 2.3) and made longer trips (two-sample t-test, $t_{25} = 2.91$, $p < 0.01$; Table 2.3) than males. Females also on average ranged further from Great Barrier Island/Aotea (two-sample t-test, $t_{23} = 3.52$, $p < 0.01$). Spatially, this difference is apparent with females ranging much further offshore than males (Figure 2.12).

During chick rearing, there was no significant difference in mean trip length (two-sample t-test, $t_{15} = 0.949$, $p = 0.358$) or mean duration (two-sample t-test, $t_{19} = 0.529$, $p = 0.603$) between male and female black petrels (Table 2.3). However, females had a significantly larger mean maximum range from Great Barrier Island/Aotea than males (two-sample t-test, $t_{16} = 2.395$, $p < 0.05$; Table 2.3). Spatially, females appeared to forage in areas further offshore whereas males utilised more inshore areas (Figure 2.12).

Table 2.3: Statistical comparisons between average trips carried out by male and female black petrels breeding on Great Barrier Island/Aotea during incubation in January-February 2019 and chick rearing in March-April 2018. Asterisk indicates a statistically significant difference.

	Male	Female	t-test
Incubation (2019)			
Mean trip length (km)	3 046	5 683	p < 0.01*
Mean trip duration (days)	7.6	12.6	p < 0.01*
Mean maximum distance from Great Barrier Island/Aotea (km)	588	1 298	p < 0.01*
Chick rearing (2018)			
Mean trip length (km)	3 299	4 273	p = 0.36
Mean trip duration (days)	8.2	9.4	p = 0.60
Mean maximum distance from Great Barrier Island/Aotea (km)	637	1 226	p < 0.05*

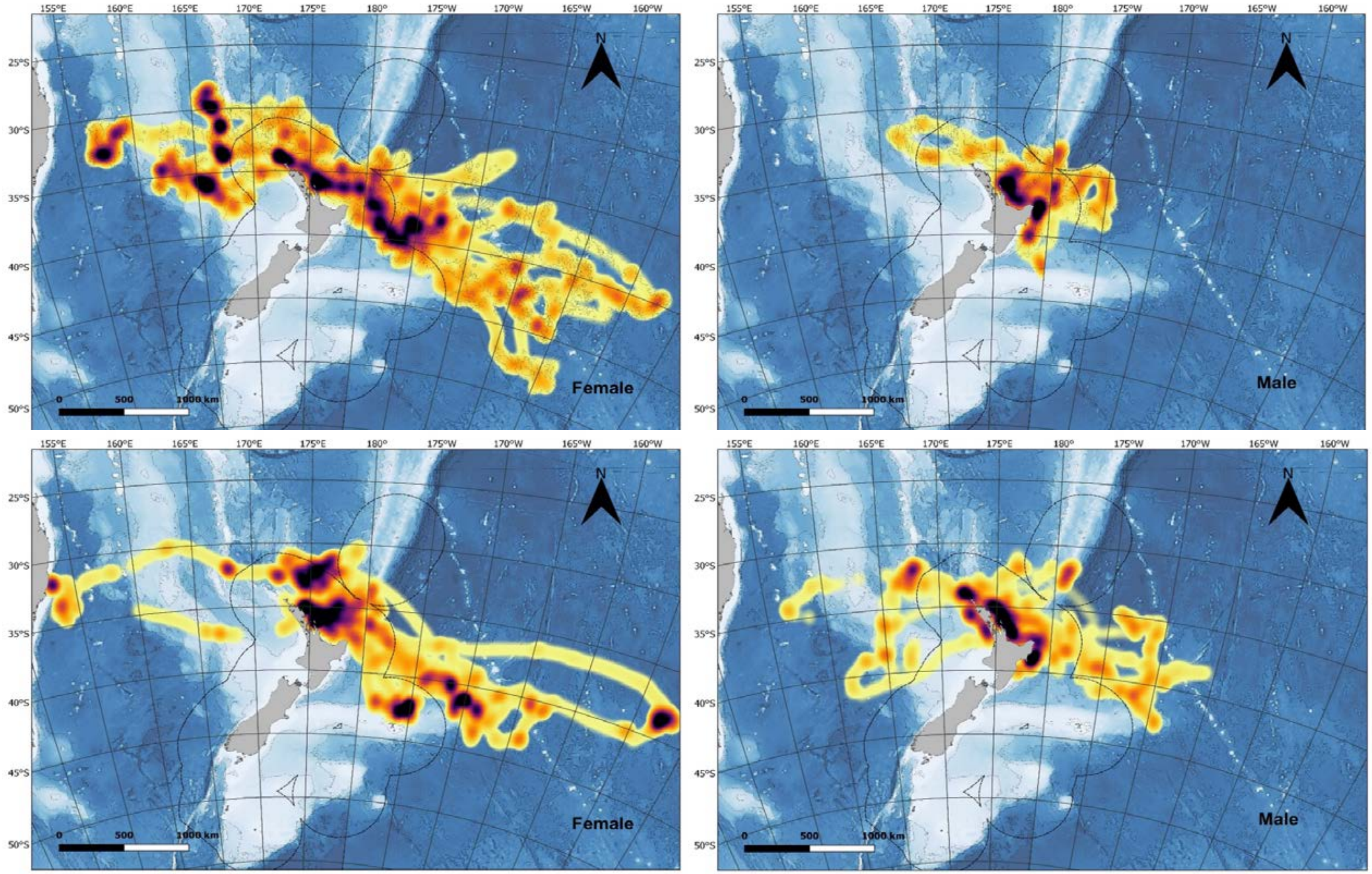

Figure 2.12: Kernel density maps comparing foraging trips for female (left-hand maps) and male (right-hand maps) black petrels breeding on Great Barrier Island/Aotea. The top two maps show foraging trips during incubation in 2019 and the bottom two maps show chick-provisioning trips in 2018. Darker areas represent greater concentrations of black petrel activity. The black dashed line represents EEZ outer boundary.

2.3.3 Comparison between breeding stages

Three birds were tracked during both the chick-rearing stage in 2018 and the incubation stage in 2019 (Figure 2.13). The tracks of these three birds suggest that individuals tend to follow a similar path or head in the same direction at different breeding stages but there was no apparent trend in trip distance or duration. One bird (35419) made a much longer trip during chick rearing; the other (36372) made a much longer trip during incubation; and the final bird (27604) made remarkably similar foraging trips during each breeding stage.

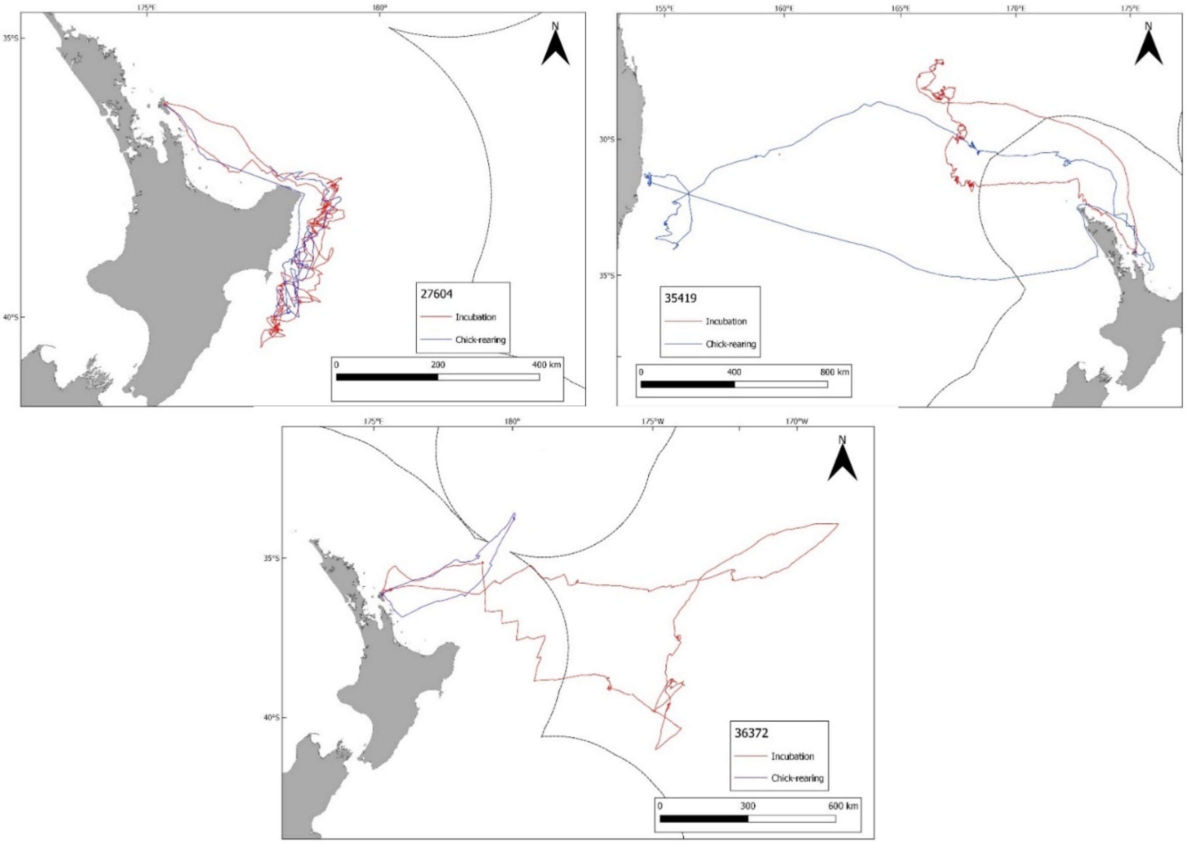

Figure 2.13: GPS tracks of the three individual black petrels on Great Barrier Island/Aotea tracked during incubation in 2019 and chick rearing in 2018. Incubation tracks are represented by red lines and chick-rearing tracks are represented by blue lines. The dashed line represents the EEZ outer boundary.

When data for both breeding stages were combined and mapped using kernel density analysis, a near-continuous pattern of activity was identified off the east coast of the North Island from Three Kings Islands/Cape Reinga to Mahia Peninsula (Figure 2.14).

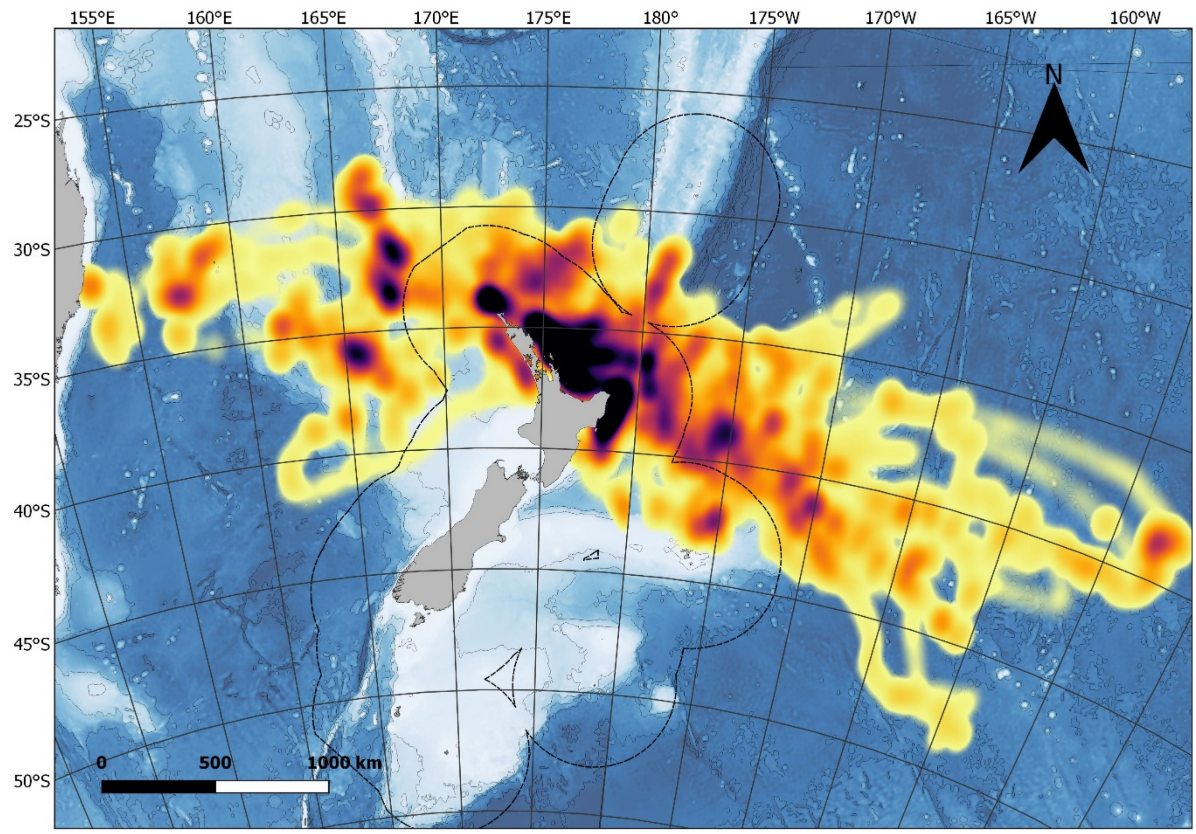

Figure 2.14: Kernel density map for all black petrel GPS points collected during incubation in 2019 and chick rearing in 2018. Darker areas represent greater concentrations of black petrel activity. The black dashed line represents the EEZ outer boundary.

2.3.4 GLS tracking of adult black petrels during their annual trans-Pacific migration

A total of 55 (29 male, 26 female) GLS devices were deployed on breeding black petrels in March 2018. Of these 55 individuals, 5 birds were not seen during burrow checks in January 2019 (or January 2020) and four returned with no GLS device attached. All 46 of the remaining devices were retrieved and yielded light data from which tracks could be obtained (Appendix 6.5).

Devices were worn for between 286 and 656 days (mean = 322 days) and most birds showed no adverse effects from carrying the devices for this extended period. Three birds returned with minor calluses near the distal end of their tarsi where the band with GLS had been pressing down against the skin. One bird returned with a moderate callus injury (see Appendix 6.6).

Of the 28 birds weighed pre- and post-deployment, 25 returned heavier than pre-deployment and three returned lighter; the average weight change was an increase of 90 g (range: -20 g to +220g) which represents an average increase of 14% (range: -3% to + 33%) of body weight. Of the 38 control birds weighed (in March 2018 and again in January 2019), 29 returned heavier than their 2018 weight and nine returned lighter; the average weight changes was an increase of 24 g (range: -150g to +165 g). There was a significant difference between the mean weight gain between tracked birds and control birds (two-sample t-test, $t_{57} = 4.25$, $p < 0.001$) with the control birds gaining less weight between captures. However, as stated earlier, these weight differences between tracked and non-tracked birds may relate to time of capture rather than body condition itself. These results suggest that carrying a device has no lasting effect on body condition, even when carrying a device for over a year.

Most black petrels tracked migrated in a band centred on the line between the points 170° W, 30° S and 110° W, 10° N. Generally, black petrels migrated east from New Zealand on a more southerly path and migrated back west toward New Zealand on a more northerly path (Appendix 6.5).

The at-sea distribution of black petrels during the non-breeding season is concentrated in two distinct areas. The first is centred off the coast of Ecuador and the second is due southwest of the Galapagos Islands stretching from the equator to approximately 1000 km south of the equator (Figure 2.15). They seem to be concentrated off the coast of Peru when they arrive between May and June and then move further north to areas off the coasts of Ecuador and Colombia and southwest of the Galapagos Islands as the season progresses (Figure 2.16). There was no apparent difference in the spatial distribution of male and female black petrels during the non-breeding season.

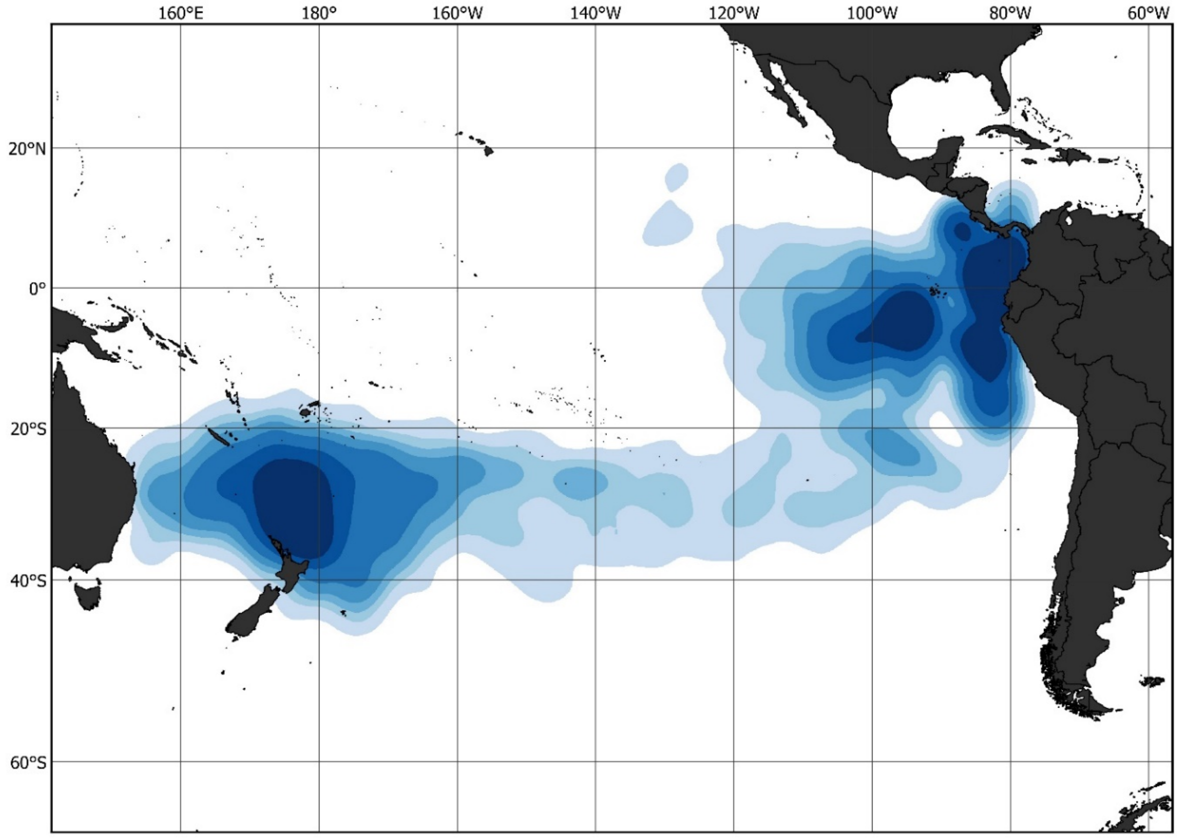

Figure 2.15: Kernel density map of GLS points for all black petrels between March 2018 and January 2019. Darker areas represent greater concentrations of black petrel activity.

