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BRIEF REPORT

Larger foraging area means greater fisheries interaction risk for juvenile yellow-eyed penguins in their sub-Antarctic range

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Abstract

Seabird foraging success is crucial for individual survival and therefore also for recruitment, breeding success, and population stability. However, there is limited information on the movements of juvenile seabirds, including penguins. This study investigates the foraging range of juvenile yellow-eyed penguins from Enderby Island, in the sub-Antarctic Auckland Islands, and their overlap with protected areas where commercial fishing is prohibited. Two juvenile penguins were tracked using GPS-Argos tags, and their movements were compared to those of breeding adults. Juveniles travelled up to 275.2 km from the colony, significantly farther than the maximum 46.7 km for breeding adults. Juveniles also used a much larger foraging area of 18,027 km^2, compared to 738 km^2 for adults. Only 7% of juvenile foraging occurred within the protected area, highlighting their potential vulnerability to commercial fishing activities. Juveniles had a 17% overlap with commercial fishing areas, compared to 4% for adults. The extensive foraging range and low overlap with protected areas suggest that juveniles are at higher risk of encountering threats, which may contribute to higher mortality rates. These findings underscore the need for conservation efforts to investigate and address threats in the broader foraging areas used by juveniles. Future research should track additional juvenile penguins and study prey availability to support effective conservation strategies for this endangered species.

Keywords GPS · Home range · Kernel density · Marine protected area

Introduction

Seabird foraging success is an important predictor of breeding success (Boersma et al. 2020), and foraging range and location are important considerations when determining resource partitioning and overlap with marine threats (Diamond and Devlin 2003). Foraging success and survival can be negatively affected by factors including prey availability, individual breeders' performance, and direct threats such as disease, predation, and fisheries interactions. Juvenile survival affects recruitment, and high juvenile mortality can therefore cause population instability or decline (Diamond and Devlin 2003; McClung et al. 2004). However, research focus is often on breeding adults, and there is a general lack of location data available on the movements of juvenile penguins and other seabirds around the world (Boersma et al. 2020).

The endangered yellow-eyed penguin (hoiho, *Megadyptes antipodes*) is found only around New Zealand, with separate northern (South Island and offshore islands) and southern (sub-Antarctic) breeding populations (Seddon et al. 2013). Age at first breeding is an average of 2.6 years in females and 4.3 years in males (Richdale 1957). Unlike breeding adults, juvenile yellow-eyed penguins are not considered to be central-place foragers (Seddon and Davis 1989).

The northern yellow-eyed penguin population has recently undergone a severe decline with a 75% reduction in nests on the Otago Peninsula since the 1990 s (Mattern et al. 2017) and the predicted extinction of the northern population within the next few decades (Mattern et al. 2017; Mattern and Wilson 2018). Threats are primarily at sea, including poor foraging success, interactions with commercial fisheries, pollution, and

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human disturbance (Couch-Lewis et al. 2016; Mattern et al. 2017; Mattern and Wilson 2018; Department of Conservation 2020). In the northern population, the median annual survival rate of juveniles in their first year is 12.4%, compared to 87.4% for breeding-age adults (Mattern et al. 2017). Low fledging weight can lead to decreased post-fledging survival rates (McClung et al. 2004), as underweight birds have fewer body reserves. As in many seabirds, juvenile penguins may be less successful at foraging than adults. They are generally smaller which can limit their diving ability (Saraux et al. 2012) and are usually less experienced at finding and obtaining food (Forslund and Pärt 1995), particularly in years of poor prey availability.

Knowledge of feeding locations, foraging success, and survival rates for juvenile yellow-eyed penguins are therefore important, but are lacking for many areas. Juvenile birds from Otago in the northern population travel 140 to 692 km north of their fledging area (Young et al. 2022). Little is known about dispersal from other breeding locations. Direct mortality due to fisheries bycatch is an ongoing problem (Ellenberg and Mattern 2012; Couch-Lewis et al. 2016; Mattern and Wilson 2018), as well as benthic habitat modification and competition with commercial fisheries (Browne et al. 2011; Mattern et al. 2013). Juveniles may be more prone to fisheries interactions due to their inexperience, and their larger foraging area which may make such interactions more likely.

