Comparing diving behaviour among three Procellaria petrels

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Summary

The *Procellaria* genus comprises five petrel species vulnerable to bycatch in longline fisheries. This genus is particularly challenging for seabird bycatch mitigation work, as these petrels can dive deep, putting themselves at risk, but also, other less deep-diving species, when they retrieve hooks to the surface. This study investigates the diving behaviour of Black (*Procellaria parkinsoni*), White-chinned (*P. aequinoctialis)*, and Westland (*P. westlandica*) Petrels to inform bycatch mitigation methods. We deployed time-depth recorders on these species during various breeding stages between 2022 and 2024 to record dive depths, durations, and descent rates. We retrieved loggers with data from 10 Black Petrels, 13 White-chinned Petrels, and 32 Westland Petrels. Black Petrels dived the deepest, with a maximum depth of 38.5 m and 25.5% of dives exceeding 10 m. Westland Petrels dived up to 17.3 m, with 99.4% of dives shallower than 10 m, and exhibited the fastest descent rates, averaging 1 m/s for dives over 5 m depth. White-chinned Petrels reached maximum depths of 21.7 m, with 97.9% of dives shallower than 10 m. Sex-specific behaviours were observed in Black and Westland Petrels, with males diving deeper. These results suggest protecting hooks to depths of at least 20 m for Black Petrels and 10 m for Westland and White-chinned Petrels may significantly reduce bycatch. Further research should include additional diving parameters, such as dive

frequencies, and influencing factors, such as time of day, to improve the effectiveness of these methods domestically, but also internationally.

Background

The *Procellaria* genus is made up of five petrel species, all of which are vulnerable to bycatch in longline fisheries (Bell 2016; Frankish et al., 2021; Reid et al., 2014; Rollinson et al., 2016; Waugh and Wilson, 2017). The White-chinned Petrel (*Procellaria aequinoctialis*) is the seabird most frequently killed in longline fisheries in the Southern Ocean and is listed as Vulnerable on the IUCN Red List (Frankish et al., 2021; Phillips et al., 2016; Rollinson 2014; Birdlife International 2018a). Westland Petrels (*P. westlandica*), listed as Endangered on the IUCN red list (Birdlife International 2018c), and Black Petrels (*P. parkinsoni*), listed as vulnerable on the IUCN red list (Birdlife International 2018b), are both Aotearoa endemics facing the ongoing threat of incidental capture in fisheries (Bell 2016; Waugh and Wilson 2017).

Bycatch mitigation methods include tori lines to scare birds away from sinking hooks, weighted branch lines to increase sink rates and reduce the time that hooks are available to seabirds, and the setting of lines at night when many seabirds are less active (Gilman et al., 2005). For these measures to be effective, they must be directly informed by seabird diving behaviour (Rollinson et al., 2016; Frankish et al., 2021). For example, dive descent rates can directly inform the necessary sink rates of hooks (Gilman et al., 2005), and known diving ability can inform depths to which hooks must be protected and the aerial extents of tori lines (Bell 2016).

Gaining insights into diving behaviour is particularly crucial for the *Procellaria* petrels as these seabirds have long posed particular challenges to seabird bycatch mitigation methods. These petrels have deep diving abilities, which not only place themselves at elevated risk levels, but also enable them to retrieve hooks back to the surface, where they then may place other, less apt divers such as albatrosses at additional bycatch risk (Jimenez et al. 2012). The aim of this study is to investigate the diving behaviour of Black, White-chinned, and Westland Petrels, to inform bycatch mitigation methods in longline fisheries.

Methods

Data loggers

Diving behaviour in seabirds can be investigated using time-depth recorders (TDRs). These loggers record depth measurements at 1-2 second intervals from which dive depths, durations, and descent rates can be extracted. We deployed time-depth recorders on adult Black, Westland, and White-chinned Petrels during various phenological stages of the 2022 – 2024 breeding periods (Table 1).

Table 1: Summaries of TDR deployments, retrievals and datasets obtained for White-chinned, Black, and Westland Petrels. Totals for each species shown in bold.