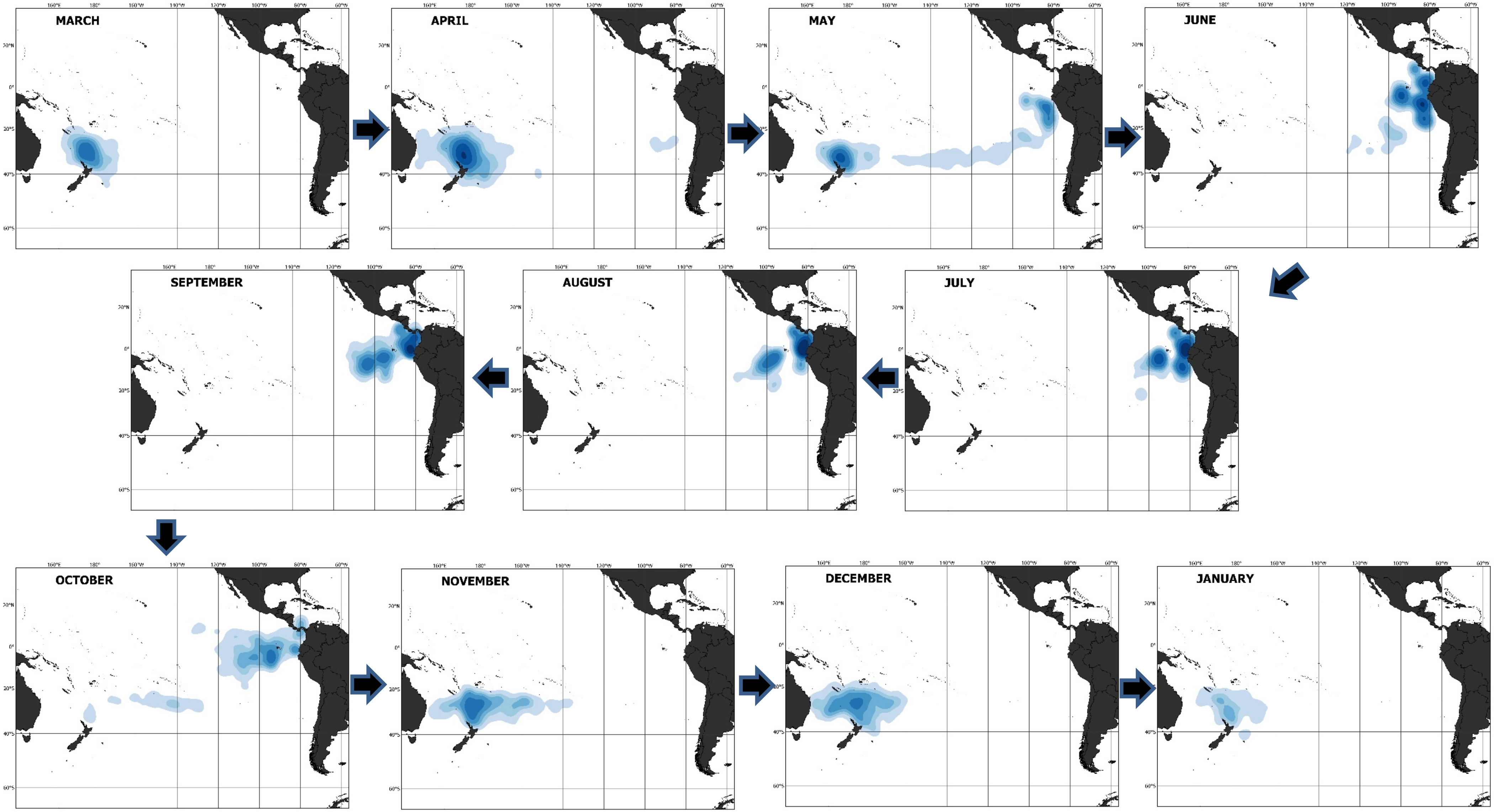

Figure 2.16: Kernel density maps of GLS points for all black petrels by month between March 2018 and January 2019. Darker areas represent greater concentrations of black petrel activity.

Some of the black petrels reached areas off the coast of South America by as early as May and all had made it by June. This migration is undertaken relatively quickly, as indicated by very few geolocation points in between New Zealand and South America. In October most birds had begun their migration back to New Zealand for the ensuing breeding season.

2.4 Discussion

The tracking data presented here provides the most comprehensive account of the at-sea distribution and behaviour of black petrels during the breeding season and their spatial distribution during the non-breeding season. These tracking data reiterate that substantial variation in at-sea habitat use occurs between individual birds, and that there is also substantial inter-annual variability in foraging behaviour. One factor that seems to be consistent with tracking studies on black petrels is the importance of continental shelf breaks for black petrel foraging as shown during the 2017–18 breeding season with black petrels foraging off shelf breaks around Northland and along the Chatham Rise (McArthur et al. 2018). Freeman et al. (2010) found a significant relationship between bathymetry and black petrel foraging movements. Shelf breaks are commonly considered important for foraging procellariforms because associated upwellings often cause high productivity (Phillips et al. 2006, Studwell et al. 2017).

A key result from this tracking work was that breeding adults undertaking chick-provisioning trips during March-April 2018 were travelling significantly further per trip than has been recorded previously (two-sample t-test, $t_{48} = 2.01$, $p < 0.01$). In March-April 2018, birds travelled an average of 3633 km per trip ($n = 32$, range 825–9437 km) in comparison to an average distance of 807 km ($n = 9$, range: 248–2396 km) travelled per trip by birds tracked in February-March 2006 (Freeman et al. 2010). This result, combined with the observation that a higher than average number of chicks starved to death in their burrows during mid-to-late chick rearing in 2018, suggests that some adult birds were struggling to adequately provision their chicks during the 2017–18 breeding season. Unusually high air pressure at sea level in the Tasman Sea and SW Pacific in late 2017 and early 2018 prevented the usual mixing of deeper, cooler sea water with surface waters, resulting in unusually high sea surface temperatures between December 2017 and February 2018 (NIWA, 2018a, 2018b). These anomalous sea surface temperatures may have altered the distribution and accessibility of the black petrels' prey, reducing the foraging efficiency of some birds.

Birds tracked in this study visited a number of foraging hotspots identified during tracking studies carried out in previous years, including the continental shelf break off the east coasts of Northland and East Cape, and waters over the eastern Chatham Rise (Bell et al. 2009, Richard et al, 2011). However, GPS tracked birds also spent time foraging off the west coast of Northland, along the Norfolk Ridge and Kermadec Ridge, Hikurangi Plateau, in the Tasman Sea, and in waters north and east of the Chatham Rise (Figures 2.4, 2.10, and 2.14). A number of these latter areas fall outside of the boundary of New Zealand's Exclusive Economic Zone (EEZ).

The area on the West Norfolk Ridge (approximately 167.6° E, 32.8° S), just outside the New Zealand EEZ, was identified as a key foraging location during both incubation and chick rearing. This same area has also recently been identified as a key foraging area for adult flesh-footed shearwaters (*Puffinus carneipes)* during both the incubation and chick-rearing phases (Kirk et al. 2017, Crowe 2018). Both black petrels and flesh-footed shearwaters are known to follow fishing boats, and this area is frequented by commercial fishing vessels (Gaskin et al. 2016, Global Fishing Watch 2018).

The foraging hotspot identified during chick rearing in 2017/18 on Northland's west coast between Kaipara Harbour and Manukau Harbour was also identified as a foraging hotspot for flesh-footed shearwaters tracked during the 2017/18 breeding season (Crowe 2018). This suggests that this area provided particularly good foraging habitat for both species during the summer of 2017/18. Interestingly, tracking in 2018/19 during the incubation stage revealed that black petrels did not exploit this area again. This could be explained by inter-annual variation in the distribution of prey species causing the birds to change their foraging habits accordingly.

There have been conflicting reports of whether black petrels are primarily nocturnal (Imber 1976, 1987, Harper 1987, Warham 1996) or diurnal (Bell 2016) foragers. The data presented here seem to agree with both perspectives but with a slight tendency towards more daytime foraging at a population level. Using Time-Depth Recorders, Bell (2016) found black petrels foraged primarily during the day but also conducted shallow dives at night, probably to catch bioluminescent squid on or just below the surface. It is possible that the foraging patterns observed here have resulted from different individual foraging strategies; i.e., some individuals may specialise in foraging at night-time whereas a slightly larger percentage of other individuals forage primarily during the daytime. This falls outside the scope of the current analysis and this report but certainly warrants further investigation.

Using a combination of GPS and saltwater immersion logger devices is a useful method for inferring behaviour types with location data and provides greater insight into black petrel behaviour. Spending just 15% of time on each trip actively foraging indicates that black petrels must be highly efficient foragers and the locations they chose to forage must be important areas with good-quality foraging habitat. One of the limitations of this particular method of determining behaviour type is, for example, the uncertainty that a bird whose behaviour has been determined as resting/rafting at a particular location is not simply sitting beside a fishing vessel scavenging off discards or dead prey. In this situation, foraging would be misidentified as resting/rafting and as a result foraging time being underestimated. Overlap of black petrel tracking data with commercial fishing vessel tracks could provide some insight into this and possibly alleviate the misrepresentation by applying a correction factor.

The three individuals that were tracked during both incubation and chick-rearing stages all foraged in the same general direction during both stages. This suggests there is individual specialisation and preferred foraging locations that exist between breeding stages and between years. Foraging site fidelity has been observed in many other seabird species and has been linked to differences in reproductive success, whereby individuals that repeatedly visit the same areas to forage have a greater chance of fledging a chick (Coleman et al. 2005, Patrick & Weimerskirch 2017, Votier et al. 2017).

Dual foraging strategies have been described for many other procellariforms, and previous tracking of black petrels has suggested that they also adopt this strategy (Berlincourt & Arnould 2015, Shoji et al. 2015, Freeman et al. 2010). Tracking of four birds that each carried out two consecutive foraging trips seems to confirm that black petrels exercise a dual foraging strategy, alternating between short trips aimed at quickly provisioning their chick and longer trips aimed at maintaining the adults' own body weight and condition. Although the data presented here are from a small number of individuals, all four individuals did alternate between trips that were longer and shorter in both duration and distance.

The tracking results presented here confirm that males and females utilise distinct foraging areas; females forage further away from Great Barrier Island/Aotea whereas males stay closer to the island and forage at more inshore locations. Black petrels are sexually dimorphic (Mischler et al. 2015) and differences in foraging distribution and behaviour have often been attributed to differences in body structure that affect foraging efficiency or competitive ability (González-Solís et al. 2000, Camphuysen et al. 2015). The data presented here wholly agree with this theory and this difference between male and female foraging areas and behaviour has inherent impacts on assessing and managing the risk of black petrel bycatch in commercial fisheries.

Geolocation data presented here from 46 individuals provide the most comprehensive view of adult black petrel spatial distribution during the non-breeding season. Although there is some variation between individuals, at a population level, black petrel activity during the non-breeding season is mostly concentrated around two areas. The first is off the coast of South America centred off Peru and Ecuador and the second is west of the Galapagos Islands. This is the exact same pattern observed by Bell et al. (2011) and confirms that black petrels show very little inter-annual variation in non-breeding spatial distribution. Because the biggest current quantifiable threat to the population viability of black petrels is adult mortality associated with commercial longline and trawl fisheries, these new tracking data can be used to improve models of the at-sea distribution and habitat use of adult black petrels during both the breeding and non-breeding seasons. These improved estimates can then be used to improve spatially-explicit models of fisheries bycatch risk and to help determine mitigation measures to reduce the incidence of bycatch of black petrels.

3. A PILOT TRIAL OF THE USE OF DISTANCE SAMPLING TO ESTIMATE BLACK PETREL BURROW DENSITY AND BREEDING POPULATION SIZE

3.1 Introduction

An accurate estimate of the global population size of black petrels, and in particular the number of mature breeding pairs, is a key piece of information required to inform the conservation management of this threatened seabird species. For example, to assign an appropriate New Zealand Threat Classification ranking to this species, accurate estimates of both black petrel population size and population trend are required (Townsend et al. 2008). Similarly, Fisheries New Zealand regularly assesses the risk posed by commercial fisheries to New Zealand seabird species, as required by its National Plan of Action (NPOA) to reduce the incidental catch of seabirds within New Zealand's Exclusive Economic Zone (Ministry for Primary Industries 2013). The current risk assessment method includes the calculation of a Population Sustainability Threshold, which in turn requires accurate estimates of a number of population demographic parameters, including an estimate of the total number of breeding pairs in a seabird population (Richard et al. 2017).

Since the mid-1990s a number of methods have been used to estimate the size of the black petrel breeding population, with varying results. One long-running series of estimates has been derived from an extrapolation of burrow density measurements from between three and nine 40 x 40 m study grids to calculate the total number of burrows present in a 35-ha black petrel study area near the summit of Great Barrier Island/Aotea (Bell & Sim 2005). These estimates have varied considerably from year to year, and it is unclear how accurate these estimates are relative to the true size of the black petrel breeding population for two reasons. Firstly, the authors acknowledge that the study grids have been intentionally situated in sites with relatively high burrow densities, so are likely to overestimate the average burrow density of the 35-ha study area (Bell & Sim 2005). Secondly, black petrels are also known to breed outside this study area, both elsewhere on Great Barrier Island/Aotea and on Te Hauturu-o-Toi/Little Barrier Island, but relatively few data are available to estimate the number of birds breeding in these locations (Richard et al. 2017).

More recently, attempts have been made to correct the first of these two problems by carrying out random, four metre fixed-width strip transect sampling throughout the 35-ha study area on Great Barrier Island/Aotea, both with and without a *post hoc* stratification of the study area into zones of high, medium, low, and zero burrow densities (Bell et al. 2007). Although this method likely provides a more representative picture of burrow density across the 35-ha study area, it does include a critical assumption that all burrows within the fixed-width strips are detected. This assumption has more recently proven to be incorrect, based on a comparison of transect surveys carried out by both field team members and a seabird detector dog on Te Hauturu-o-Toi/Little Barrier Island in 2016 (Bell et al. 2016). Furthermore, the *post hoc* stratification of the study area into zones of high, medium and low burrow densities based on the data collected during these transect surveys is potentially prone to error, due to chance encounters of localised concentrations of burrows in areas of low- or medium-grade black petrel habitat; or to localised gaps in burrow distribution in areas of high-grade black petrel habitat leading to incorrect "zoning" during the *post hoc* stratification process.

In an attempt to overcome a number of these issues, Richard & Abraham (2015) used fisheries bycatch data and a Bayesian modelling approach to create an estimate of the total number of breeding black petrels on both Great Barrier Island/Aotea and on Te Hauturu-o-Toi/Little Barrier Island. This approach used transect survey results from the 35-ha study area on Great Barrier Island/Aotea to determine a lower limit for a constructed prior probability distribution, and at-sea survey results from South American waters to determine an upper limit for this prior distribution. The resulting breeding population estimate of 2750 breeding pairs (5500 breeding birds) is the estimate currently being used for the NPOA risk assessment for black petrels (Richard et al. 2017). Despite these more recent efforts to model black petrel population size, Richard et al. (2017) acknowledge that the black petrel population size is still “not well known” and identify three sources of uncertainty in existing estimates: 1) uncertainty regarding the proportion of breeding adults that breed in any particular year; 2) changes in the actual population size of black petrels; and 3) uncertainty from the sampling processes used on Great Barrier Island/Aotea and Te Hauturu-o-Toi/Little Barrier Island. Richard et al. (2017) recommend the development of a demographic model to estimate the size of the black petrel population, including a more robust estimate of the number of black petrels that breed in suitable habitats on Great Barrier Island/Aotea outside the 35-ha study area at Mt Hobson/Hirakimata and on Te Hauturu-o-Toi/Little Barrier Island.

Due to the large size of both Great Barrier Island/Aotea and Te Hauturu-o-Toi/Little Barrier Island, and rugged terrain and dense vegetation, the use of randomly-located grids or fixed-width strip transects to sample black petrel burrow density across all occupied breeding habitats on both islands would be too costly and time-consuming to be feasible. Added to this, any population estimate derived from data collected by either of these two methods relies on the assumption that burrow detection probability within these census grids or strip transects is 100%; an assumption which has been tested and found to be false (Buckland et al. 2001, Bell et al. 2016). To overcome these challenges, a trial using distance sampling to generate an estimate of occupied black petrel breeding burrow density within the 108-ha high-grade habitat on Great Barrier Island/Aotea was completed during the 2018/19 breeding season.

Distance sampling is a simple and cost-effective method for estimating the absolute density of objects within a particular sampling area (Buckland et al. 2001). Distances are recorded from points or line transects to the objects of interest (in this case, black petrel burrows), and the resulting distribution of distances is used to model how detection probability declines with increasing distance from the point or line transect (Buckland et al. 2001). However, to generate unbiased estimates of density, five key assumptions need to be met: 1) that the probability of detecting objects of interest situated on the survey line or point is 100% and declines outwards from the survey line (detection gradient/detection function); 2) that the lines or points sampled are randomly distributed in relation to the objects of interest; 3) that detections are independent of one another; 4) that measurements are exact; and 5) that objects are detected at their initial locations.

The purpose of this trial was to test the feasibility of using distance sampling to estimate the total number of black petrels breeding on Great Barrier Island/Aotea and Te Hauturu-o-Toi/Little Barrier Island, by directly sampling all the occupied breeding habitat on each island. More specifically, the aim was to test whether or not the key assumptions of distance sampling could be successfully met when sampling burrow density in densely vegetated and rugged terrain, and to quantify how much effort would be required to achieve a minimum sample size of 60–80 object detections. If successful, this pilot trial would also produce a black petrel occupied breeding burrow density estimate and breeding population estimate for 108-ha high-grade black petrel habitat on Great Barrier Island/Aotea, over three times the area of occupied breeding habitat that has previously been surveyed.