The southern population is less-studied than the northern population, although at least 60–79% of the total population is estimated to breed there, making it an important breeding area for the species (Muller et al. 2020b). However, sub-Antarctic breeding success fluctuates (Muller et al. 2020b, 2024) and diving, foraging behaviour and diet of breeding adults also vary between years (Muller et al. 2020a, 2021, 2022), indicating possible fluctuations in prey availability. Adult breeding success also varies, likely as a result of prey availability and foraging success, amongst other factors (Muller et al. 2024). The area around the Auckland Islands is protected from commercial fishing within 12 nm (22.22 km) from shore, however, breeding adults do forage outside this area (Muller et al. 2021). There are no published data on juvenile foraging range for the southern population. The aims of this study were therefore (1) to investigate foraging range of juvenile yellow-eyed penguins in the sub-Antarctic and (2) to determine the extent of their range overlapping with the protected area versus that used by commercial fisheries.

Materials and methods

Fieldwork

Fieldwork was carried out in January 2017 (during the 2016–17 breeding season) on Enderby Island (Fig. 1), Auckland Islands (50°29′45″S 166°17′44″E, Fig. 2) in the New Zealand sub-Antarctic. Two juvenile yellow-eyed penguins were selected opportunistically in the vicinity of the breeding area known as Rocky Ramp (Muller et al. 2021). Juvenile birds were identified from their lack of yellow adult plumage and iris colour which is gained by the time they are 18 months old (Richdale 1949), making the study birds at least one year old, but under two years old. Their sexes were unknown since morphometric analysis is unreliable for sexing juveniles (Setiawan et al. 2004). Birds were captured by hand and placed in a capture bag for processing and collection of morphometric data using a spring balance and callipers, then were marked with a microchip (Allflex, Palmerston North, New Zealand) for permanent identification (Muller et al. 2020b). Tracking devices were attached to both birds on 13 January 2017. Trackers were custom-built Fastloc (fast-acquisition GPS) with download via Argos satellite, weight ~ 130 g, 95 mm long × 25 mm high × 40 mm wide, external antenna length 177 mm (Sirtrack, Havelock North, New Zealand). Trackers were attached using waterproof tape (TESA, Beiersdorf, Germany) to the lower back to optimise streamlining (Bannasch et al. 1994) and orientation to the sky during the typical posture adopted during swimming (Muller et al. 2020a). Both trackers were programmed to take fixes every 1 h, although this could vary due to the action of the wet/dry sensor. Foraging location and dive depth data were also collected from adult birds guarding chicks (breeding adults) in a parallel study (Muller et al. 2020a, 2021) and were used for comparison purposes. Since breeding adults utilised different foraging areas in 2016 and 2017 (Muller et al. 2021) data were combined from both seasons to indicate the maximum known extent of the area used.

Data analysis

Position data from GPS-Argos tags fitted to juveniles were filtered to leave only high-quality GPS positions (with Fastloc residuals < 35) and excluding all Argos-only positions.

Spatial analyses were performed in ArcGIS 10.2.2 (ESRI), with NIWA New Zealand region bathymetry data at 50-m depth contours overlaid for comparison (Mitchell et al. 2016). Points on land, generated before or after a foraging trip, were removed using a spatial selection tool in ArcGIS. Data were projected in the NZTM coordinate system, and geodesic distance calculations between points were automated in a Python script using the GeoPy library.