Species	***Location***	***Year***	***TDR***		***N deployed***	***N retrieved***	***% retrieved***	***N with data***	***% with data***
			Type	**Sampling frequency**					
White-chinned Petrel	Antipodes	2022	Star-ODDI	2 s	9	8	89%	6	75%
	Antipodes	2022/23	CEFAS	1 s	15	11	73%	7	73%
					24	**19**	**79%**	**13**	**68%**
Black Petrel	Aotea	2023	CEFAS	1 s	10	9	90%	3	33%
	Aotea	2023/24	CEFAS	1 s	10	7	70%	6	86%
	Aotea	2024	CEFAS	1 s	1	1	100%	1	100%
					21	**17**	**81%**	**10**	**59%**
Westland Petrel	West coast	2022	Star-ODDI	2 s	10	9	90%	9	100%
	West coast	2022	CEFAS	1 – 2 s	20	18	90%	14	78%
	West coast	2023	CEFAS	1 s	15	12	80%	9	75%
					45	**39**	**87%**	**32**	**82%**

We fitted 21 Black Petrels with CT G5 long life TDRs (CEFAS Technology, Suffolk, UK) on Aotea/Great Barrier Island during incubation and early chick-rearing periods in the 2022/23 and 2023/24 breeding period, with a single redeployment in the 2023/24 chick-rearing to fledging period (Table 1). We deployed a total of 24 TDRs on White-chinned Petrels during incubation and chick-rearing on the Moutere Mahue/Antipodes. Of these, 9 were DST milli F-TD TDRs (Star-ODDI, Garðabær, Iceland) deployed in the

2021/22 breeding period, and 15 were CEFAS G5 TDRs deployed in the 2022/23 breeding period (Table 1). We deployed 45 TDRs on Westland Petrels on the West Coast of Te Waipounamu/the South Island. Of these, 35 were CEFAS G5 TDRs deployed in the chick-rearing period of the 2022 breeding period (n = 20) and the pre-laying to incubation period of the 2023 period (n = 15), and 10 were Star-ODDI TDRs deployed in the 2022 breeding period during incubation (Table 1).

We programmed Star-ODDI TDRs to record depth at 2 s intervals, and the CEFAS G5 TDRs to record depth at 1 s intervals. All TDRs were attached with a strip of rubber threaded through a TDR's casing that we custom-made through 3D-printing or mold-casting for each TDR model, wrapped around the tarsi, and secured with superglue. We removed the loggers by cutting the rubber strip with scissors (Table 1).

Data analysis

All data filtering and analyses of dive depth, duration, and descent rates were performed using R Statistical Software (v4.4.1 2024). We extracted and cleaned the dive data using the *diveMove* package in R (Luque and Fried, 2011; Luque, 2024). TDR pressure data can drift over time, causing recorded depths to deviate from true depths. Zero-offsetting filtering in *diveMove* corrects these deviations by adjusting the recorded depths to match the true depths by recalibrating surface measurements to 0 m depth. This method involves recursively smoothing and filtering the pressure time series with moving quantiles, applying two window widths and quantiles in succession, with the second filtering the output of the first. This process can be limited to bounds which encompass surface fluctuations. Tags may experience differing levels of noise. By analysing the raw plotted data, we can identify drift and level shifts, and adjust the windows and quantiles accordingly (Luque and Fried, 2011). To exclude residual surface noise, we set the dive threshold at 1 m (Navarro et al. 2014). We also excluded all dives with dive durations longer than 10 minutes, and descent rates exceeding 3 m/s as these were considered unrealistic (Frankish et al., 2021).

When reporting summary statistics, we calculated an overall mean descent rate, as well as a mean that excludes dives <5 m. Surface noise can lead to the overestimation of descent rates, disproportionately affecting shallow dives. Therefore, excluding dives <5 m may provide a more accurate reflection of true descent rates (Rollinson, 2014). We investigated the diving behaviour of the three *Procellaria* species by comparing dive depths, durations, and descent rates with permutation tests (Voeten, 2023). Separate models were performed for each diving behaviour, species, and sex. Results have not been adjusted for multiple comparisons. Descent rate, maximum depths, and dive durations are all gamma distributed. Most White-chinned Petrels were of unknown sex, and therefore sex-specific diving is not tested for. Black Petrel sexing is based on behaviour and morphological observations ('clacking' for female, size of bird, and bill depth), and has not yet been confirmed with genetic analysis. It should thus be noted that these are preliminary analyses and may be subject to changes.