3.2 Methods

3.2.1 Habitat stratification

Breeding black petrels are unevenly distributed across Great Barrier Island/Aotea, with significantly higher densities of breeding birds found on high altitude ridges under mature, unlogged, and unburnt native forest than at lower altitudes or in other vegetation types on the island (Marchant & Higgins 1990; WMIL, unpublished data). For this reason, to optimise the efficiency of the sampling design, Great Barrier Island/Aotea was stratified into high-, medium-, and low-grade black petrel habitat strata. First, all existing data on the presence and location of black petrel breeding burrows on the island were collated using ArcMap version 10.6.1. Map layers describing altitude, vegetation type, and the presence and absence of feral pigs (a major threat to burrow-nesting shorebirds on land, e.g., Cuthbert 2002) were overlaid, and the relationship between these three habitat variables and the densities of known black petrel burrows on the island were visually examined to create definitions of high-, medium-, and low-grade black petrel habitat strata on Great Barrier Island/Aotea as described in Table 3.1.

Table 3.1: Definitions of high-, medium-, and low-grade habitat strata for black petrels on Great Barrier Island/Aotea.

Habitat stratum	Vegetation type	Altitude (metres a.s.l.)	Feral pigs	Total area (ha)	Example sites
High-grade	Mature Forest	>400	Absent	108	Mt Hobson/Hirakimata Mt Heale
Medium-grade	Mature Forest	>400	Present	3 207	Te Paparahi Block
		250–400	Present		
		<250	Absent		Glenfern Sanctuary
	Shrubland	>250	Present		
		<250	Absent		Glenfern Sanctuary
Low-grade	Mature Forest	<250	Present	24 520	
	Shrubland	<250	Present		
	Other*	<250	Present		Okupu

* Includes settlements, farms, etc.

The boundaries of these three habitat strata were mapped using ArcMap, according to the criteria outlined in Table 3.1 (Figure 3.1). The random start points and compass bearings were generated for eighty 100-m long line transects within the high-grade habitat stratum (Figure 3.2).

3.2.2 Line transect surveys

A team of two fieldworkers navigated to the start location of each randomly-generated transect using a handheld Garmin GPS. One fieldworker then laid out a tape measure along the pre-defined compass bearing for the transect, before a second fieldworker slowly walked along the tape measure, scanning the ground for black petrel burrows. Burrows were detected either by directly sighting burrow entrances, or via the detection of visual cues indicating the likely presence of a burrow. These cues included signs of fresh digging, the presence of a semi-circular mound of soil or sticks in front of a burrow entrance, and/or the presence of fresh guano, eggshell remains, or fresh feathers. Once a potential burrow or cue had been detected, one of the fieldworkers inspected the potential burrow, or searched within a 2-m radius of the cue, to confirm whether or not a black petrel burrow was present. When a black petrel burrow was confirmed, it was carefully checked to determine whether or not it was being, or had been used, as a breeding burrow during the current season. Burrows were checked manually, either by reaching an arm or stick into the nest chamber, either via the burrow entrance or through a small inspection hole dug directly into the nest chamber. Burrows were recorded as being current breeding burrows based of the presence of incubating adults or lone chicks, or of fresh egg or chick remains. Once confirmed, the perpendicular distance of each burrow from the transect was measured to the nearest 0.1 m using a tape measure. Extreme care was taken to ignore any burrows detected by either fieldworker whenever they were not standing at the tape measure. Similarly, care was taken to ignore the presence of blue tags marking the locations of pre-existing study burrows or the presence of burrow hatches – plywood hatches covering nest chamber inspection holes. Any study burrow that was known to be present, but wasn't detected from the tape measure by visually sighting the burrow entrance or via the detection of the visual cues listed above, was ignored and treated as a non-detection.

Wherever possible, the full 100-m length of each transect was surveyed, in 20-m increments. However, several transects were truncated either where they crossed the boundary of the high-grade stratum, or because the fieldworkers encountered hazardous terrain such as cliffs and bluffs. A total of 80 transects, comprising a total length of 7.582 km, were surveyed (Figure 3.1).

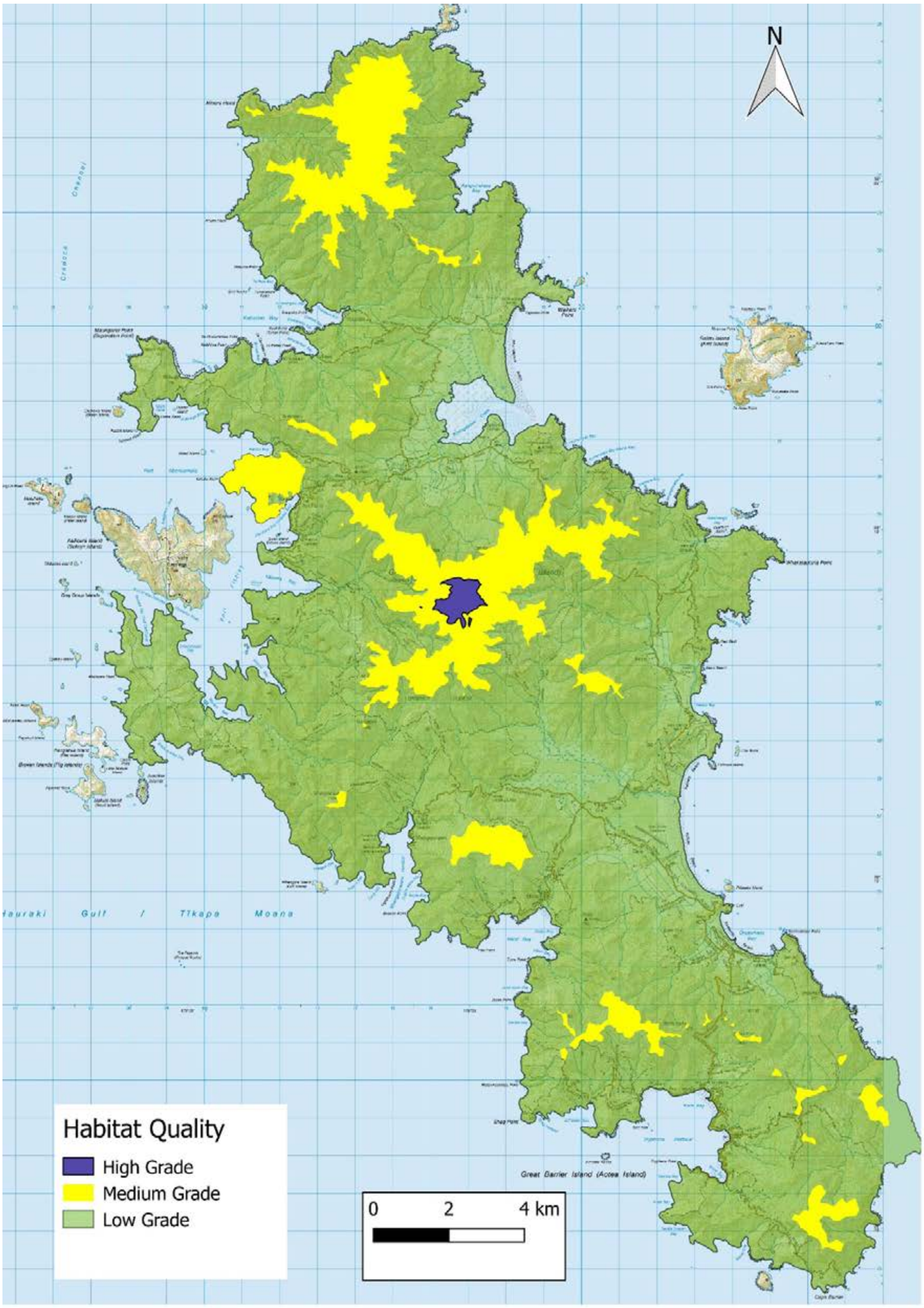

Figure 3.1: Habitat stratum on Great Barrier Island/Aotea as generated by information in Table 3.1 (i.e., existing presence of black petrel burrows, vegetation type, altitude, presence of feral pigs).

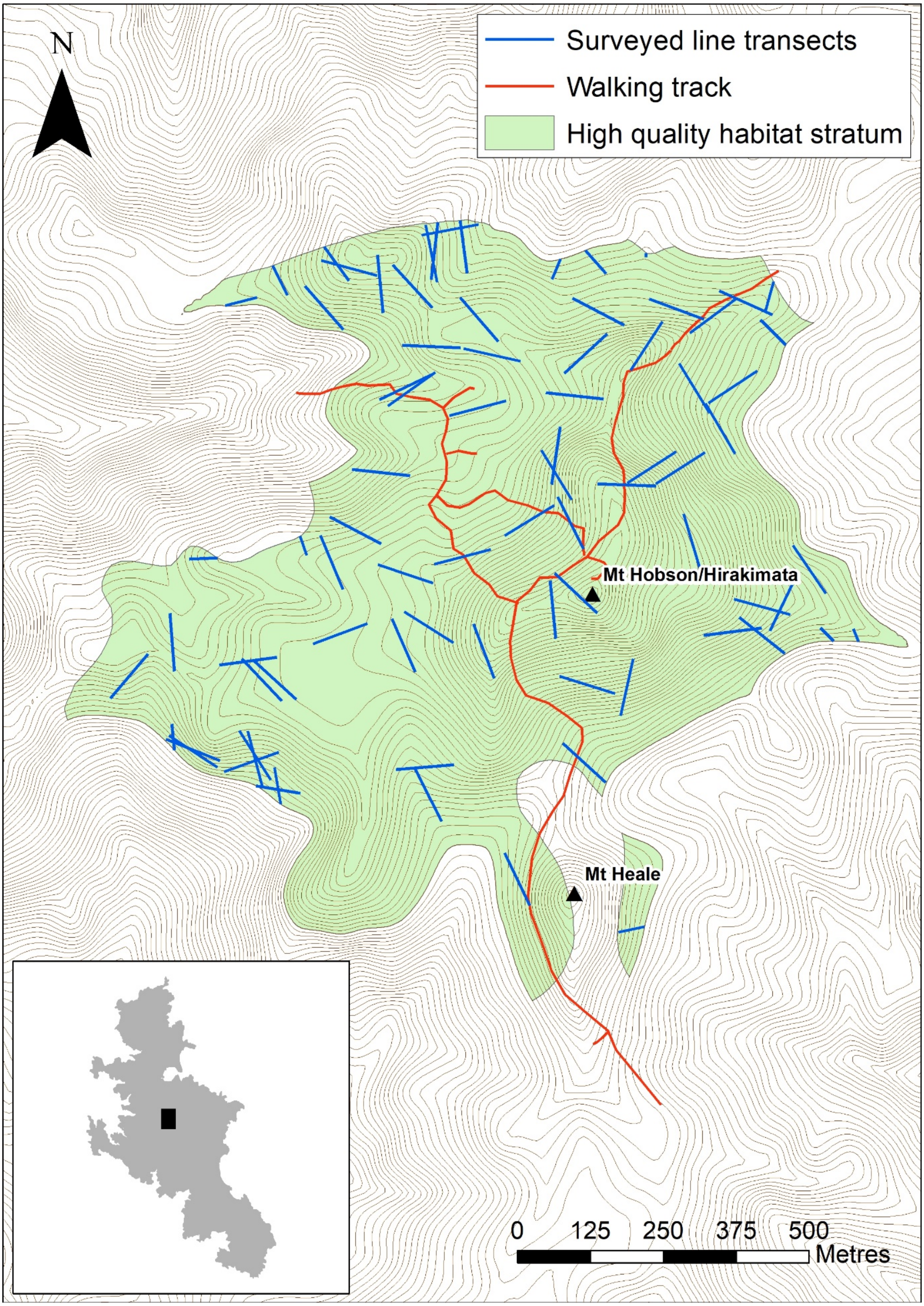

Figure 3.2: High-grade habitat stratum line transects surveyed on Great Barrier Island/Aotea in January and February 2019.

3.2.3 Data analysis

Line transect data were entered into Microsoft Excel, and histograms of the perpendicular distance data were created to examine whether the assumptions underlying the distance sampling methodology had been met, and to identify an appropriate distance at which to truncate these distance data. The distance data were modelled using the Conventional Distance Sampling Engine in Distance 7.2 (Thomas et al. 2010), which allows detection probability to be estimated as a function of distance from the transect line. In this analysis, each burrow detection was treated as a single object and this dataset was truncated at a perpendicular distance of > 7.0 m to reduce any disproportionate effect of outliers on both model fit and model selection (Buckland et al. 2001). Four alternative detection models were fitted to these data: the uniform key function with a cosine or simple polynomial adjustment term, and the half-normal key function with a cosine or hermite polynomial adjustment term. The detection model with the lowest AIC_c (Akaike Information Criterion) value was selected and this model was used to generate an estimate of the number of black petrel burrows present per hectare in the high-grade habitat stratum.

An 8-m resolution Digital Elevation Model of Great Barrier Island/Aotea (from the LINZ Data Service website at https://data.linz.govt.nz/) was used to create a Triangular Irregular Network (TIN) describing the 3-D surface of Great Barrier Island/Aotea using the "Raster to TIN" tool in ArcMap. This TIN was 'clipped' using a shapefile describing the boundary of the high-grade black petrel habitat defined in Table 3.1 and Figures 3.1 and 3.2, and the 3-D surface area of the high-grade black petrel habitat on Great Barrier Island/Aotea was determined using ArcMap's "Surface Volume" tool. Lastly, the estimate of the number of burrows present per hectare was multiplied by the 3-D surface area of the high-grade habitat stratum, to generate an estimate of the number of breeding pairs, and breeding adults, present within this habitat stratum.

3.3 Results

A total of 158 burrows were detected during this survey, scattered throughout the 108-ha high-grade black petrel habitat stratum (Figures 3.3 and 3.4). Of these, a total of 79 burrows were determined to have been used as breeding burrows during the 2018/19 breeding season and a further 74 burrows were either unoccupied, or occupied by non-breeding birds, providing a breeding burrow occupancy rate of 0.516 within this habitat stratum. The breeding status of the remaining five burrows detected could not be determined due to the length of the burrow and the inaccessibility of the nest chamber.

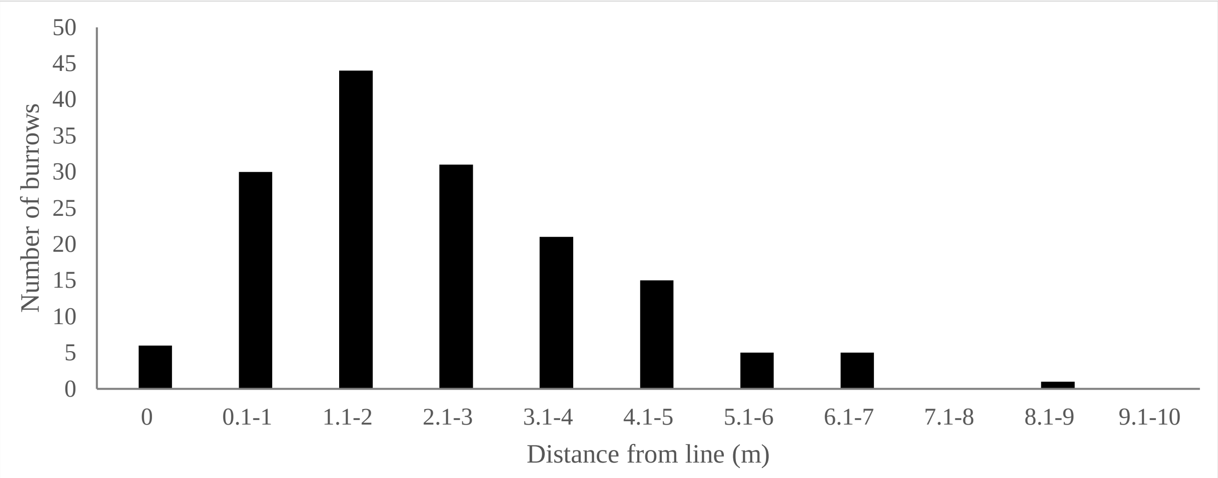

Figure 3.3: Distribution of burrow detection distances for all black petrel burrows detected by fieldworkers during this pilot line transect survey.