Foraging areas were analysed using GME 0.7.3.0 (Spatial Ecology LLC) and ArcGIS functions, and position data were used to generate Kernel Density Estimates (KDE) which were determined with smoothed cross-validation bandwidth, and a cell size of 50 m (see Muller et al. (2021) for details). Values were calculated using 95% kernel contours

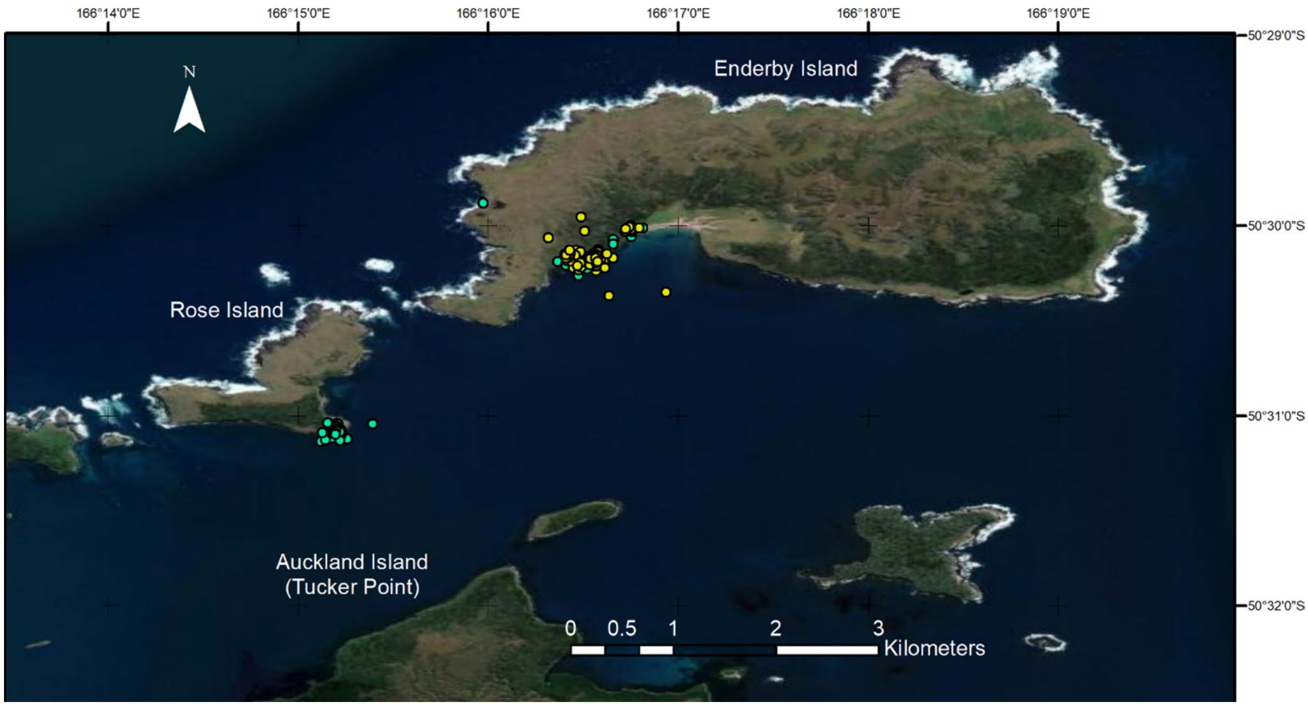

Fig. 1 Map showing islands in the northeast of the Auckland Islands group, including Enderby and Rose Islands. Dots show land and coastal sea area use by two juveniles: J01 (yellow) and J02 (green)

to represent the home range, and isopleth and polygon features were imported into ArcGIS for further spatial analysis. The intersection between home range kernel density polygons was used to compare the percentage overlap of juveniles and breeding adults.

The foraging distance (maximum straight-line distance away from the shore, measured from the sea access point) and the total trip distance (cumulative distance travelled between all points in a foraging trip, including the start and end location at the sea access point) were calculated from GPS data. Summary data were calculated from these distances (mean + SD).

We carried out behavioural change point analysis (BCPA) to identify behavioural change points in foraging tracks from juvenile penguins. Data were analysed using the net squared displacement method (NSD) (Edelhoff et al. 2016), similar to that used for analysing juvenile penguin tracks from the northern population (Young et al. 2022). Analysis was carried out using the BCPA package (v1.3.2) (Gurarie 2014) in R Studio (v2025.05.1 Build 513), running R (v4.5.1). The analysis used a Window size of 30 and a threshold of 7.

