DIVING BEHAVIOR OF PINK-FOOTED SHEARWATERS *ARDENNA CREATOPUS* REARING CHICKS ON ISLA MOCHA, CHILE

JOSH ADAMS[1*], JONATHAN J. FELIS[1], MAX CZAPANSKIY[1], RYAN D. CARLE[2] & PETER J. HODUM[2]

[1]*US Geological Survey, Western Ecological Research Center, Santa Cruz Field Station, 2885 Mission Street, Santa Cruz, CA 95060, USA*
**(josh_adams@usgs.gov)*
[2]*Oikonos Ecosystem Knowledge, Yerbas Buenas 498, Valparaíso, Chile*

ABSTRACT

ADAMS, J., FELIS, J.J., CZAPANSKIY, M., CARLE, R.D. & HODUM, P.J. 2019. Diving behavior of Pink-footed Shearwaters *Ardenna creatopus* rearing chicks on Isla Mocha, Chile. *Marine Ornithology* 47: 17–24.

Recent information reporting Pink-footed Shearwater *Ardenna creatopus* mortality from fisheries bycatch throughout its range has encouraged fisheries managers in Chile to evaluate and consider shearwater foraging behaviors to better evaluate risk. In response, we tracked six chick-rearing adult Pink-footed Shearwaters from Isla Mocha, off south-central Chile, from 19 to 28 March 2015 using global positioning sensors and time-depth recorders. We recorded seven complete trips averaging 4.2 ± 2.5 d (mean ± SD). Chick-provisioning adults foraged within 334 km (i.e., 175 ± 100 km) of Isla Mocha. Dives (*n* = 515) occurred throughout the measured foraging range but most frequently occurred within 5–30 km from the mainland coast, in continental shelf waters north of Valdivia. Other regions with diving behavior were within ~20 km of Isla Mocha, and from Lebu to north of Talcahuano. Based on movement behavior analysis, adults spent most of their time at sea "resting/foraging" (62% ± 6%), with the remainder spent "searching" (16% ± 4%) and "transiting" (20% ± 5%). The proportions of total number of dives associated with these three behaviors were similar. On average, dives were relatively shallow (1.6 ± 1.2 m, maximum depth = 10.1 m) and brief (4.7 ± 4.8 s, maximum duration = 25.7 s). Dives occurred during the day, at night, and at twilight, with most activity occurring at twilight and during the day. Although based on a small sample size, our results may be useful for informing modifications to fishing gear or fisheries policy to reduce the likelihood of bycatch and thus meet Chilean conservation goals for Pink-footed Shearwaters.

Key words: Pink-footed Shearwater, *Ardenna creatopus*, foraging behavior, diving, Isla Mocha, fisheries interactions, Chile

INTRODUCTION

Outside of the polar oceans, shearwaters are widespread. Given their considerable morphological variation and distinct physiological adaptations, they display variable modes of foraging including scavenging, surface seizing, shallow plunging, and deep wing-propelled diving (Kuroda 1954, Brown *et al.* 1978, Burger 2001). Furthermore, their ability to commute long distances and dive for prey is facilitated by adaptations that enable both the efficient flight abilities needed during the breeding season and, for some species, impressive diving ability. Among *Ardenna* shearwaters, the Sooty Shearwater *A. grisea* and Short-tailed Shearwater *A. tenuirostris* have longer, narrower wings and greater wing-loading compared to the similarly-sized Pink-footed Shearwater *A. creatopus*, Flesh-footed Shearwater *A. carneipes*, and Great Shearwater *A. gravis* (Howell 2012). As a group, the *Puffinus* and *Ardenna* shearwaters show a relatively linear increase in maximum dive depth with increasing body mass (Shoji *et al.* 2016), and for the Wedge-tailed Shearwater *A. pacifica*, there is some evidence that foraging behavior associated with diving varies according to sex (Peck & Congdon 2006).