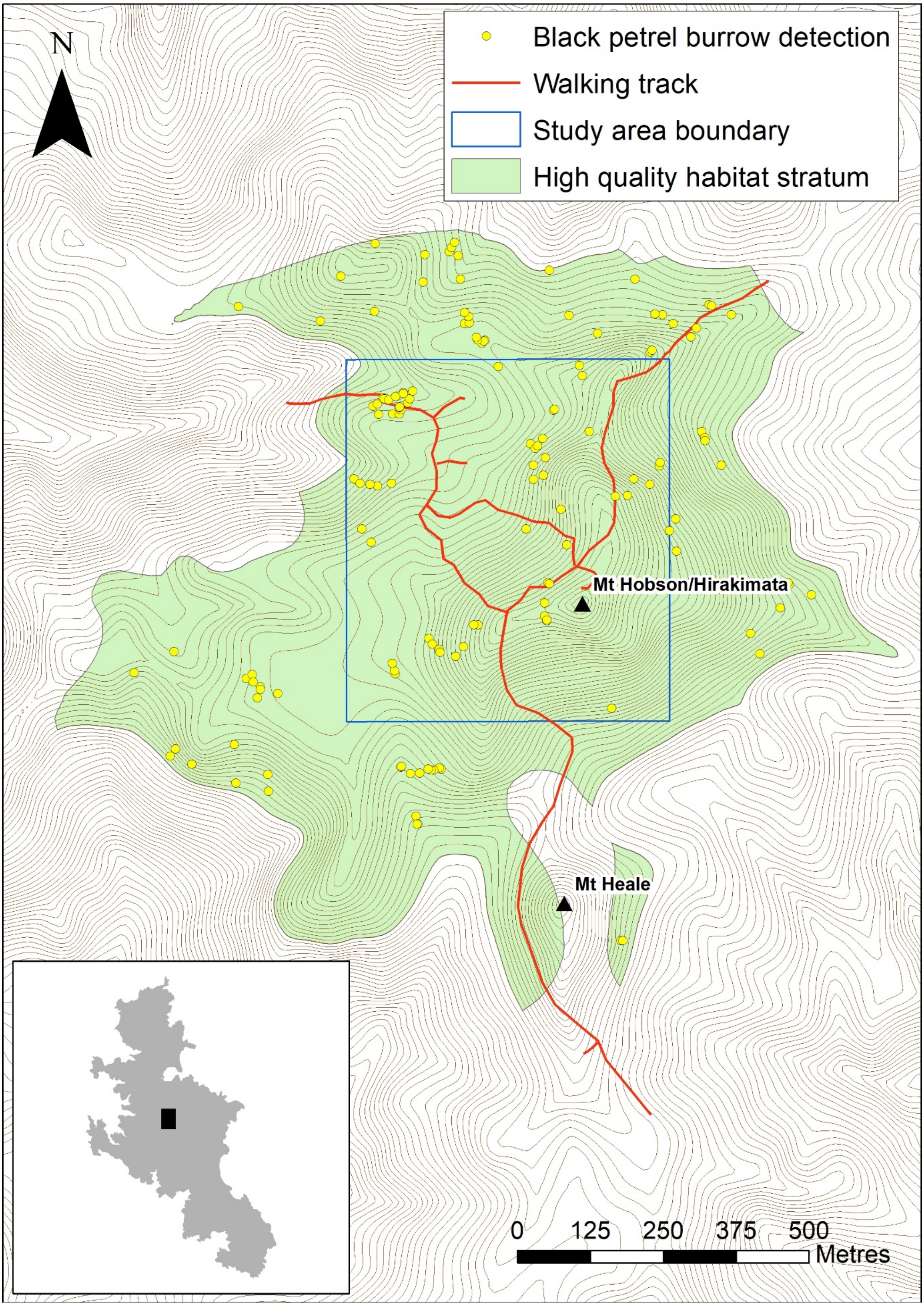

Figure 3.4: Locations of black petrel burrows detected within the high-grade habitat stratum on Great Barrier Island/Aotea in January and February 2019.

The four detection functions fitted to these line transect data all provided a reasonable fit to the data, but the uniform key function with a cosine adjustment term was the model with the lowest AIC_c value (Standard error = 4.077, coefficient of variation = 14.23); thus this model was used to generate estimates of burrow detection probability and burrow density (Figure 3.5).

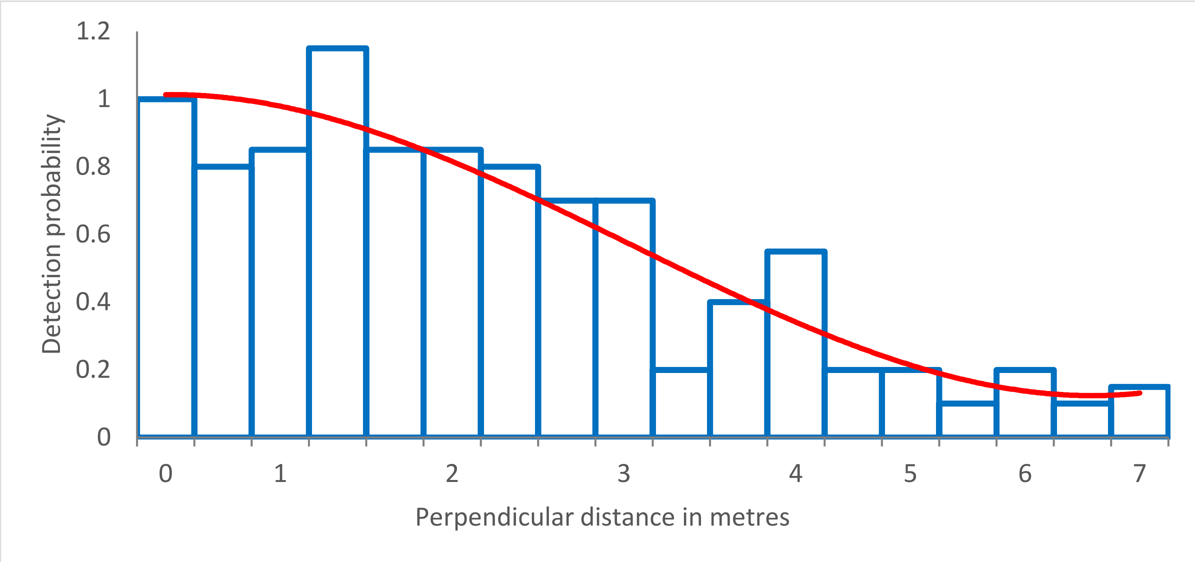

Figure 3.5: Detection probability and distribution of perpendicular burrow detection distances (histogram) for black petrel burrows detected during this line transect survey. The red line represents the uniform cosine detection function fitted to these data, from which burrow detection probabilities and burrow density estimates were generated.

According to this model, the total density of black petrel burrows in the high-grade habitat stratum is 27.37 burrows/ha (20.99–35.69 burrows/ha, 95% confidence limits). By multiplying this by the proportion of these burrows used for breeding during the 2018/19 breeding season, the density of breeding burrows (0.516) in the high-grade habitat stratum was estimated as 14.13 burrows/ha (10.84–18.43 burrows/ha, 95% confidence limits) during the 2018/19 breeding season. When multiplied by the total area of the high-grade habitat stratum (108 ha), this yields an estimate of 1532 black petrel breeding pairs (1175–1997 breeding pairs, 95% confidence limits) present in the high-grade habitat stratum, or 3064 breeding adults (2349–3995 breeding adults, 95% confidence limits).

3.4 Discussion

This pilot trial has demonstrated that distance sampling provides a more robust and cost-effective alternative to the use of grids or fixed-width strip transects to estimate black petrel breeding burrow density and breeding population size on Great Barrier Island/Aotea.

Surveying line transects using distance sampling proved to be 3–4 times more efficient than grid-searching fixed-width transects, with each line transect taking an average of 2.5 person hours to survey, in comparison with an average of almost 8 person hours spent surveying each fixed-width strip transect (WMIL, unpublished data). Furthermore, whereas fixed-width strip transect sampling relies on an assumption that 100% of the burrows present within each fixed-width transect are detected, distance sampling instead assumes that detection probability declines with increasing distance from the marked transect and uses the distribution of perpendicular distances between detected burrows and the transect to fit models describing how detection probability declines with increasing distance. This modelling approach therefore allows for any underestimation of burrow density caused by the accidental non-detection of burrows.

The generation of unbiased estimates of density using distance sampling is reliant on several key assumptions being met. These include: 1) that the probability of detecting objects of interest situated on the survey line is 100%; 2) the lines sampled are randomly distributed in relation to the objects of interest; 3) that detections are independent of one another; 4) that measurements are exact; and 5) that objects are detected at their initial locations. Based on the results of this pilot survey, the authors are confident that all five of these assumptions can be met when surveying for black petrel burrows in rugged and densely vegetated terrain. A careful examination of a histogram (see Figure 3.4) of perpendicular distances recorded during this pilot survey indicates that a large proportion of burrows were detected between 0 m and 1 m from the marked transect (22.8%), indicating that detection probability approached the maximum on and very near the transect (assumption 1). All the survey transects were situated at random within the 108-ha survey area, using random start points and random bearings that were generated prior to the survey being carried out (assumption 2). Among the burrows detected, very little sign of clustering was evident (Figure 3.4; N. McArthur, personal observation), and all burrow detections represented individual detection 'events' made by the fieldworker from the line transect (assumption 3). All measurements were made using a tape measure and were recorded to the nearest 0.1 m, with no further rounding or "binning" of measurements carried out either in the field or during analysis (assumption 4); and, because the objects of interest were burrows rather than living birds, all objects were detected at their initial locations (assumption 5).

The generation of an accurate and unbiased breeding population estimate from a burrow density estimate is also reliant on an accurate assessment of whether detected burrows are being, or have been, used as breeding burrows during the current season. Any incorrect assessment of the breeding status of detected burrows may lead to either an under- or over-estimate of the proportion of detected burrows being used for breeding, which in turn will result in an under- or over-estimate of the number of breeding black petrels within the survey area. The accuracy of the assessment of the breeding status of the burrows detected during this pilot survey was tested by carrying out two separate distance sampling analyses on this dataset. In the first analysis (reported above), all 158 burrow detections were used to produce an estimate of burrow density for the 108-ha survey area, which was then multiplied by the proportion of burrows determined as breeding burrows during the 2018/19 breeding season (51.6%). This produced an estimated density of 14.1 breeding burrows per ha, or a total of 1532 breeding burrows (and 3064 breeding adults) within the survey area. In the second analysis, only the 79 confirmed breeding burrows were used to estimate burrow density; thereby treating all non-breeding or unknown breeding status burrows as 'non-detections' and thus avoiding any need to multiply the resulting burrow density estimate by the proportion of burrows used for breeding during the 2018/19 season. The resulting estimated burrow density of 13.7 breeding burrows per ha, or a total of 1487 breeding burrows (and 2974 breeding adults) was similar to the estimates generated from the first analysis. The results of this test provided strong evidence that the field team accurately determined the breeding status of the majority of the 158 black petrel burrows detected during this pilot trial.

Since 1995, estimates of the number of breeding black petrels present within the 35-ha study area on Great Barrier Island/Aotea have varied between a low of 1760 birds (Bell et al. 2016) to a high of 5000 birds (Bell et al. 2017). The estimate of 3064 black petrels breeding within 108 ha of habitat (including the 35-ha study area) falls roughly midway between these previous upper and lower estimates, despite the fact that over three times the area of habitat had been surveyed during this distance sampling pilot trial. This result could be due to one of at least four reasons: 1) one or more of the key assumptions of distances sampling weren't met during this pilot trial; 2) the breeding burrow occupancy rate was not assessed accurately during this pilot trial; 3) the proportion of breeding black petrels breeding in any given year varies considerably from year to year; or 4) at least some of the earlier population estimates have over-estimated the number of breeding black petrels in the 35-ha study area. As discussed above, the authors are confident that this pilot trial successfully met the assumptions inherent in the distance sampling method, and that the breeding status of the burrows that were detected was accurately determined. Re-sighting rates of known banded adult black petrels from study burrows in the 35-ha study area over the past 24 years also suggests that the proportion of these adults breeding in any particular breeding season doesn't vary by more than a few percent per year (Biz Bell, pers. comm.). However, further work could be done to examine this particular source of variation in breeding population estimates, by generating temporally-explicit estimates of the proportion of banded adult black petrels breeding in the network of permanent study burrows each year, and applying these proportions as "correction factors" to previous breeding population estimates, including the one generated as a result of this pilot trial. This is unlikely to be transferable to other habitat grades because burrow utilisation (i.e., proportion used for breeding) may differ in medium- or low-grade habitat. This essentially repeats a recommendation made by Richard et al. (2017), namely that a demographic model be used to estimate the breeding population of black petrels, by combining representative and unbiased estimates of burrow density with population demography parameters such as the annual "local survival" rates of breeding adults. Lastly, as already stated by previous authors such as Bell et al. (2016) and Bell et al. (2017), at least some of the earlier population estimates generated for the 35-ha study area almost certainly are over-estimates, due to biases in the sampling approaches taken, and possibly due to inaccuracies in the *post hoc* stratification of the study area using burrow density results calculated from the fixed-width strip transects used to sample the study area.

In contrast, the estimate of 3064 breeding birds within 108 ha of occupied breeding habitat on Great Barrier Island/Aotea appears to be consistent with the estimate of 5500 black petrels breeding on both Great Barrier Island/Aotea and Te Hauturu-o-Toi/Little Barrier Island, provided by Richard et al. (2017) and used to inform the NPOA risk assessment for this species. This result suggests that the 108-ha high-grade black petrel habitat in the vicinity of Mount Hobson/Hirakimata supports approximately 56% of the estimated global breeding population of black petrels, with the remaining 44% breeding elsewhere on Great Barrier Island/Aotea and on Te Hauturu-o-Toi/Little Barrier Island. To confirm whether or not this is the case, and to further improve the accuracy of the global breeding population estimate for black petrels being used to inform the NPOA risk assessment, the distance sampling methodology tested in this pilot trial could be used to generate black petrel burrow density estimates for the pre-defined medium- and low-grade habitat strata on Great Barrier Island/Aotea, and for Te Hauturu-o-Toi/Little Barrier Island. Including burrow density estimates for these remaining occupied habitats on both islands in the population demographic model recommended by Richard et al. (2017) will allow Fisheries New Zealand to produce the most robust and accurate global population estimate of this species, and in turn will eliminate or minimise several sources of uncertainty inherent in many of the previous population estimates that have been generated to date.

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6. APPENDICES

6.1 Summary of GPS deployments during Incubation 2019 (continued on next page)

Burrow	Band no.	Sex	Complete Track	Trip Length (km)	Maximum Range from GBI (km)	Trip Duration (days)	Δ Weight (g)	Δ Weight (%)	Chick Status May	Flight	Forage	Rest	Notes
1	41592	F	y	8114	2872	15	-	-	Fledged	75%	12%	12%	Removal weight not recorded
3	35298	F	-				-	-	Fledged				Removed before departure
6	33540	F	n	3025	633	10	-	-	Failed (egg)	56%	16%	28%	Removal weight not recorded
10	34401	F	y	2379	777	7	-60	-7.9%	Failed (chick)	33%	12%	55%	
10	36396	M	y	3460	901	7	30	4.0%	Failed (chick)	69%	12%	18%	
12	42890	F	n				10	1.3%	Fledged				GPS failed. No tracks
16	36372	F	y	6170	1580	14	-10	-1.3%	Fledged	54%	18%	28%	
21	41488	F	-				-80	-11.4%	Fledged				Dropped below weight threshold
31	41562	F	n				-50	-7.4%	Fledged				GPS failed. No tracks
42	41472	F	-				-	-	Fledged				Dropped below weight threshold
45	39441	M	y	1686	288	4	-	-	Failed (egg)	60%	14%	26%	Removal weight not recorded
50	33747	F	y	10275	2538	16	-10	-1.3%	Fledged	71%	14%	15%	
67	34255	F	y	6674	1041	17	40	5.3%	Fledged	52%	16%	31%	
69	39515	M	-				-	-	Fledged				Dropped below weight threshold
70	27604	M	y	4226	519	10	80	10.3%	Failed (unknown)	57%	11%	32%	
76	37572	F	n				-40	-5.1%	Fledged				GPS failed. No tracks
77	28390	F	n	10479	1254	26	50	6.9%	Fledged	60%	19%	21%	
77	36354	M	-				-	-	Fledged				Dropped below weight threshold
83	42076	M	y	3800	601	8	50	6.8%	Fledged	62%	16%	22%	
93	42075	F	y	5764	979	15	40	5.1%	Fledged	55%	16%	29%	
94	42881	F	y	4738	1206	6	-20	-2.7%	Fledged	78%	10%	12%	
102	36397	F	n				-	-	Fledged				GPS failed. No tracks
107	42947	F	n	5608	1829	18	-	-	Failed (egg)	50%	20%	29%	Removal weight not recorded

110	33654	M	n				-20	-2.7%	Fledged				GPS failed. No tracks
140	29809	M	y	3166	689	9	130	17.6%	Fledged	53%	15%	32%	
140	36179	F	y	8635	2519	16	115	15.9%		67%	16%	17%	
147	34903	M	y	3167	821	7	80	9.5%	Fledged	64%	18%	18%	
171	36346	F	y	2955	828	5	-120	-17.1%	Fledged	69%	11%	20%	
203	35233 (trip 1)	F	y	522	99	2	-50	-6.7%	Fledged				No saltwater immersion data
	35233 (trip 2)		y	2651	743	6				52%	14%	34%	
	30930	M	-				-	-					Removed before departure
204	35399 (trip 1)	M	y	1218	189	3	-70	-9.1%	Failed (chick)	54%	13%	33%	
	35399 (trip 2)		y	4391	965	10				50%	18%	33%	
	35399 (trip 3)		y	1397	221	5				33%	15%	53%	
212	35459	F	n				-20	-2.6%	Failed (chick)				GPS failed. No tracks
270	37510	F	-				-	-	Fledged				Dropped below weight threshold
271	37571	F	y	8355	1988	14	150	22.7%	Fledged	69%	15%	16%	
295	37615	F	-			30+	-	-	Failed (egg)				Bird did not return
309	33476	M	n				50	7.1%	Failed (egg)				GPS failed. No tracks
355	33467	M	y	2133	409	9	160	24.2%	Fledged	23%	11%	66%	
358	33474	F	y	2443	420	8	130	19.4%	Fledged	42%	14%	44%	
364	34854	M	n				60	8.2%	Fledged				GPS failed. No tracks
367	38628	M	y	4865	869	12	90	11.8%	Fledged	54%	18%	28%	
	39751	F	-				-	-					Removed before departure
391	28377	F	n				80	10.8%	Fledged				GPS failed. No tracks
397	41780	F	-			28+	-	-	Fledged				Bird did not return
434	42908	F	y	4578	846	10	-20	-2.6%	Failed (egg)	47%	13%	41%	
	42924	M	-				-	-					Dropped below weight threshold
Extra	35419	F	y	6190	1218	22	30	4.1%	Failed (unknown)	36%	21%	43%	