Fisheries data for the 2015–2018 seasons (Area SQU6T) were obtained for comparison purposes (MAF, pers comm). Vessel fishing tracks were pooled, and a 95% kernel polygon created using the same methods. Overlaps between data sets were compared using the ArcGIS Intersect, and area calculation functions.

Results

Two foraging tracks were collected for juvenile birds in the current study. These were compared to a total of 91 GPS foraging tracks from breeding adults, from 69 individual birds (Muller et al. 2021). Juvenile 1 transmitted data for 22.5 days (239 raw positions) and Juvenile 2 for 31.8 days (321 raw positions), with an average of 10.6 and 10.1 positions per day, respectively. Data were filtered to give a total of 164 and 217 positions, respectively (Table 1).

Both juveniles initially spent some time on land on Enderby Island, in the vicinity of Rocky Ramp where they were caught (Fig. 1). J01 initially spent around 4 days on land, and J02 spent one day on land before heading to sea (Table S1). At sea, both juveniles spent up to 5 days in an area approximately 115 km northeast of Enderby Island (Fig. 2), presumably foraging (Foraging Area 1). No at-sea transit data were recorded for J01 between land and foraging areas. After returning to land, J02 alternated between time ashore on Enderby Is and on neighbouring Rose Island (Fig. 1). After time ashore, both birds returned to the same Foraging Area 1 before heading further north to different foraging areas (Foraging Areas 2a and 2b, travelling N and NW, respectively), where communication was lost. Identified foraging areas were in water depth ranging from 150 to 900 m deep (Mitchell et al. 2016), implying pelagic foraging behaviour (Muller et al. 2020a).