Results

Summary statistics of White-chinned, Black, and Westland Petrel diving ecology are presented in Table 2. Most Westland and White-chinned Petrel dives were <5 m (92.1% and 87.2% respectively), and almost all dives for these species were <10 m (99.4% and 97.9% respectively) though the dive limits for both birds far exceeded these thresholds, with the maximum depth for Westland at 17.3 m, and at 21.7 m for White-chinned Petrels (Figure 1). In contrast, the minority of Black Petrel dives were <5 m (48.0%), and still only 74.5% were below 10 m (Figure 1). The maximum dive for the Black Petrel was also significantly deeper, at 38.5 m.

We found maximum dive depths differed significantly across species, with Black Petrels diving deeper than both Westland (β = -0.90, $p < 0.001$) and White-chinned Petrels (β = 0.77, $p < 0.001$; Sup. Mat 1). Westland Petrel dives were significantly shallower than White-chinned Petrels ($p < 0.001$), but the difference was less pronounced (β = -0.13). Black Petrel dive durations were on average the longest (mean = 17.25 s), but this was only statistically significant when compared to Westland Petrels (mean = 5.23 s; β = -1.13, $p < 0.001$). Descent rates were greatest in the Westland Petrel at 1.01 m/s compared to both the Black (β = 1.98, $p < 0.001$) and White-chinned Petrel (β = 0.21, $p < 0.001$), and no significant difference was found between Black and White-chinned Petrel. Sex-specific diving behaviour was found in both Westland and Black Petrels. In both species, males dived significantly deeper (Westland: β = 0.1, $p < 0.001$; Black: β = 0.16, $p <0.001$). In Black Petrels male descent rates were faster than females (β = 0.15, $p <0.001$). No sex-specific dive durations were found.

Table 2 Summary statistics of diving behaviour for each species and sex. NAs are present where subgroups had too few individuals. Note that there is only one sexed female White-chinned in this study. Depth measured in metres; duration measured in seconds, descent rate measured in m/s; dive frequencies per day from first to last recorded dive.

		Depth m		Mean dive duration	Mean descent rate Excl. dives < 5 m	Mean descent rate Incl. dives < 5 m	Mean dive frequency
		Max	*Mean*	s	*m/s*	*m/s*	n/day
Westland	Female	12.22	2.21 ± 0.13	4.37 ± 0.37	1.02 ± 0.07	1.61 ± 0.06	6.40 ± 0.63
	Male	17.31	2.42 ± 0.09	5.82 ± 0.30	1.00 ± 0.02	1.47 ± 0.04	8.85 ± 0.92
	All	17.31	2.31 ± 0.10	5.23 ± 0.26	1.01 ± 0.03	1.52 ± 0.04	7.86 ± 0.63
White-chinned	Female	4.43	1.72 ± NA	3.46 ± NA	NA ± NA	1.75 ±	2.17 ± NA
	Male	21.72	3.68 ± 0.54	8.21 ± 1.92	0.90 ± 0.04	1.53 ± NA	3.36 ± 0.65
	Unknown	14.19	2.51 ± 0.29	6.17 ± 0.95	0.80 ± 0.05	1.34 ± 0.14	5.80 ± 1.06
	All	21.72	2.63 ± 0.57	6.59 ± 0.86	0.84 ± 0.04	1.43 ± 0.09	4.77 ± 0.76
Black	Female	25.50	5.78 ± 2.09	20.05 ± 6.82	0.79 ± 0.06	0.86 ± 0.03	9.28 ± 2.50
	Male	38.50	6.91 ± 1.05	18.51 ± 3.35	0.92 ± 0.04	1.15 ± 0.15	13.46 ± 2.89
	Unknown	29.12	4.29 ± 2.85	10.75 ± 7.92	0.90 ± NA	1.44 ± 0.36	6.73 ± 5.23
	All	38.50	6.16 ± 0.88	16.44 ± 2.88	0.89 ± 0.04	1.15 ± 0.12	11.28 ± 2.10