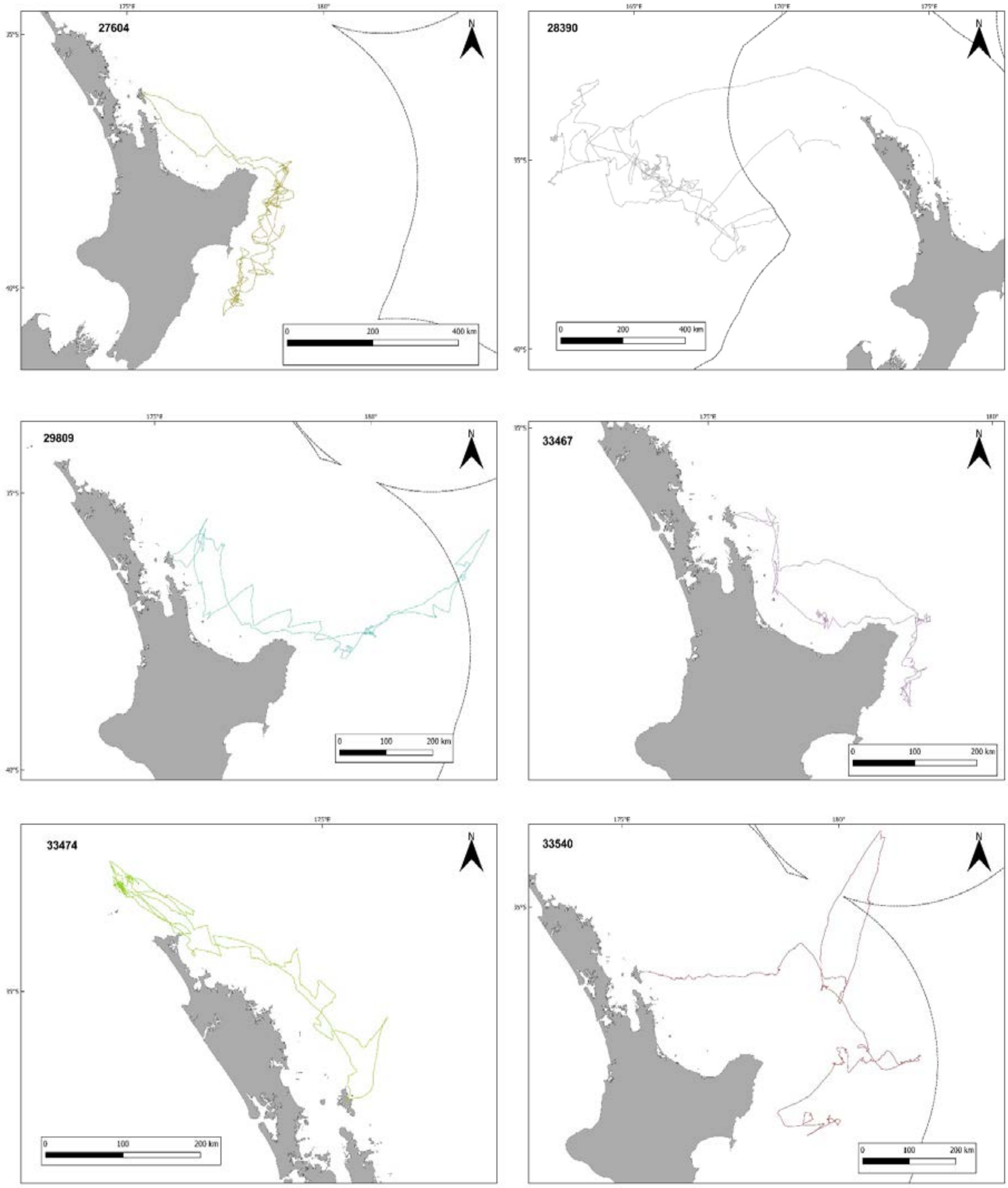
6.2 Summary of GPS deployments during chick-rearing 2018 (continued on next page)

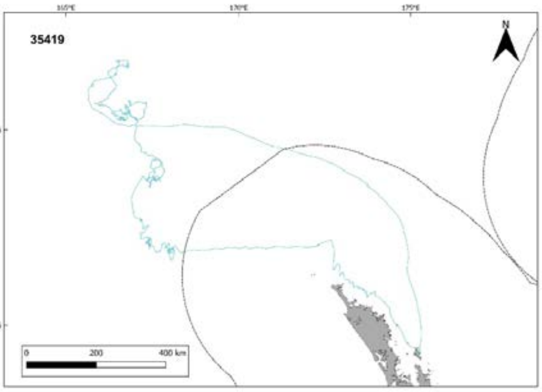
Burrow	Band no.	Sex	Complete Track	Discarded from analysis	Trip Length (km)	Maximum Range from GBI (km)	Trip Duration (days)	Δ Weight (g)	Δ Weight (%)	Notes	Chick Status in May
16	36372	F	Y	N	1420	544	3	0	0.0%		Fledged
16	42885	M	Y	N	7651	1353	14	95	15.0%		
17	38624	F	Y	N	9437	2902	16	-5	-0.8%		Fledged
27	41883 (trip 1)	F	Y	N	976	174	2	75	11.8%		Fledged
27	41883 (trip 2)	F	Y	Y	367	142	1				
49	36322 (trip 1)	M	Y	N	876	151	2	-15	-2.0%		Fledged
49	36322 (trip 2)	M	Y	N	3383	647	6				
68	35315 (trip 1)	M	Y	N	2267	615	4	35	5.5%		Dead
68	35315 (trip 2)	M	Y	N	1220	415	2				
68	42062	F	N	Y			24+			Tracked adult not recaptured	
70	27604	M	N	N	2079	499	6	-15	-2.1%		Fledged
70	31240	F	Y	N	7437	1971	15	105	17.6%		
81	28370	F	N	N	4504	1622	9	40	6.7%		Fledged
81	28046 (trip 1)	M	Y	N	2670	469	5	5	0.7%		
81	28046 (trip 2)	M	Y	N	1612	221	4				
101	42026	F	N	Y			28+			Tracked adult not recaptured	Fledged
102	33389	M	Y	N	5769	1487	14	40	6.2%		Fledged
102	36397 (trip 1)	F	Y	N	4201	1653	4	50	7.8%		
102	36397 (trip 2)	F	Y	Y	282	108	1				
110	33654	M	Y	N	7317	1699	12	85	13.2%		Fledged
112	28037	M	Y	N	2913	454	7	70	10.4%		Fledged
192	35187	M	Y	N	2563	430	7	200	31.3%		Fledged
192	39615	F	N	Y			26+			Tracked adult not recaptured	
201	38705	M	Y	N	4840	768	9	75	11.3%		Fledged
210	35151	M	N	N	519	439	11	35	6.0%		Dead
211	41471 (trip 1)	M	Y	N	1526	398	5	-15	-2.0%		Fledged

211	41471 (trip 2)	M	Y	Y	470	207	1				
257	38915	F	Y	N	825	300	2	30	4.7%		Fledged
278	36419	M	N	N			22	15	2.2%	GPS Failed	Fledged
278	39541	F	N	N	7788	749	22			Returned weight not recorded	
280	41470	F	Y	N	2862	992	6	45	7.0%		Fledged
281	32995 (trip 1)	M	Y	N	1467	165	3	-45	-6.0%		Dead
281	32995 (trip 2)	M	Y	N	4114	445	11				
286	42946	M	N	N	2711	1719	15	25	3.8%		Fledged
286	41466	F	N	Y				20+		Tracked adult, not recaptured	
294	36185	M	Y	N	1116	256	3	45	6.6%		Fledged
300	42078	F	Y	N	1252	344	2	-55	-8.0%		Fledged
304	36209 (trip 2)	M	Y	Y	160	69	1	-35	-4.9%		Fledged
304	36209 (trip 1)	M	Y	N	3325	897	6				
315	33714	M	N	N			11			GPS Failed. Returned weight not recorded	Fledged
335	34379	F	N	Y			25+			Tracked adult not recaptured	Dead
335	28358	M	Y	N	5737	992	17	45	7.0%		
364	34854	M	Y	N	1420	164	3	-75	-10.1%		Fledged
364	38598	F	Y	N	5834	1143	13	0	0.0%		
372	41523	M	Y	N	2678	390	8	-35	-4.6%		Fledged
372	42903	F	Y	N	4891	1412	9	60	9.1%		
Extra	35419	F	Y	N	7865	2131	19	55	8.7%		Fledged
Extra	35597	M	Y	N	4798	1091	7	20	3.0%		

6.3 Individual GPS tracks – Incubation 2019

Note that the scale bars differ for some figures. The figures for 35233 and 35399 contain multiple foraging trips by the same individual. The dashed line seen in some figures represents the New Zealand EEZ.

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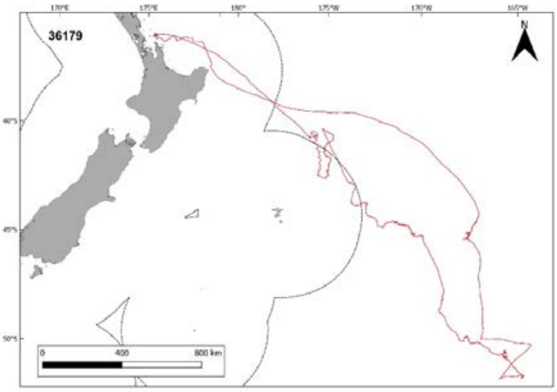
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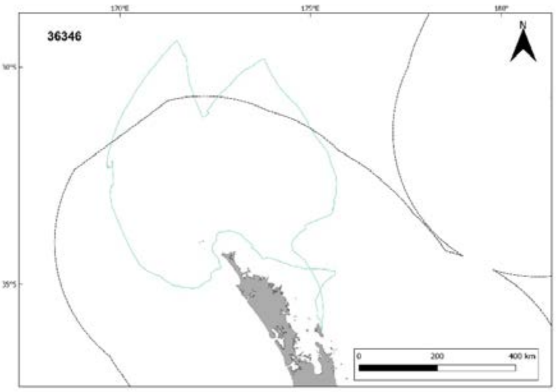
N
0 400 800 km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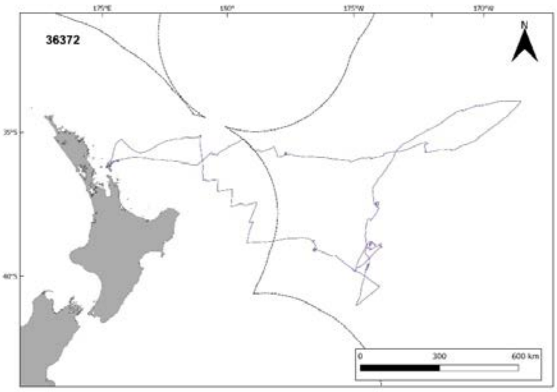
N
0 200 400 km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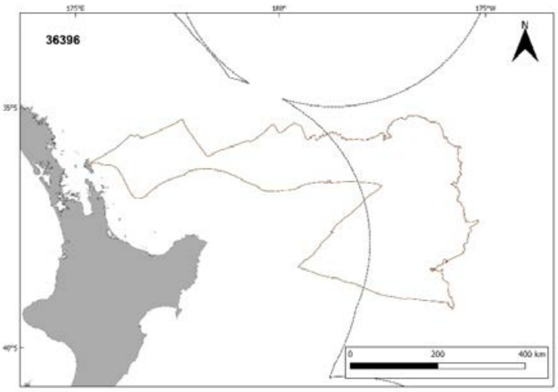
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N
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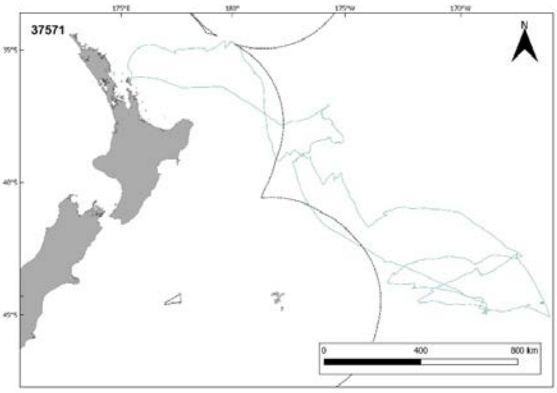
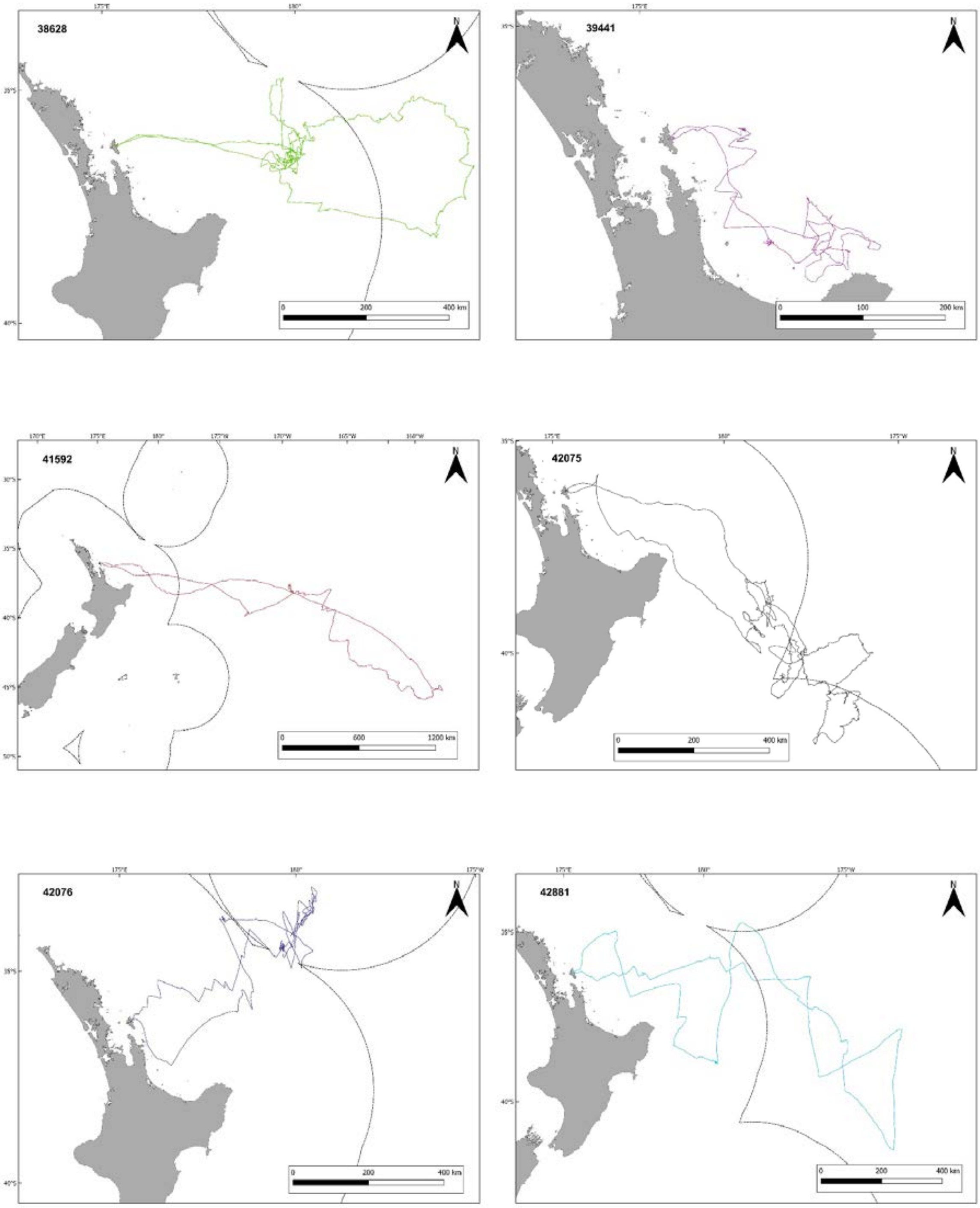

37571
N
0 400 800 km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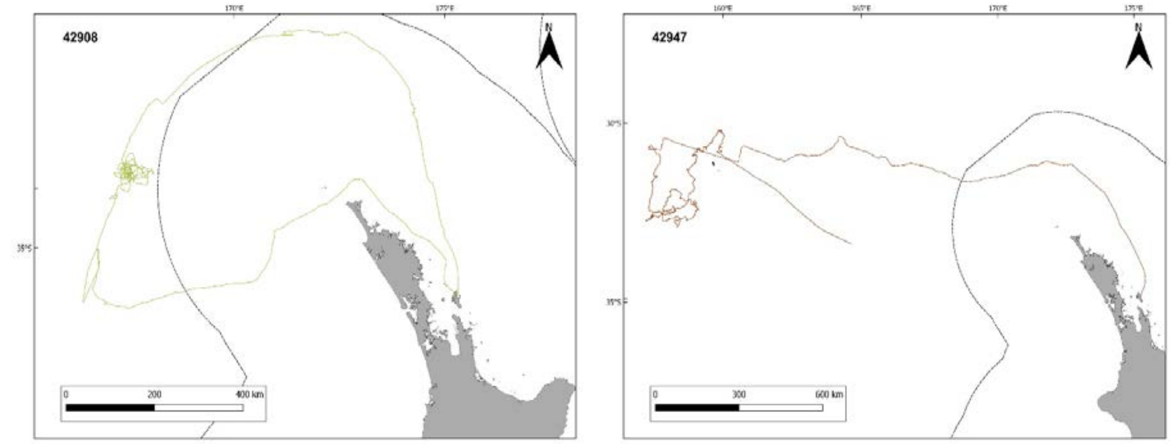
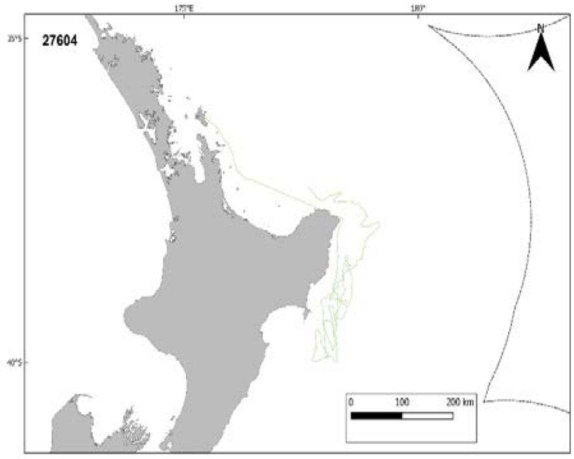
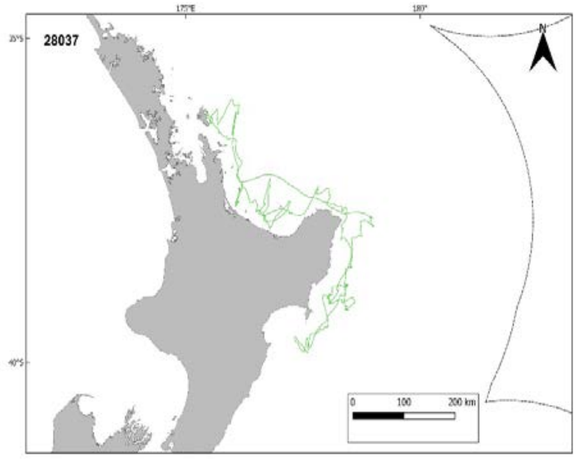
39441
41592
42075
42076
42881