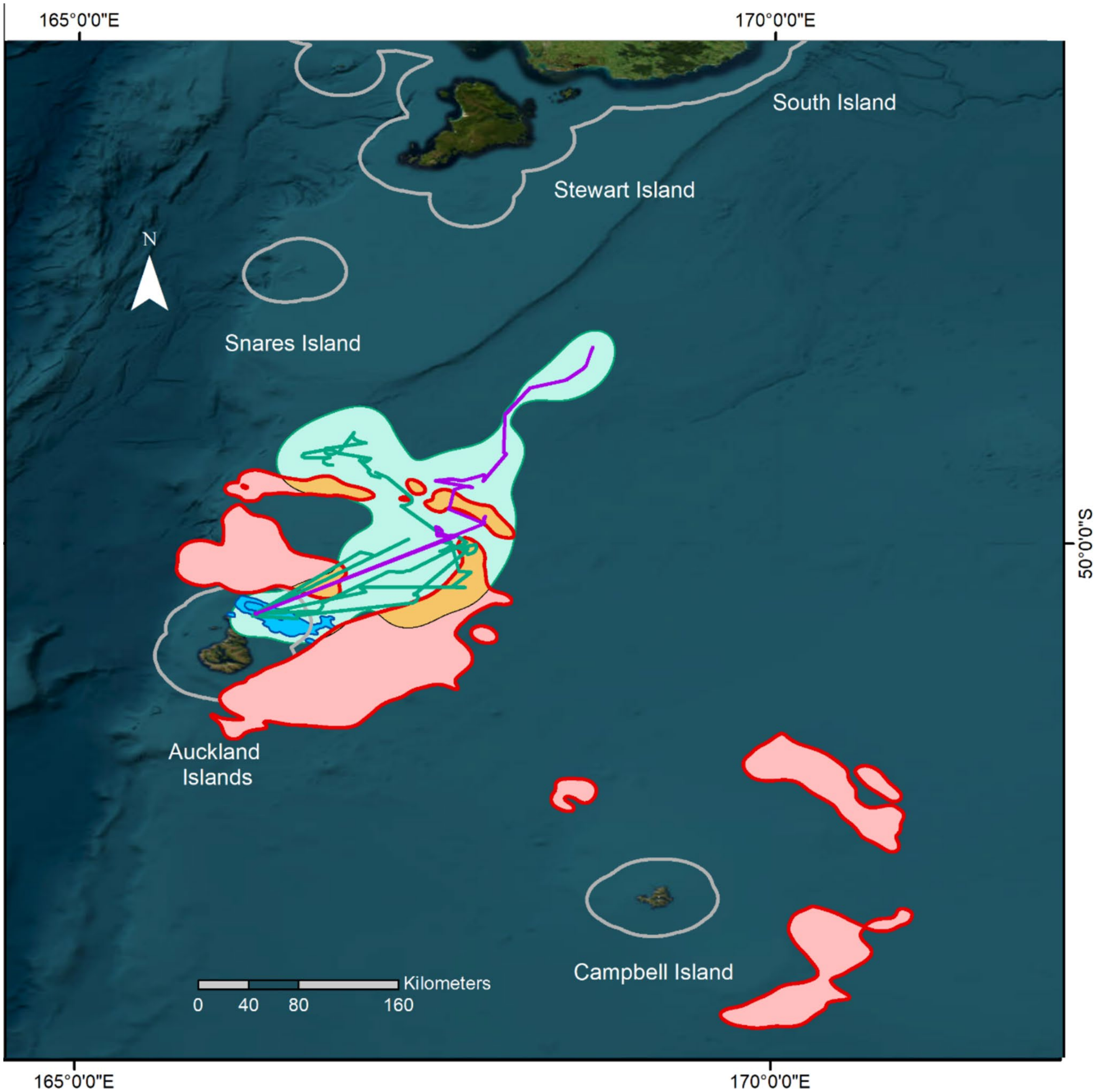

Fig. 2 Map of juvenile yellow-eyed penguin foraging from Enderby Island in the Sub-Antarctic Auckland Islands in the 2016 breeding season. Lines show foraging tracks of two juveniles: J01 (purple) and J02 (green). Shaded areas show combined 95% KDA home range area for tracked juveniles (light green), known adult foraging (blue), known commercial fishing effort (red), and overlap between the foraging area of tracked juveniles and fishing effort (orange). Grey lines show marine protected zones extending 12 nm from land

Table 1 Foraging trip details for juvenile yellow-eyed penguins from Enderby Island in the New Zealand Sub-Antarctic

Bird ID	No. GPS fixes	Deployment time (days)	Max distance (km)	Total distance (km)
J01	164	22.5	275.2	668.8
J02	217	31.8	153.0	992.5

BCPA results identified change points between behaviour on land and at sea (Figure S1 and S2), but only one instance of a change at sea for J01 (Figure S1). J01 exhibited faster mean daily velocity values (> 1 km per hour) in the middle and end of the monitoring period, however, J02 had faster velocities interspersed throughout the monitoring period (Table S2).

Juvenile 1 travelled the greater distance from the colony reaching more than half-way to the South Island of New Zealand (Table 1). Despite this, Juvenile 2 travelled a greater cumulative distance with a total recorded distance of 993 km. Both tracks represent partial trips as logging ended whilst birds were still at sea.

Between them, the two juvenile birds used an area at sea of 18,027 km^2 (95% CI), compared to only 738 km^2 for the total known area used by breeding adults (Table 2), an area more than 24 times greater. Furthermore, whilst 80% of the area used by adults at sea was within the 12 nm reserve boundary where fishing is prohibited, only 7% of juvenile movement at sea was within the protected area. Juveniles had a 17% overlap with known fishing areas, compared to only 4% for breeding adults.

Discussion

Foraging location data from two juvenile yellow-eyed penguins showed both individuals travelled northeast from Enderby Island. Water depth in this area generally ranges from 150 to 3000 m (Mitchell et al. 2016), indicating juvenile foraging is likely predominantly pelagic (Muller et al. 2020a, 2021). Juvenile yellow-eyed penguins returned to land near the area where they were originally caught, displaying some evidence of central-place foraging at the beginning of the monitoring period. Monitoring ended when both birds were travelling much further from shore, however, it cannot be determined if this was the beginning of a dispersal phase, or merely a longer central-place foraging trip. In comparison, breeding adults from the same population had much shorter foraging trips, an average of 1.8 days long, before they returned to shore to feed chicks (Muller et al. 2020a). Statistical comparisons were not attempted for juvenile foraging data due to the small sample size. However, birds were travelling much further and spending longer at sea than foraging breeders.