The Pink-footed Shearwater (PFSH) breeds on only three islands in Chile (Guicking *et al.* 1999). The number of adults has been estimated to be in the tens of thousands, but this is not well reported in the available literature (Brooke 1987, Guicking *et al.* 1999); more recent efforts estimate the 2016 breeding population at 53 000–65 000 birds (P. Hodum *et al.* unpubl. data). PFSHs are listed as Vulnerable by the International Union for Conservation of Nature (IUCN 2018), Threatened by Canada (Environment Canada 2008), and Endangered by Chile (Ministerio Secretaría General de la Presidencia 2005). They have also been included in Annex 1 of the Agreement on the Conservation of Albatrosses and Petrels (ACAP 2013). Habitat loss and degradation (Carle *et al.* 2016), predation by introduced mammals (Oikonos, unpubl. data), mortality from fisheries bycatch (Mangel *et al.* 2013, Suazo *et al.* 2014), and a small global population have increased conservation attention and influenced global conservation classifications for PFSHs. Recent reports of PFSH mortality from fisheries bycatch in Chile (Mangel *et al.* 2013, Suazo *et al.* 2014, Vega *et al.* 2018), Peru and Ecuador (Mangel *et al.* 2011), Guatemala (Dávila Pérez *et al.* 2009), Mexico (Velarde *et al.* 2017), and the USA (Gladics *et al.* 2017) have encouraged fisheries managers in Chile to evaluate PFSH foraging behaviors when assessing risk in certain fisheries. The single prior study of PFSH foraging behavior indicated that birds from the main colony at Isla Mocha foraged coastally in Chile (Guicking *et al.* 2001), which put them at risk of becoming bycatch in industrial and small-scale purse seine fisheries (Suazo *et al.* 2014, Vega *et al.* 2018). Therefore, we undertook this study to characterize PFSH foraging behavior and help inform modifications to fishing practices, thus decreasing the risk of PFSH entanglement.

STUDY AREA AND METHODS

We studied adult PFSHs provisioning chicks on Isla Mocha, 30 km off south-central Chile (38°22′S, 73°54′W; Fig. 2). On 19–20 March 2015, we captured breeding PFSHs and fitted them with Global Positioning System (GPS) sensors (modified