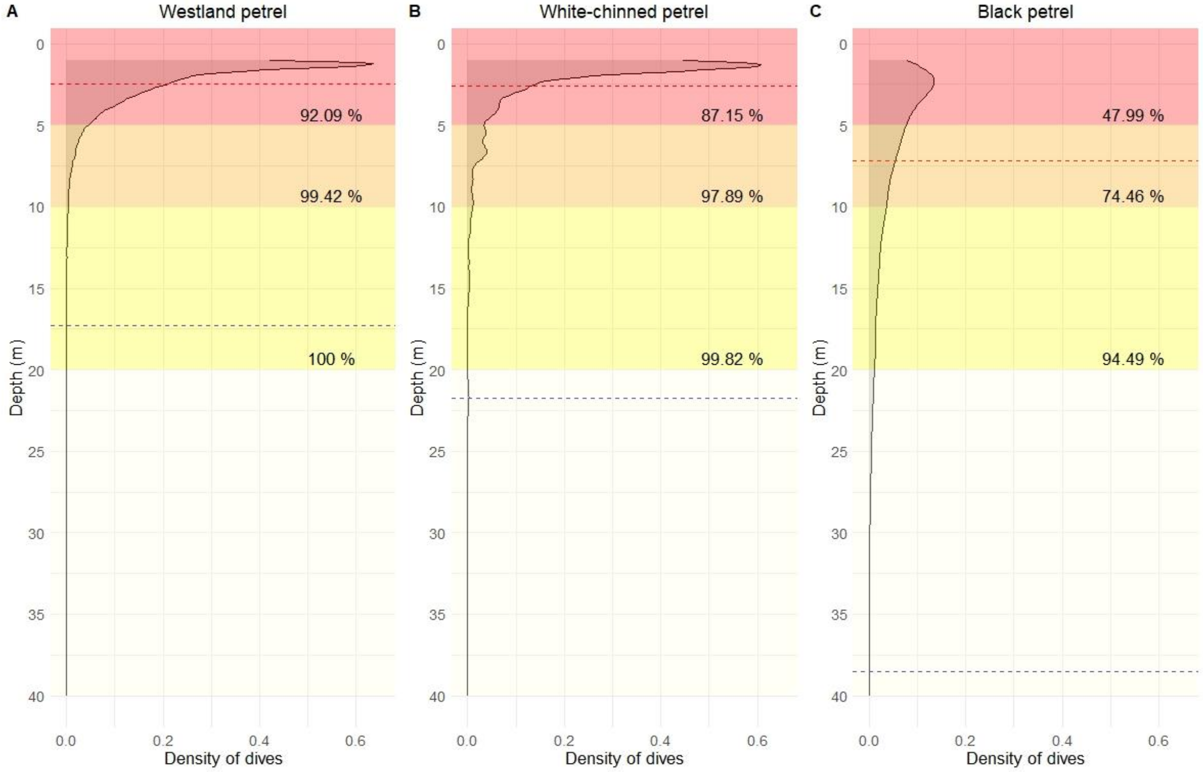

Figure 1 Density plot of maximum dive depths for A) Westland, B) White-chinned, and C) Black Petrels. Red dotted lines represent species' mean when dives are not grouped by individual, blue dotted lines represent species' maximum depth. Percentages on right-hand side of each graph indicate the following: in red sections, the percentage of dives between 0 and 5 m is shown, in orange, the percentage between 0 and 10 m, and yellow, the percentage between 0 and 20 m.

Discussion

The results from this study contribute to our understanding of seabird diving behaviour, which can in turn be used to revise bycatch mitigation methods for the conservation of these species.

This study found deeper mean and maximum dive depths in Black Petrels than previously recorded (Bell, 2016). In addition, a greater proportion of dives were recorded above the 5 m and 10 m thresholds. These results have the potential to revise bycatch mitigation measures. Previously, the recommendation was to protect hooks until 10 m, however, 25.5% of dives would still be at risk at this depth. These results suggest a minimum depth of 20 m for unprotected hooks would substantially decrease bycatch of Black Petrels, with only 5.5% of dives exceeding this depth (Figure 1). Interestingly, we found male Black Petrels dived deeper than female, which contrasts with Bell's (2016) findings. Further studies with a larger sample size of genetically sexed individuals throughout multiple phenological stages may be necessary to extract a thorough understanding of sex-specific foraging behaviours in Black Petrels.

Previous studies on Westland Petrels with capillary tubes recorded a maximum depth of 7.6 m (Freeman and Nicholls, 1997). Our results suggest much deeper depths of up to 17.31 m. With the vast majority of dives shallower than 10 metres (99.4%), protecting hooks up until this threshold may be sufficient to substantially reduce bycatch of Westland Petrels in longlines. It should be noted that descent rates are particularly fast in Westland Petrels, with an average of 1 m/s in dives > 5 m, so sufficiently weighting branch lines in combination with tori lines may required to prevent bycatch of this this species. However, we note that the surface longline requirements will be adjusted in the New Zealand EEZ to accommodate this, so domestically this species should be at a lower risk. Regardless, the information presented here is still of crucial information to prevent bycatch in international waters.