Juveniles used a considerably larger ocean area than breeding adults with a total recorded trip distance of up to 993 km in 32 days, and reached a maximum distance of 275.2 km away from Enderby Island. This is consistent with post-fledging birds from the northern population which disperse 140 to 692 km (mean ± SD = 359.9 ± 129.3 km) away from their natal locations on the Otago coast (Young et al. 2022). It is not known whether the trackers ceased transmitting data due to the expenditure of their battery life, failure of the attachment, or a predation event at sea. However, since both trackers lasted a similar amount of time, either expenditure of battery life or failure of the attachment is considered more likely. Consequently, these data represent a partial trip, and therefore, a minimum extent of the actual area used. This is a limitation of this study, so undertaking research specifically targeting juveniles and using instruments with a verified longer battery life (to overcome at least one of the identified limitations of this study) should be undertaken to better understand the full extent of the foraging area used by juvenile birds from the southern population.

Juveniles initially returned to land one or more times in the vicinity of where they were caught, and made one or more trips at sea to the same general area (Foraging Area 1), before both ventured further out to sea at the end of the monitoring period. BCPA results showed changes in behaviour between land and sea, although only one at-sea behaviour change was identified. Both birds returned to land from Foraging Area 1, before making additional trips further afield (Figure S2, Table S1). In comparison, juveniles from the northern population undertook an initial dispersal period along the coast from their natal colony, ranging from 5 to 24 days. This was followed by a residency period of 2–60 days based at a new location along the New Zealand mainland up to 692 km from their natal colony (Young et al. 2022). This contrasting behaviour could be explained by the absence of other land around the Auckland Islands. This requires any dispersal to include crossing large areas of open sea, and necessitating sub-Antarctic juveniles swim greater distances, travel further offshore, and undertake more pelagic foraging compared to juveniles from the northern population. Similarly, juvenile Antarctic penguins utilise a much larger area than breeding adults, including king penguins (*Aptenodytes patagonicus*) (Orgeret et al. 2019), and emperor penguins (*Aptenodytes forsteri*) (Thiebot et al. 2013), although juveniles forage at shallower depths (Enstipp et al. 2021). Juvenile king penguins from different breeding areas (Falkland Is and South Georgia) forage at different depths and locations depending on their local habitat (Pütz et al. 2014). Other juvenile penguin species also travel long distances and have experienced a survival bottleneck due to predation and starvation, including Pygoscelis penguins (Adélie, chinstrap and gentoo) (Hinke et al. 2020) and African penguins (*Spheniscus demersus*) (Sherley et al. 2017). Juvenile African penguins had low survival in areas where prey availability was

Table 2 Foraging area comparison between juvenile and breeding adult yellow-eyed penguins from Enderby Island in the New Zealand Sub-Antarctic. Foraging areas show 95% kernel density estimates

Age	Sample size	Area use (km^2)	Protected area use		Fisheries area overlap	
			size (km^2)	%	Size (km^2)	%
Juvenile	2	18,027	1,332	7%	3040	17%
Adult	91	738	590	80%	32	4%

reduced by climate change and over-fishing (Sherley et al. 2017), highlighting dangers faced by many penguin species (Crawford et al. 2017).

In comparison, breeding adult yellow-eyed penguins forage to the south-east of Enderby Island where the water depth averages 50–100 m, with a maximum of 150 m deep (Muller et al. 2021). Amongst adult birds there was some partitioning due to foraging type, with pelagic foragers using a larger foraging area than benthic foragers and also some variability between different years, presumably as a result of differences in prey availability (Muller et al. 2020a, 2021, 2022). Breeding adults in the Southern population also travelled a shorter maximum foraging distance of 46.7 km from shore, with a mean of at least 19.5 ± 12.6 km from shore. The total trip distance for adults was a maximum of 136.7 km, and an estimated mean of 70.7 ± 25.8 km travelled, although trip length varied between years (Muller et al. 2021).