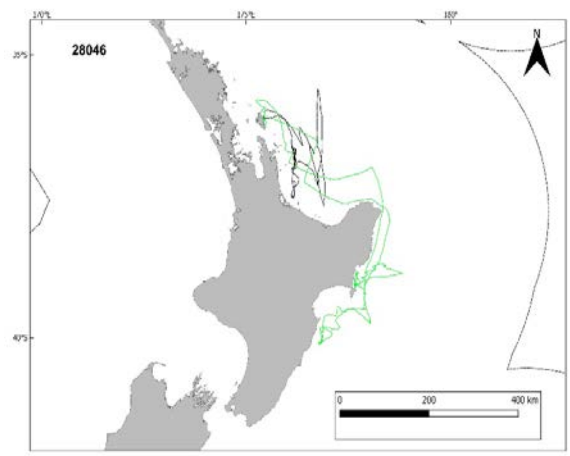

42908
170°E
175°E
35°S
N
0
200
400 km
42947
160°E
165°E
170°E
175°E
30°S
35°S
N
0
300
600 km

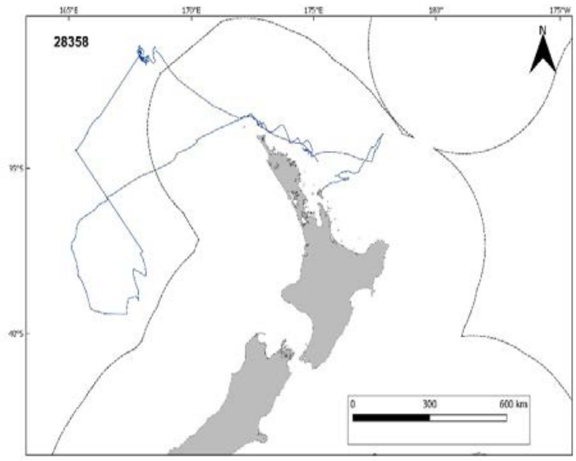
6.4 Individual GPS tracks – Chick rearing 2018

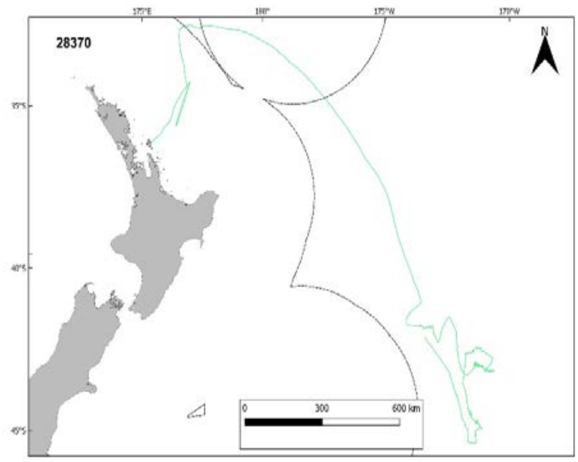
Note that the scale bars differ for some figures. The figures for 28046, 32995, 35315, and 36322 contain multiple foraging trips by the same individual. The dashed line seen in some figures represents the New Zealand EEZ.