Sex-specific foraging behaviours with male Westland Petrels diving significantly deeper than females, similar to Black Petrels in our study, is a novel contribution to our understanding of this uniquely winter-breeding *Procellaria* petrel. Westland Petrels have male-biased sexual size dimorphism, which has in other seabird species been linked to sex-specific foraging behaviours (Landers et al., 2011; Gianuca et al., 2017; Poupart and Waugh, 2020). When investigated with GPS and accelerometer deployments, Westland Petrel sexes only differed by the influence of oceanic variables on time spent foraging (Poupart and Waugh, 2020). Poupart and Waugh (2020) suggest this may be due to finer scale habitat specialisation between sexes. Our findings provide a novel contribution to our understanding of these fine-scale foraging strategies by revealing sex-specific diving behaviours, which are important to note as sex-specific foraging can put sexes at different risks of bycatch (Gianuca et al., 2017; Cortés et al., 2018). The potential for sex-specific bycatch risk in Westland Petrels emphasizes the need to thoroughly understand the foraging behaviour of these at-risk species.

Our study shows similar distributions of White-chinned Petrel dive depths to Frankish et al., (2021), though the maximum depth recorded in this study (21.7 m) is several metres deeper than the previous record of 16 m (Rollinson et al. 2014). Despite this impressive diving ability, 97.9% of dives were still below 10 m, indicating this is an appropriate minimum depth to protect hooks to.

This study provides preliminary insights into the diving behaviour of three *Procellaria* petrel species vulnerable to bycatch in a range of fisheries, potentially informing improved mitigation methods in such fisheries. Further studies should explore additional diving behaviour parameters, such as dive frequencies and profiles, and factors influencing behaviour, including the time of day, which is relevant for understanding the effectiveness of night setting as a bycatch mitigation measure.

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Supplementary Material 1

Supplemental Table 1 Preliminary results from permutation tests with 1000 iterations, comparing dive depths, durations, and descent rates among species. P-values have not been corrected for multiple comparisons. Descent rates exclude dives < 5 m.

Model	**Reference**	**Factor**	**LRT**	**beta**	**t**	**p - value**
Maximum depths ~ Species	Black	(Intercept)	42399.48	1.73	15.97	
		Westland	7198.43	-0.90	-7.18	< 0.001
		White-chinned	455.19	-0.77	-5.55	< 0.001
	Westland	(Intercept)	17566.86	0.83	12.95	
		White-chinned	81.76	0.13	1.18	< 0.001
Dive duration ~ Species	Black	(Intercept)	63431.05	2.76	20.79	
		Westland	2632.60	-1.13	-7.41	< 0.001
		White-chinned	230.59	-0.96	-5.55	0.09
	Westland	(Intercept)	34909.13	1.63	20.96	
		White-chinned	73.32	0.17	1.17	0.11
Descent rate ~ Species	Black	(Intercept)	289.43	-0.12	-2.25	
		Westland	138.84	0.12	1.98	< 0.001
		White-chinned	4.27	-0.09	-1.19	0.06
	Westland	(Intercept)	5.92	0.00	-0.01	
		White-chinned	28.48	-0.21	-3.58	< 0.001

Supplemental Table 2 Preliminary results from permutation tests with 1000 iterations, comparing dive depths, durations, and descent rates between sexes in Westland and Black Petrels. White-chinned Petrels have been excluded from this analyses due to insufficient sample sizes of sexed individuals. P-values have not been corrected for multiple comparisons. Descent rates exclude dives < 5 m.

Model	**Species**	**Factor**	**LRT**	**beta**	**t**	**p - value**
Maximum depths ~ Sex	Westland	(Intercept)	10974.76	0.76	13.27	
		Male	567.04	0.10	1.51	< 0.001
	Black	(Intercept)	11079.21	1.68	5.50	
		Male	387.92	0.16	0.45	< 0.001
Dive duration ~ Sex	Westland	(Intercept)	20040.99	1.46	19.18	
		Male	1444.89	0.28	3.01	0.72
	Black	(Intercept)	19728.17	2.94	7.32	
		Male	3.14	-0.16	-0.34	0.99
Descent rate ~ Sex	Westland	(Intercept)	0.25	-0.02	-0.40	
		Male	6.93	0.02	0.52	0.41
	Black	(Intercept)	814.11	-0.24	-3.75	
		Male	459.13	0.15	1.98	<0.001