Negative interactions with fisheries occur in the northern population, including direct mortality as bycatch (Couch-Lewis et al. 2016; Ellenberg and Mattern 2012; Mattern and Wilson 2018), and reduced prey availability due to competition, as well as benthic habitat modification as a result of commercial fishing activities (Browne et al. 2011; Mattern et al. 2013). Gillnet fishing has been identified as a significant threat for yellow-eyed penguins from the northern population, including juveniles (Crawford et al. 2017; Darby and Dawson 2000). In the sub-Antarctic, juveniles from Enderby Island had a 17% overlap with known commercial fishing areas, compared to only 4% for breeding adults. Of particular note is that Foraging Area 1 used by both juveniles was adjacent to and in some cases overlapping with fisheries activities. Bycatch of yellow-eyed penguins was not reported by commercial fishers in the study area (Ministry of Primary Industries 2018a), although this does not rule out indirect interactions such as competition and habitat modification. Fishing data in this study represent the general fishing effort in this area over several seasons (2015–2017) and therefore should not be used to infer interactions between individual birds and vessels. The data also represent a number of different fishing methods (including trawling, longlining, and jigging at various depths), which would have different inherent risks for different species. Since fishing effort and area may change between years, and at different times of the year, these results can only provide a general indication of the known extent of the area used by fisheries. Consequently, since juveniles use a much larger area than adults and have a greater overlap with fishing areas, they may therefore be exposed to an increased level of risk. Further research is required to determine the nature and scope of any fisheries interactions for juvenile yellow-eyed penguins in the sub-Antarctic, and whether these may constitute a threat to individual survivorship or population stability.

The two juvenile penguins we monitored foraged in protected waters only when around the immediate vicinity of the Auckland Islands, with just 7% of their time spent within the boundary of the marine protected area, in comparison to 80% recorded for breeding adults (Muller et al. 2021). Foraging data from breeding adults at the Auckland Islands represent only the guard phase of breeding where birds often make the shortest foraging trips, and therefore represent a minimum estimate of the adult foraging area (Muller et al. 2021). In the northern population, breeding adults forage further away during incubation and post-guard stages (Moore 1999) and in winter (M. Young pers. comm.). Therefore, these data represent the minimum extent of foraging areas used by both adult and juvenile birds in the sub-Antarctic. A larger sample size was not possible in this study due to permitting restrictions and logistical constraints, however, we recommend additional research with a larger sample size and longer deployment duration to investigate the full extent of the foraging area used by juvenile birds from this population. Additionally, analysis of dive data or activity logs could provide more precise information on the location of foraging dives, when birds may be more vulnerable to interactions with fishing gear (Crawford et al. 2017). Further research would also be beneficial to identify foraging areas used by juveniles from other breeding colonies in the sub-Antarctic, including from elsewhere on the Auckland Islands, and from Campbell Island.

In summary, we found that juvenile yellow-eyed penguins can travel far beyond protected waters and into areas utilised for commercial fisheries. Juvenile survival is important for recruitment, and therefore also for long-term population stability. Outside the protected area, potential exposure to interactions with commercial fisheries including trawling, longlining, and jigging is therefore a concern for at least 20% of the known sea area used by breeding adults and 93% of the area used by foraging juveniles (Ministry of Primary Industries 2018b). Since any birds which forage outside the marine protected area are potentially exposed to direct interaction with commercial fisheries, more research is needed to examine the nature and extent of any interactions, and the potential effects of commercial fishing on adults and particularly juvenile yellow-eyed penguins from the southern population.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00300-025-03425-2.

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Author contributions CGM: conceived and designed the experiments, carried out the fieldwork, analysed the data, and wrote the paper. RKF: assisted with fieldwork and data collection, and data analysis. BLC and PFB: provided general oversight and assisted with ecological aspects of the project. All authors reviewed the manuscript and gave final approval for publication. The authors declare no competing interests or conflicts of interest. Raw data are available on request.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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