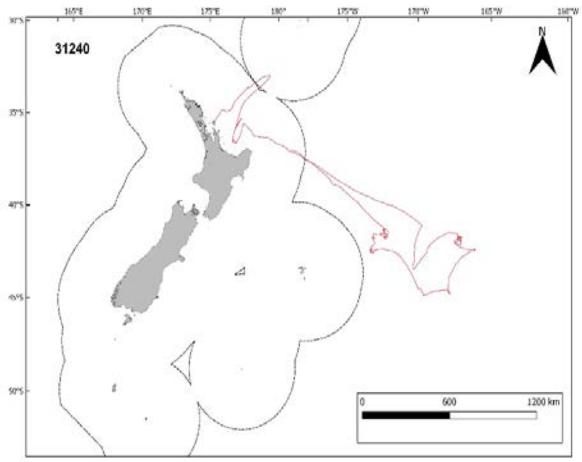


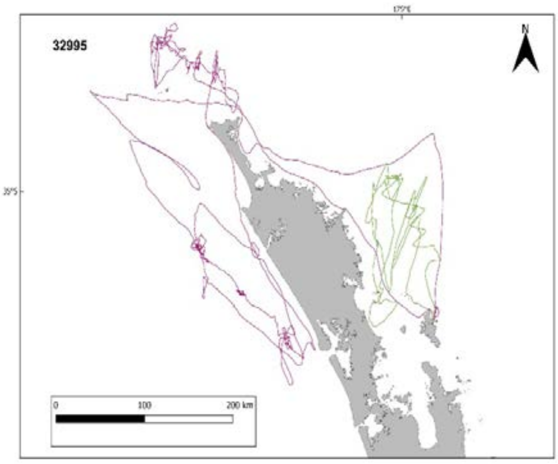


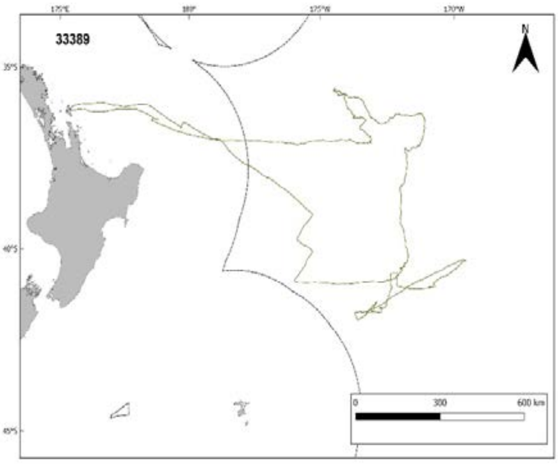


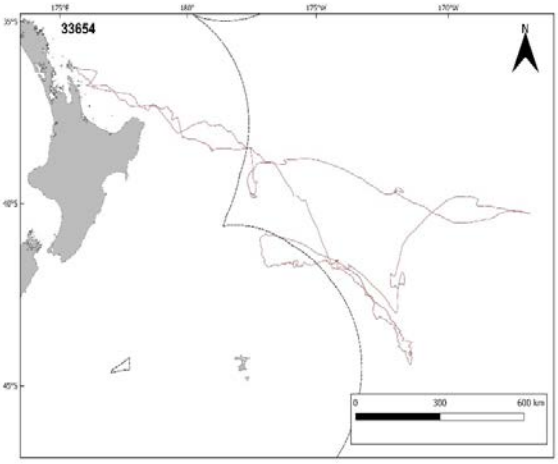


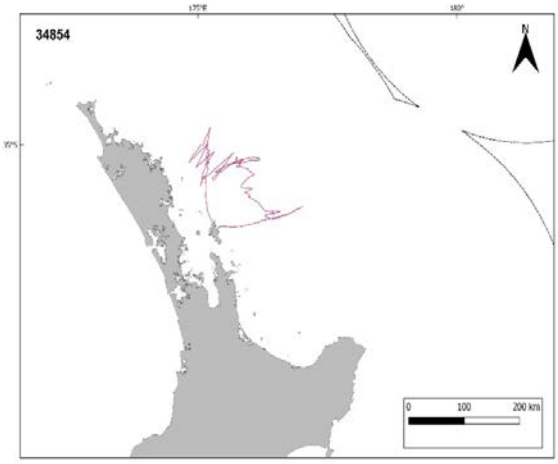


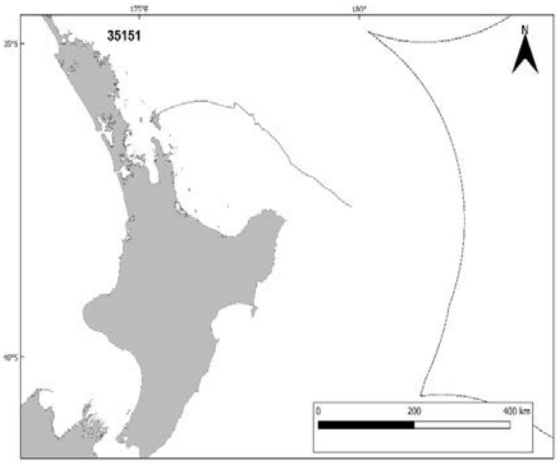


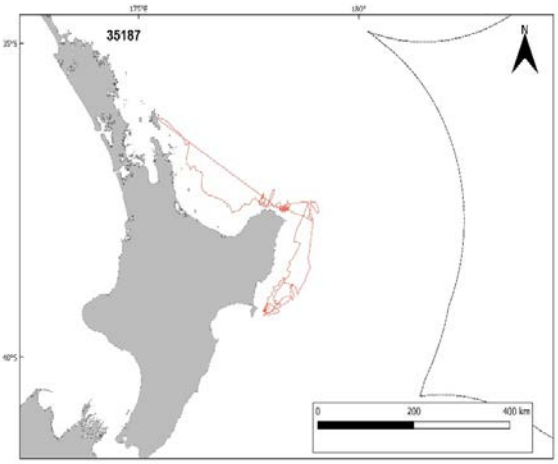

32995
N
0
100
200 km

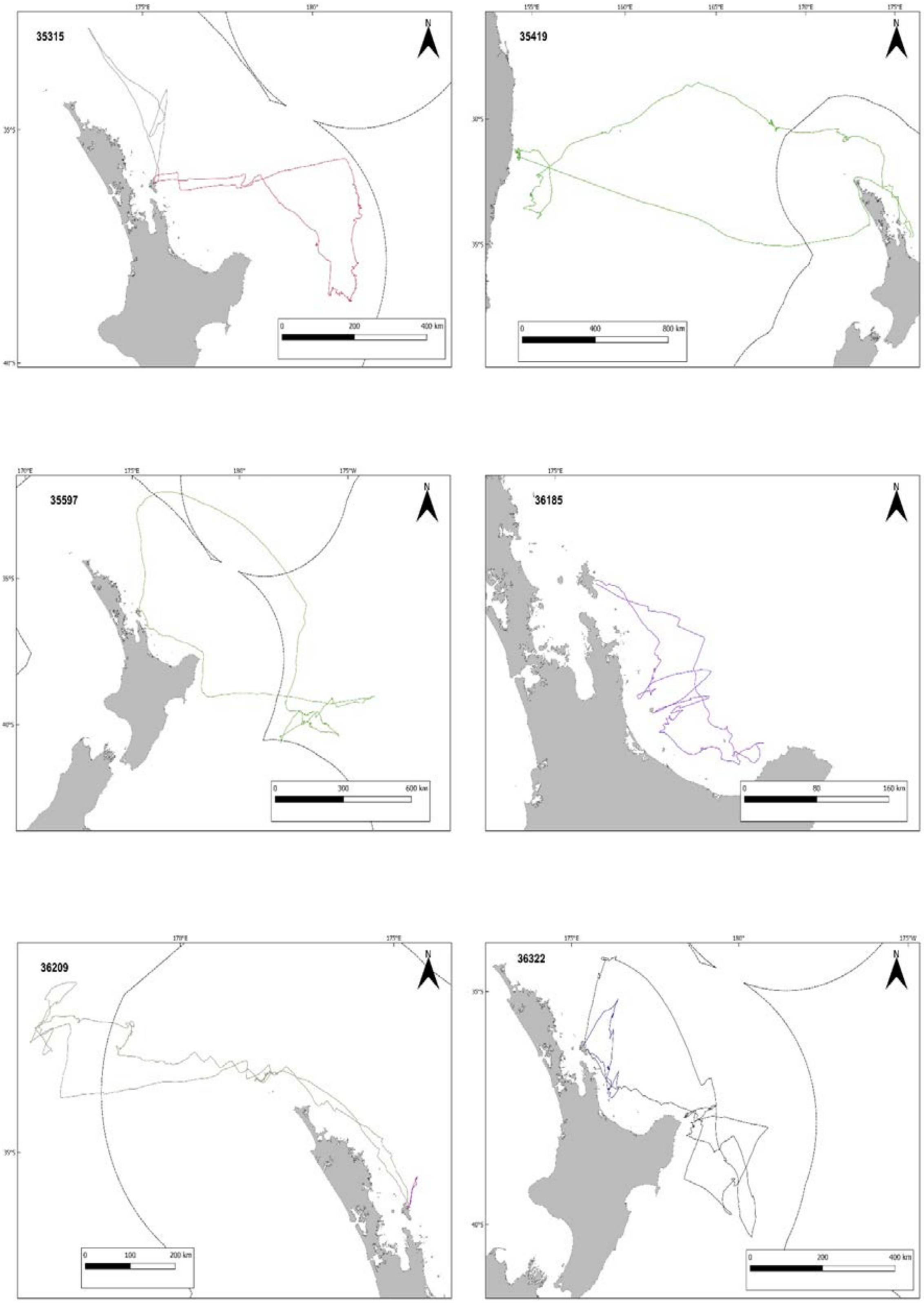

33389
N
0
300
600 km


33654
N
0
300
600 km

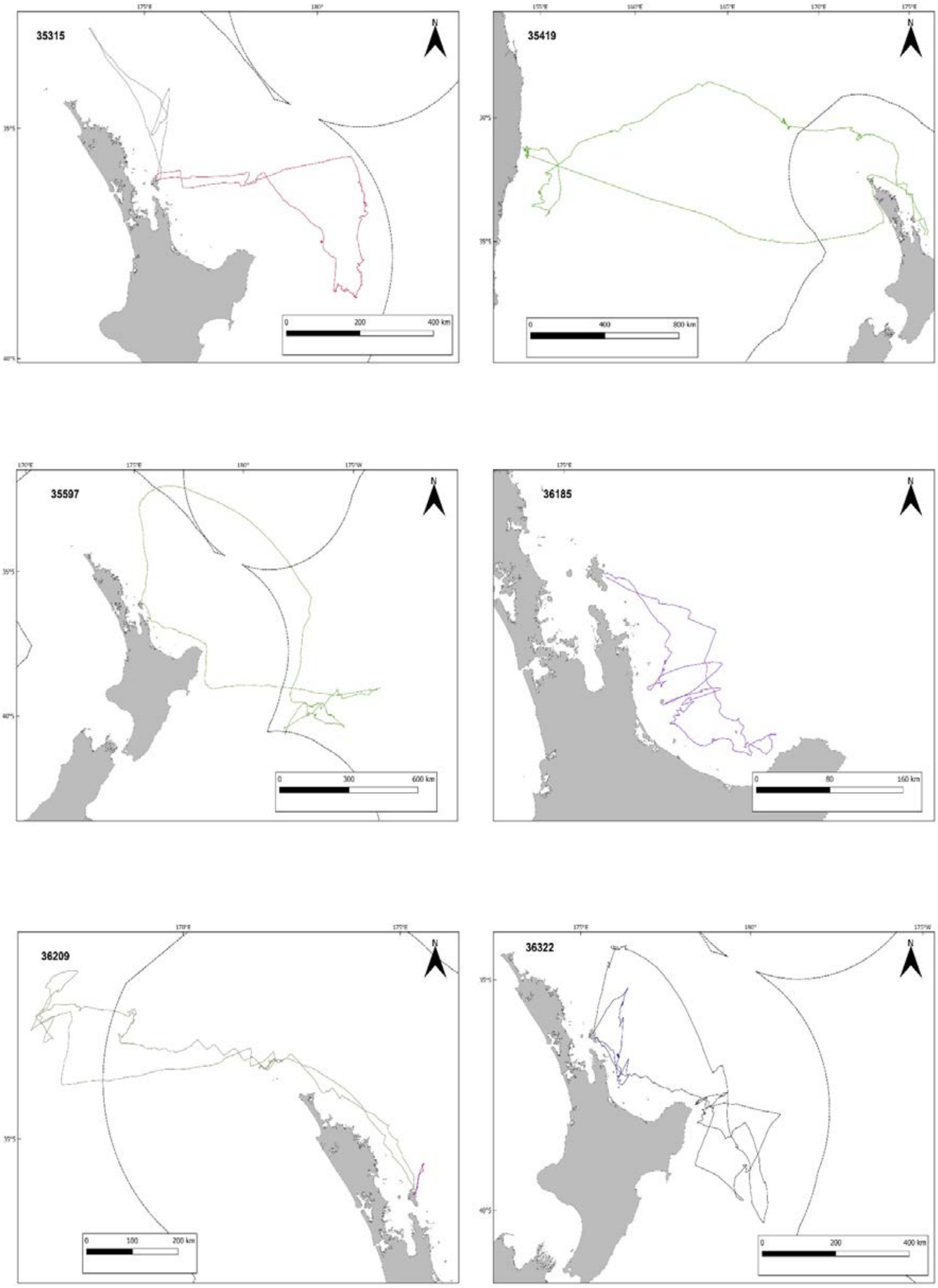

34854
N
0
100
200 km

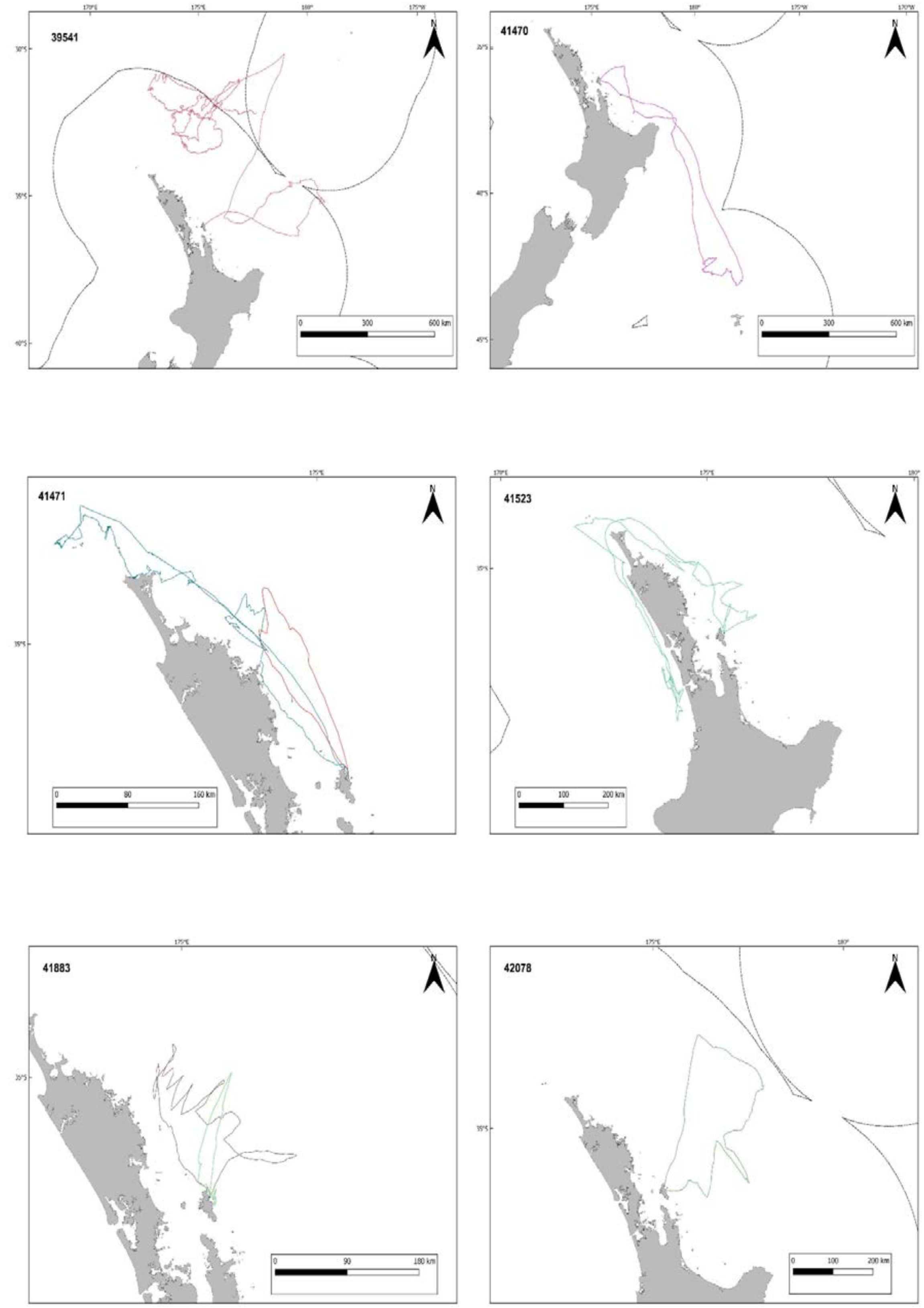

35151
N
0
200
400 km

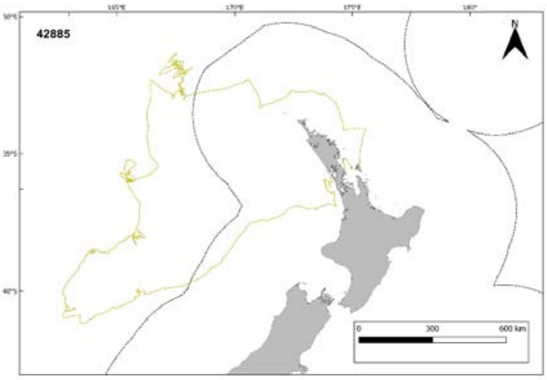

35187
N
0
200
400 km

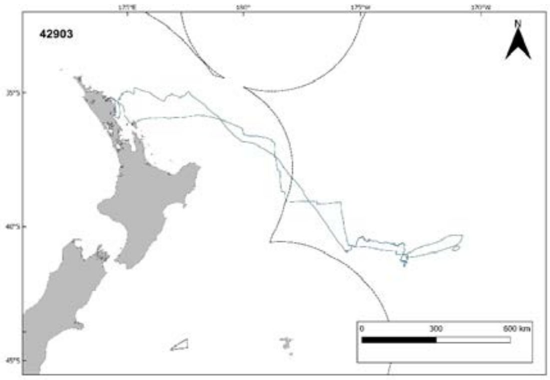


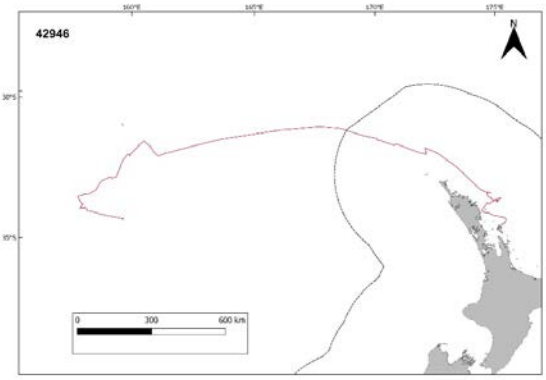
35315
35419
35597
36185
36209
36322


35315
0 200 400 km
35419
0 400 800 km
35597
0 300 600 km
36185
0 80 160 km
36209
0 100 200 km
36322
0 200 400 km


39541
0 300 600 km
41470
0 300 600 km
41471
0 80 160 km
41523
0 100 200 km
41883
0 90 180 km
42078
0 100 200 km