i-gotU GT-120 GPS loggers, Mobile Action Technologies, New Taipei City, Taiwan) to record location, as well as time-depth recorders (TDRs; Cefas G5, 3 g, Cefas Technology Ltd., Lowestoft, UK) to record diving behavior. We stripped the GT-120 loggers from their factory housings and sealed them within 2:1 low-shrink-temperature polyolefin heat-shrink tubing (AMS-DTL-23053/5-310, BuyHeatShrink.com, Deerfield Beach, Florida) to create a lightweight, waterproof housing. The repackaged GPS logger weighed 17 g with the original battery (380 mA·h). We attached the modified GT-120s (cross-sectional area = 3 cm^2) to several central back feathers using four strips of tape (1 cm wide, Tesa® 4651, Norderstedt, Germany). We programed the GPS loggers to collect location data every five minutes, to achieve a maximum expected duration of approximately 10–14 d. To measure high-resolution diving behavior, we co-deployed the miniature TDRs (cross-sectional area = 0.5 cm^2) on the same birds. We taped TDRs to metal leg bands and programmed each to record depth (12-bit resolution, ± 0.1 m) once per minute when dry and at 10 Hz when both wet and below a pre-set threshold pressure that was equivalent to one meter in depth (i.e., Cefas FastLog data). The combined mass of the devices (GPS + TDR = 20 g in air) was 2.8% of the mean adult mass measured on Isla Mocha (703 g, males and females combined; Guicking *et al.* 2004), in accordance with the 3% body-mass maximum recommended for devices attached to procellariiform seabirds (Phillips *et al.* 2003). Similar leg-mounted devices (e.g., GLS/TDRs) have been shown to affect individual Sooty Shearwaters and their offspring's growth rates when deployed long-term (see Adams *et al.* 2009). We attempted to minimize potential device effects by equipping only one bird from each breeding pair and by recapturing birds at their burrows to remove devices after short-duration (4–9 d) deployments; the recapture period was 23–28 March 2015.
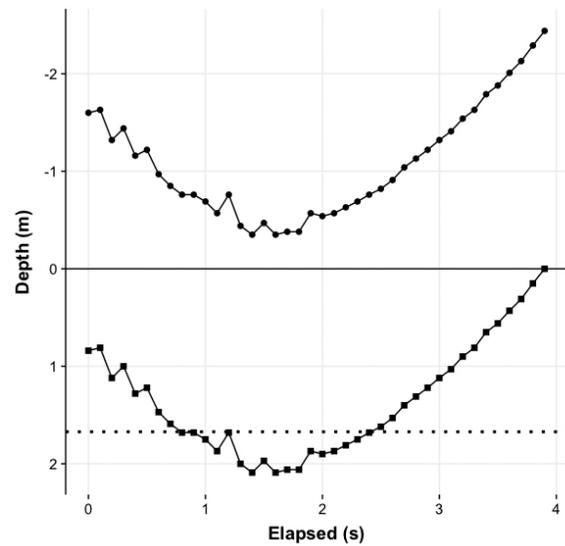
Fig. 1. Representative Pink-footed Shearwater time-depth profile. The top profile indicates the uncalibrated FastLog dive record with recorded depths indicated every 0.1 s (round dots). The bottom profile indicates the post-calibrated record with corrected depths (filled squares). The solid horizontal line indicates the surface at 0 m. The dotted horizontal line indicates the depth at 80% max depth, which was used to calculate descent and ascent rates. Negative values on the y-axis indicate real, uncalibrated values that are not possible because they would be above the reference surface at 0 m. Note that in the bottom dive profile, the beginning of the dive record is below the 0.5-m threshold, and that the descent is more variable from point to point compared with a smoother ascent. This was likely caused by pressure on the sensor from foot-assisted diving during descent.
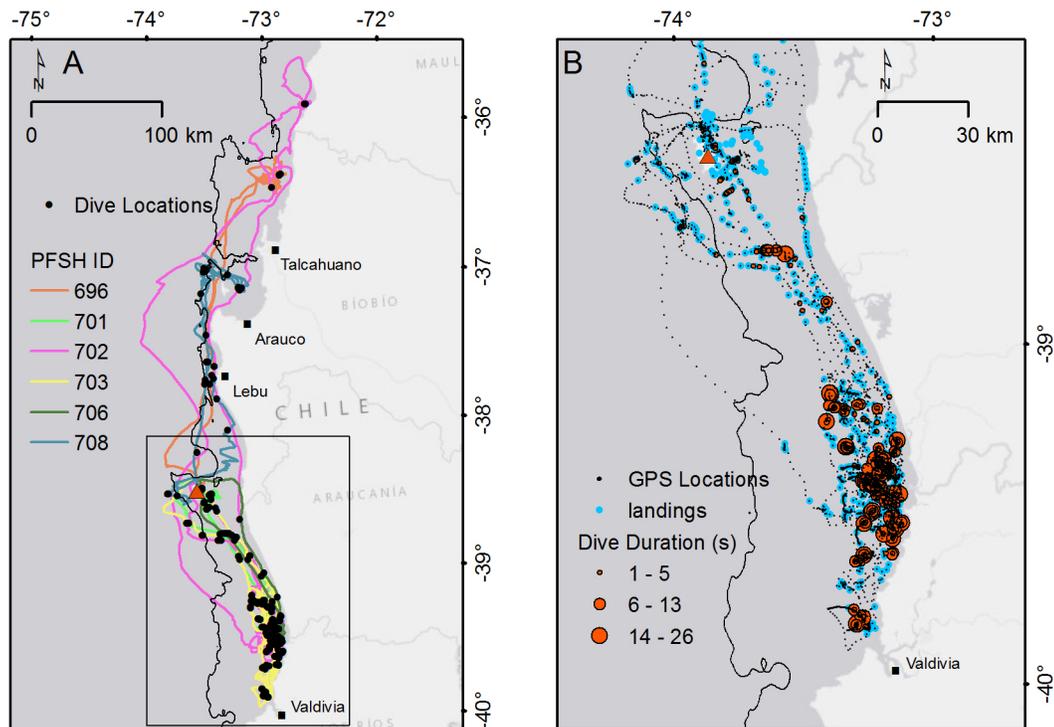

Fig. 2. Tracks and dive locations of Pink-footed Shearwaters breeding on Isla Mocha (red triangle in A) in 2015 (*n* = 6 birds, 7 tracks, 515 dives). Inset rectangle in (A) corresponds with the core foraging area (B) that shows 5-min GPS records (small black dots) FastLog "landing events" with no diving (blue dots)., and locations of recorded dives scaled to dive duration (s, red circles). The 200-m isobath (thin black line) is indicated in both panels.