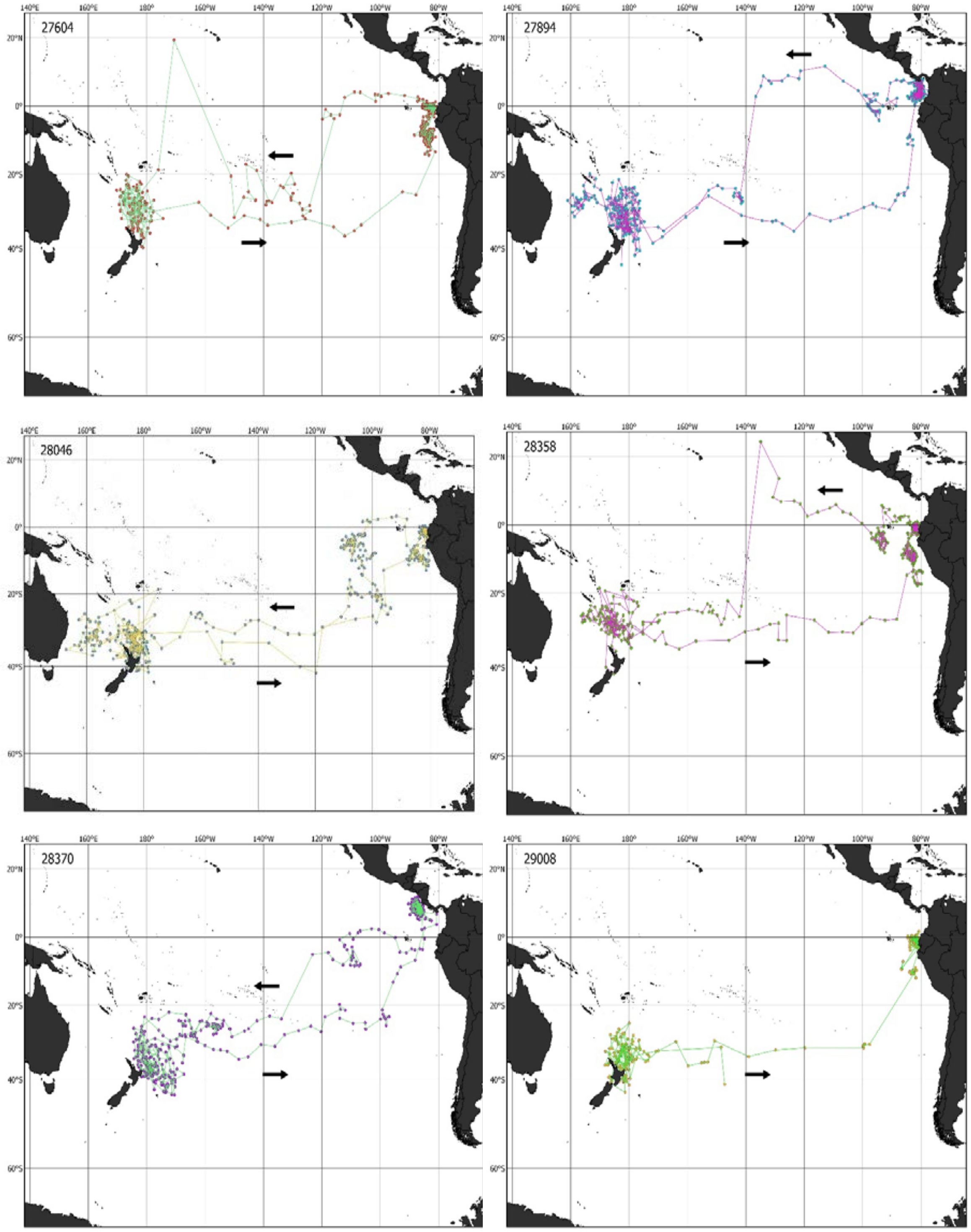

42885
N
0
300
600 km

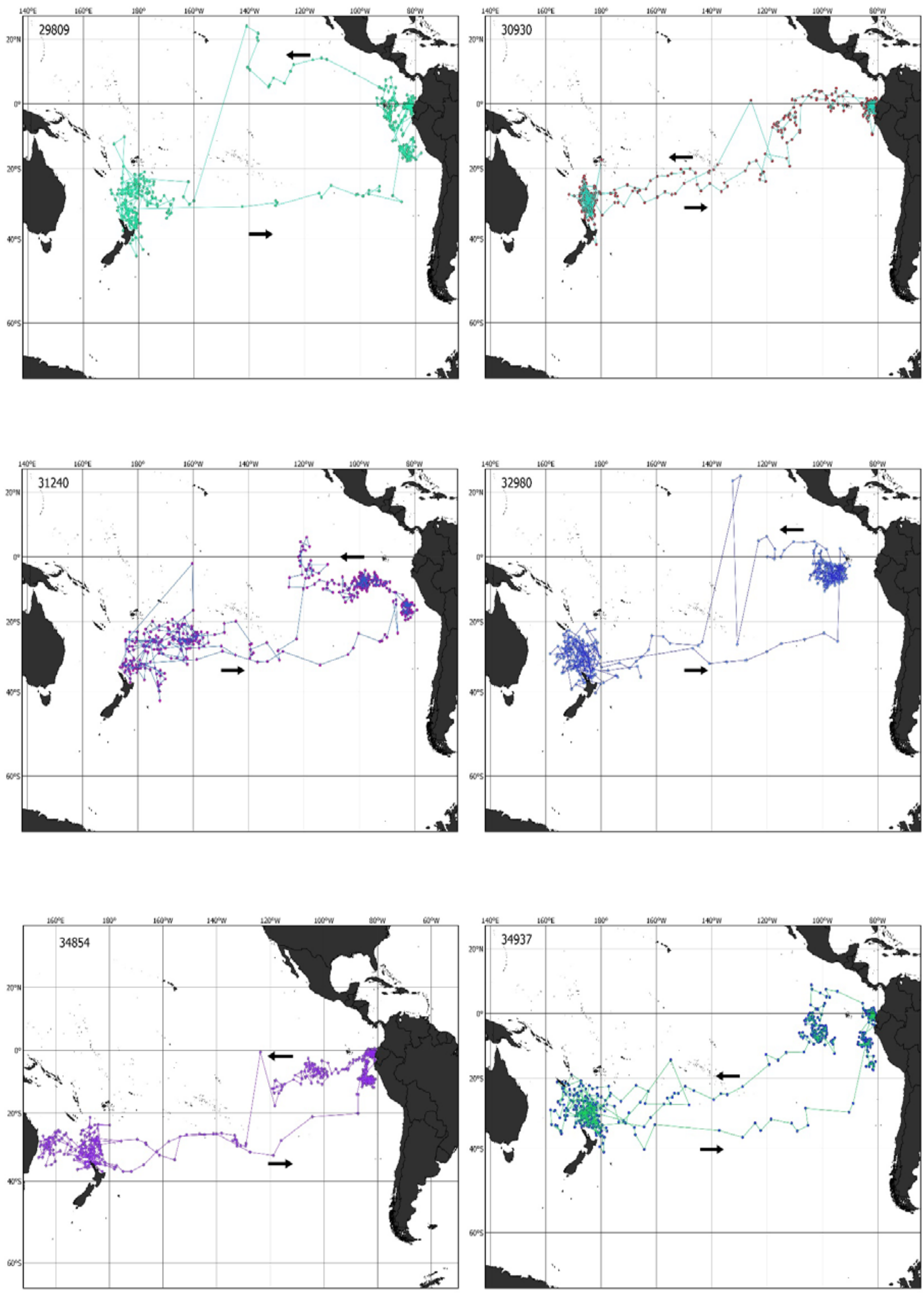

42903
N
0
300
600 km

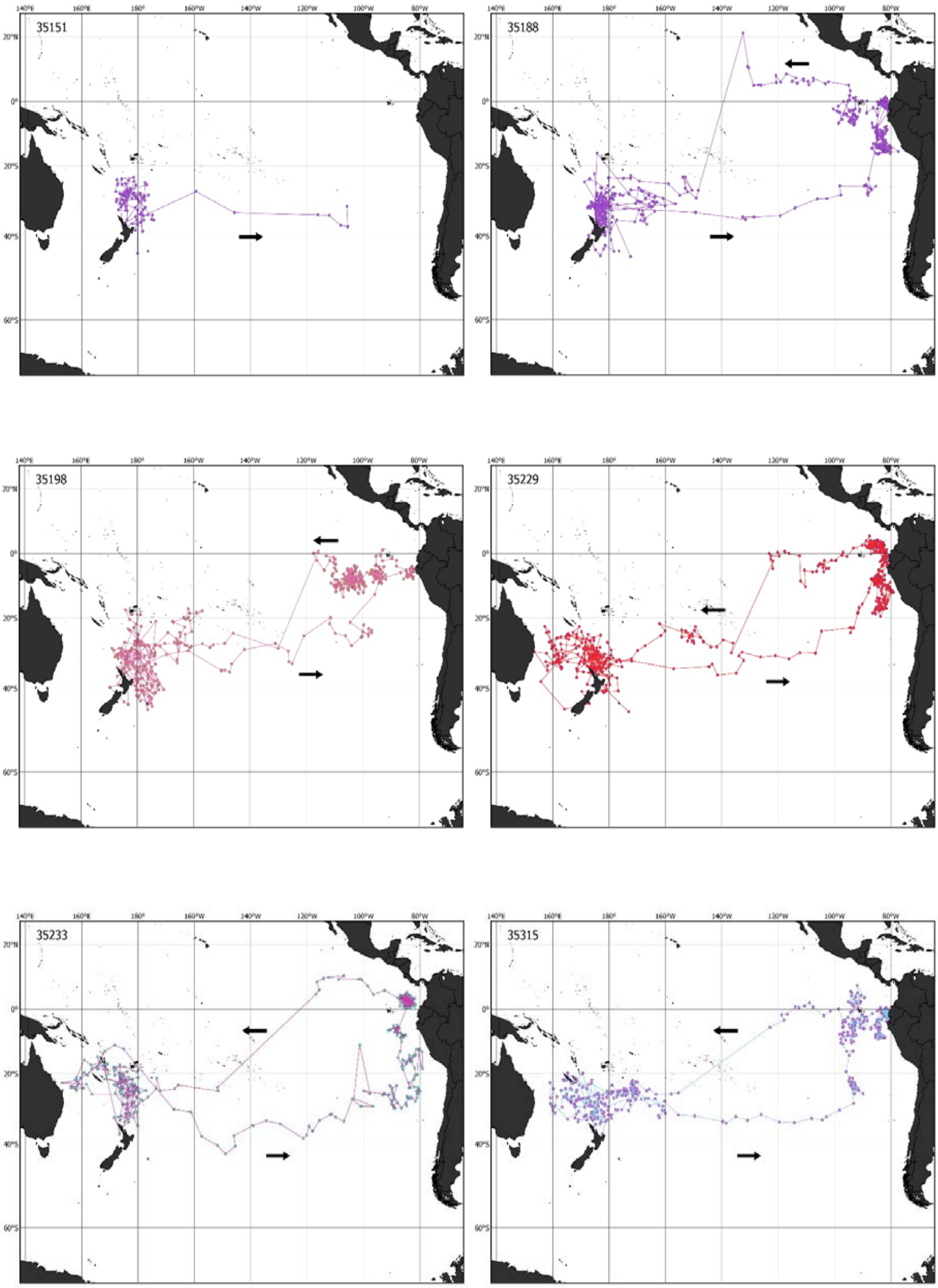

42946
N
0
300
600 km

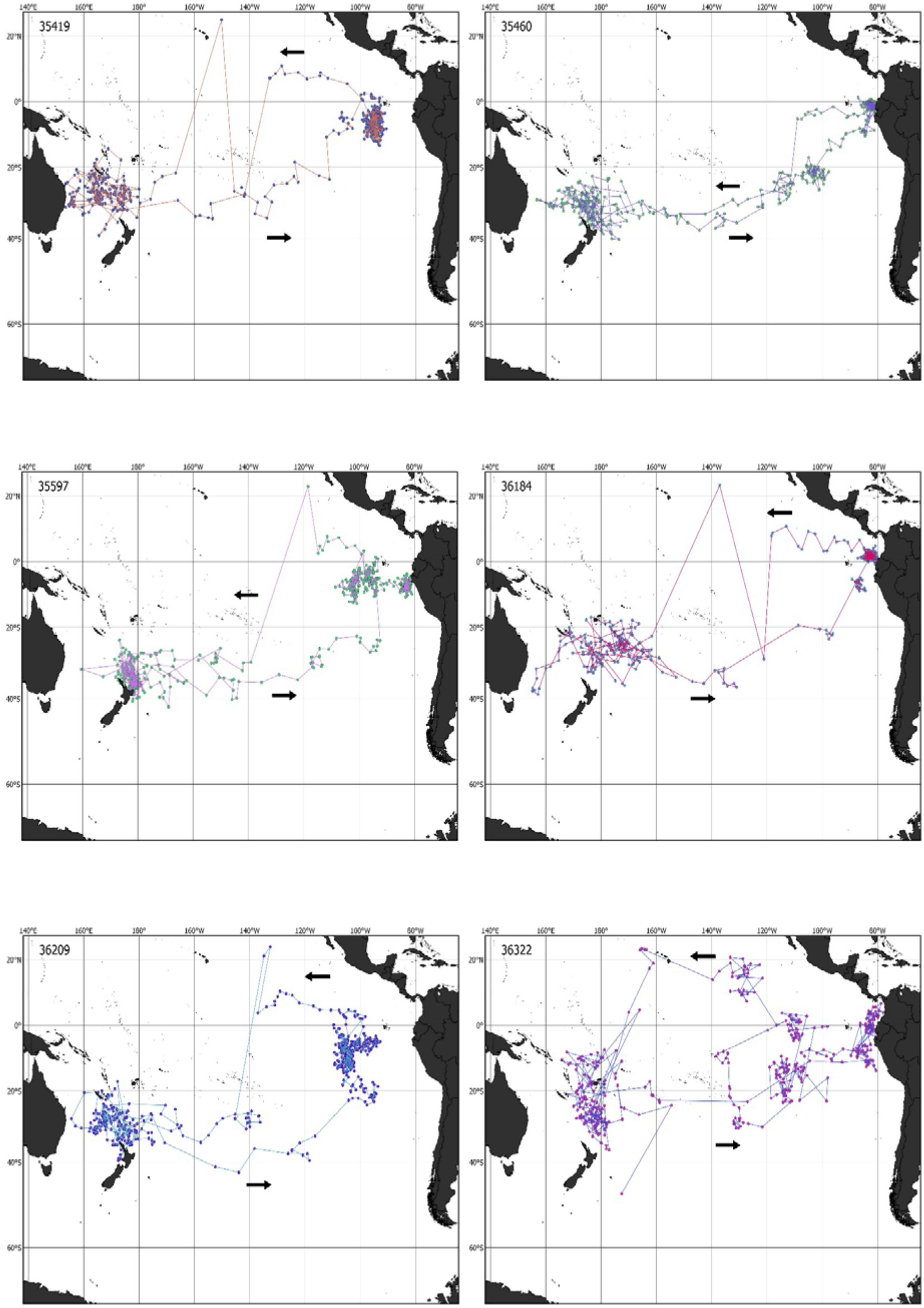
6.5 Individual GLS tracks

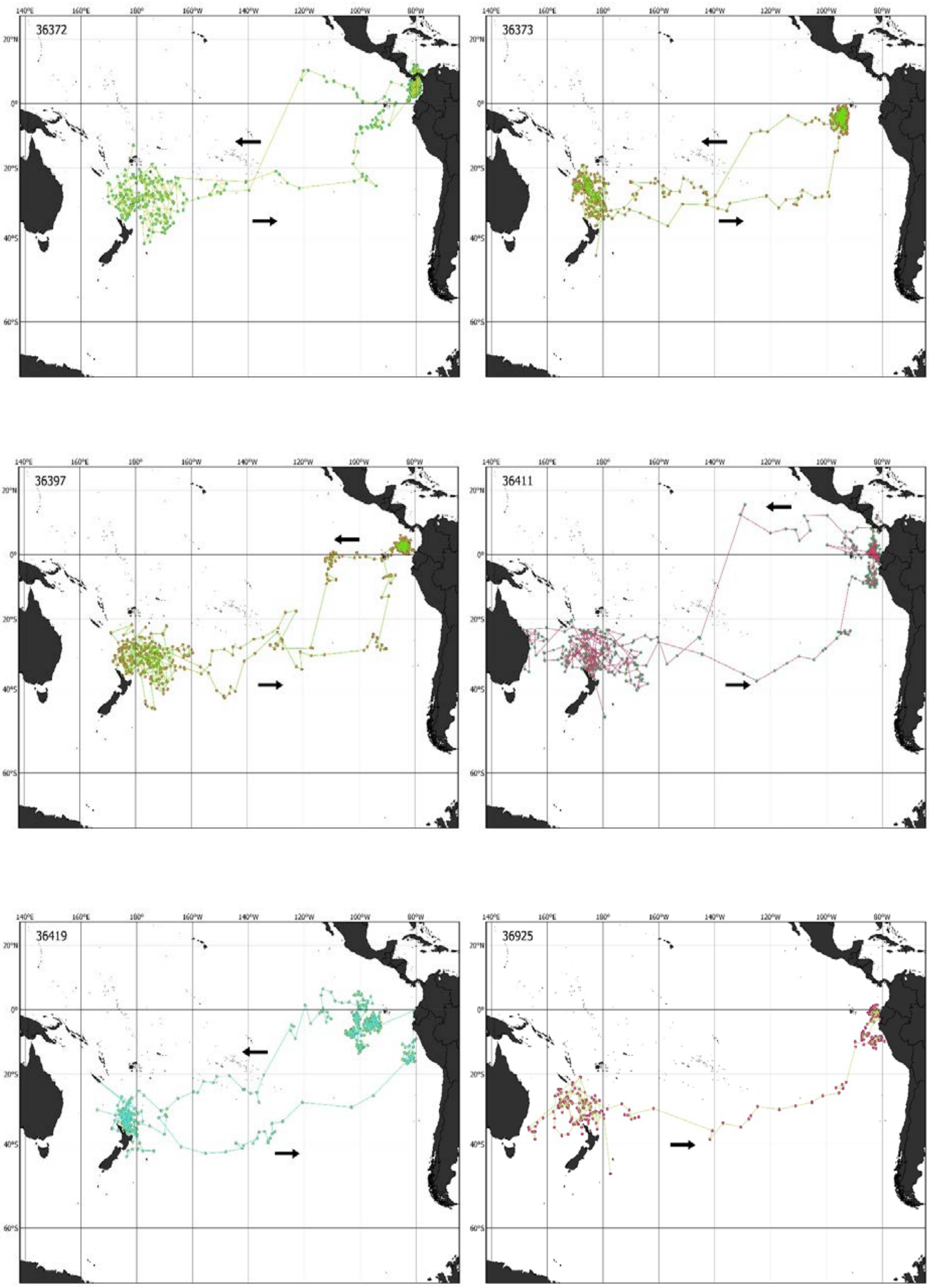
Arrows on maps indicate the direction of travel (departing track and returning track).

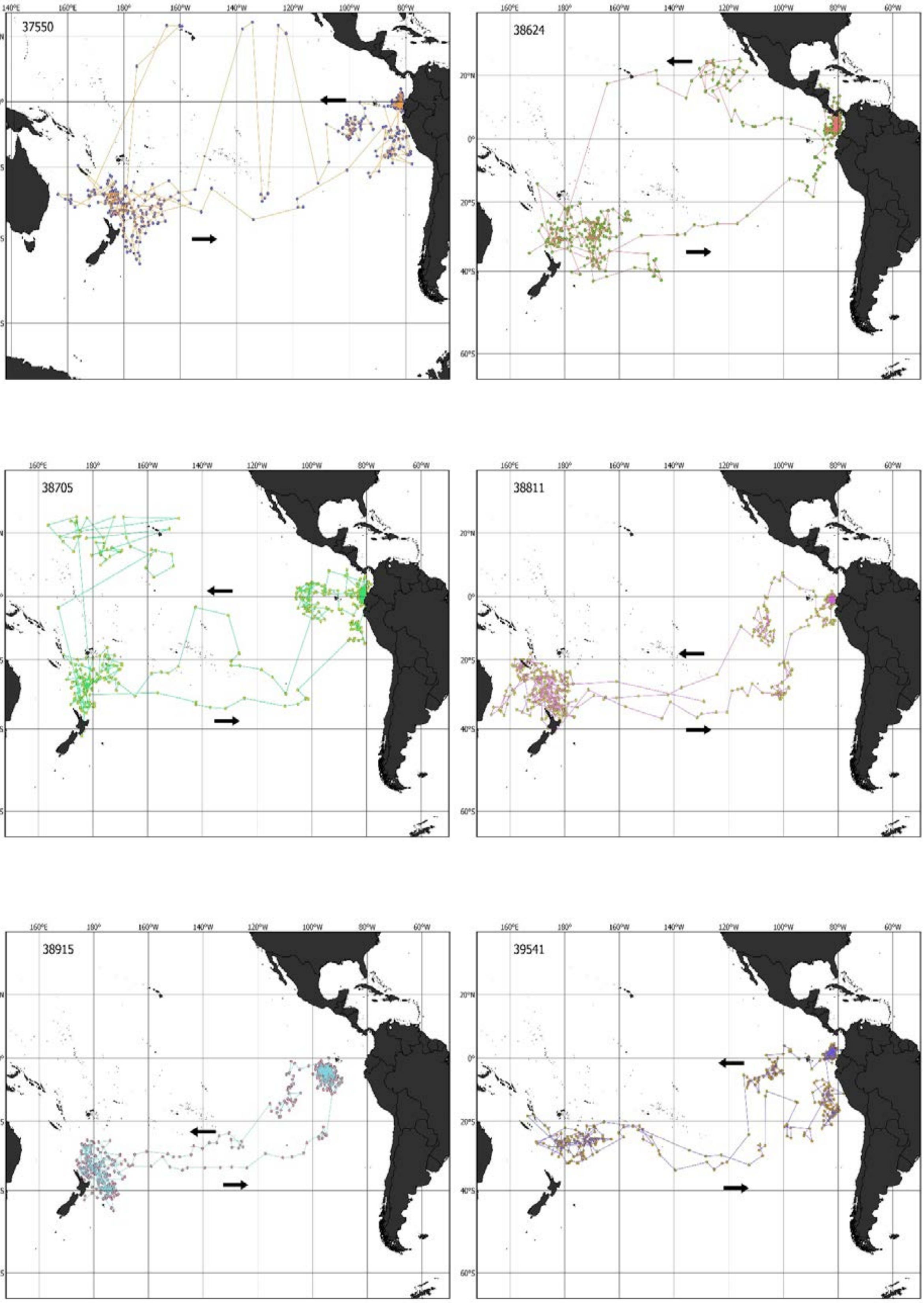


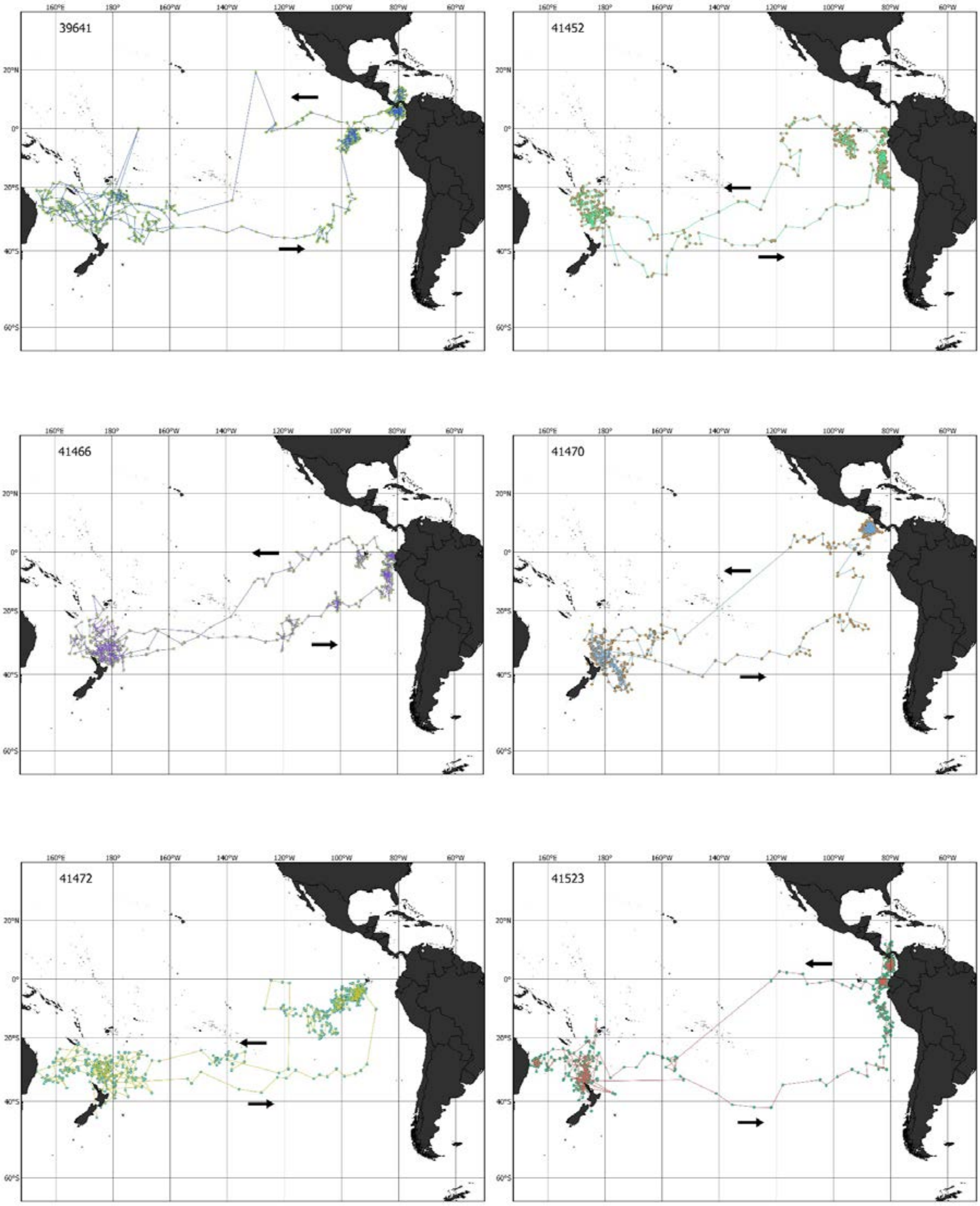

29809
30930
31240
32980
34854
34937

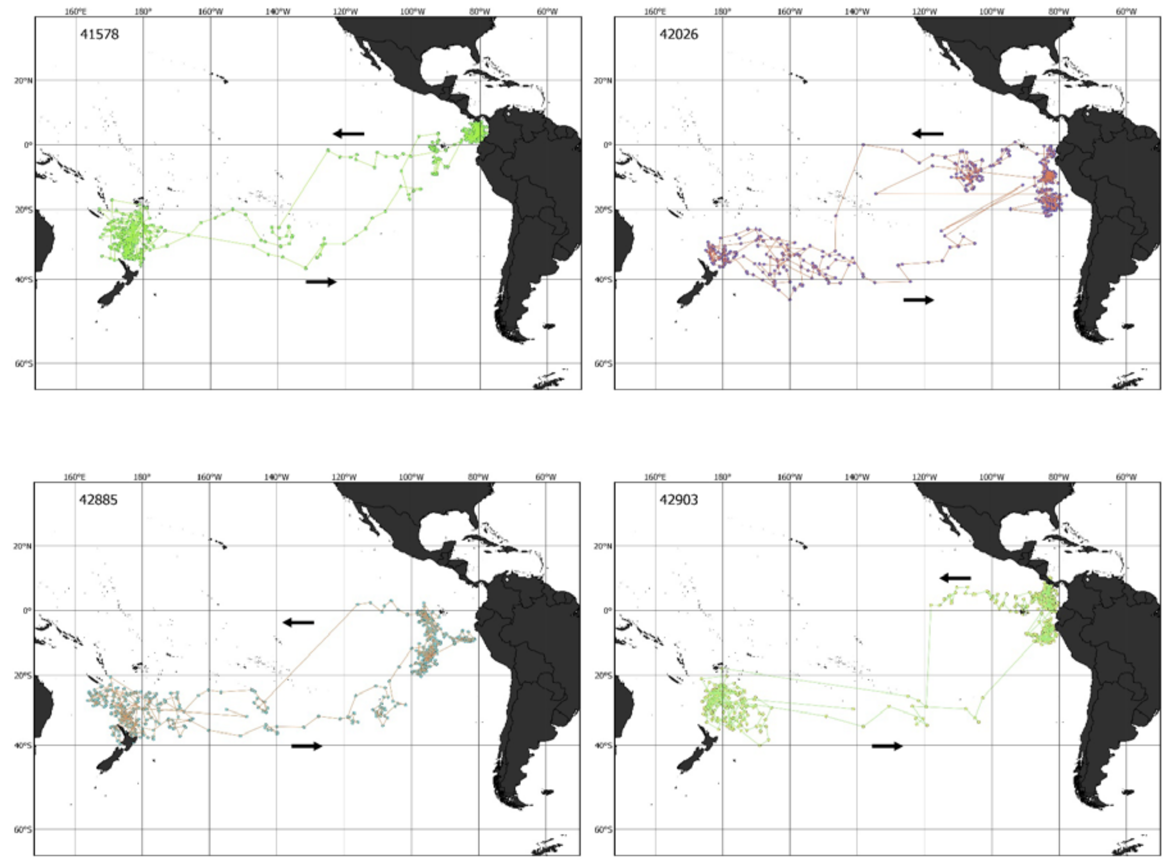

35151
35188
35198
35229
35233
35315
140°E
160°E
180°
160°W
140°W
120°W
100°W
80°W
20°N
0°
20°S
40°S
60°S


35419
35460
35597
36184
36209
36322
140°E
160°E
180°
160°W
140°W
120°W
100°W
80°W
20°N
0°
20°S
40°S
60°S


36372
36373
36397
36411
36419
36925
140°E
160°E
180°
160°W
140°W
120°W
100°W
80°W
20°N
0°
20°S
40°S
60°S


37550
38624
38705
38811
38915
39541


39641
41452
41466
41470
41472
41523
160°E
180°
160°W
140°W
120°W
100°W
80°W
60°W
20°N
0°
20°S
40°S
60°S


41578
42026
42885
42903
160°E
180°
160°W
140°W
120°W
100°W
80°W
60°W
20°N
0°
20°S
40°S
60°S

6.6 GLS device-related injury to the leg of a black petrel

This damage to an individual black petrel's leg occurred as a result of wearing one of the GLS devices for 10 months to track its winter migration. The band with attached GLS caused a large, raw callus near the ankle. The band and GLS became wedged in place and started cutting into the leg where the upper margin of the band meets the leg (photo is after GLS was removed and the band was shifted up the leg from where it was wedged). The skin was not broken, and because we'd removed the GLS that was almost certainly causing the problem, we opted to leave the band on the bird, but left it on the upper tarsus to hopefully give the swelling and rawness some time to subside.