We created purpose-built scripting in the software program R to process dive data. Original data and custom scripting are available online at https://github.com/mczapanskiy-usgs/pfsh.dive. The text file output from the TDRs contained tag metadata and up to three types of additional data: background low-frequency sampling, FastLog events, and wet/dry status. To systematically identify and verify dives, we used the FastLog event data and wrote a custom script that used functions in the R package diveMove (Luque & Fried 2011). Although TDR depth resolution (i.e., precision) was estimated by Cefas Technology Ltd. to be better than ± 0.15 m, we determined that surface calibration was necessary because the "surface" indicated by the FastLog data could be ± 1.0 m or more from the actual surface of the water. We accounted for surface discrepancies using a fixed offset equal to the minimum depth—for example, if the shallowest point was recorded at −2.4 m (i.e., above the ocean's surface), we added 2.4 m to all points (see Fig. 1). This corrected the dive record to surface = 0 m. Even with a high-frequency (10 Hz) sampling rate, corrected FastLog data indicated some time-at-depth patterns that could not confidently be classified as dives because the pressure variability created some short, noisy patterns that may have resulted from paddling, wave-slap, or other submerged movements. Therefore, we defined dives as consecutive points deeper than a minimum corrected surface threshold of 0.1 m depth, with a corrected dive threshold of 0.5 m depth and a minimum duration of 0.5 s. If the TDR did not exceed its pre-programed wet/depth threshold to sustain logging after 0.5 s, it recorded a short (0.5 s) FastLog event indicating a water landing or a very short, shallow surface dive less than 0.5 m deep. Such landings were not included in our summary analysis of dives. We visualized results using plots of the individual dives and the entire FastLog data set for context. Lastly, because the automated dive-identification script can identify false-positive dives, we wrote a custom quality assurance/quality control (QAQC) tool using the R package Shiny (Chang *et al.* 2016) to visualize, evaluate, and flag questionable dives. Three people evaluated all graphical dive profiles, and dives were classified as valid when at least two viewers agreed. We calculated the following dive parameters: ledge depths (measured in m, defined as 80% of maximum depth to accommodate extended bottom times when calculating ascent and

descent rates; see Fig. 1), times between ledge depths and surface (i.e., descent and ascent rates, $m \cdot s^{-1}$), maximum depth (m), dive duration (s), and post-dive surface interval (PDSI). We used a PDSI of 52 s (i.e., double the observed maximum dive duration = 26 s) to define discrete dive bouts. We used the R package oce (Kelley & Richards 2015) to characterize the timing of individual dives, based on sun angle, into the categories of astronomical twilight (−18° < sun angle < −12°), day (sun angle > −12°; nautical dawn) and night (sun angle < −18°). We determined the locations for dives and FastLog "landing events" by matching the TDR data timestamp with that of the co-deployed GPS.

Individual foraging trips were identified as a set of consecutive locations when tagged birds left a fixed radius (2.5 km) around the nesting colony and returned to this buffer for an extended period (> 30 min). We excluded trips lasting less than 30 minutes from further analysis. To evaluate diving activity associated with movement behaviors during foraging trips, we used the Residence in Space and Time method (RST; Torres *et al.* 2017) to classify behavior into "resting/foraging," "searching," and "transiting." The RST algorithm calculates a normalized residual between time- and space-intensive behaviors. Like the First-Passage Time (FPT) method (Fauchald & Tveraa 2003), RST requires a biologically meaningful radius to classify behavioral states, but unlike FPT, it can be used to discriminate between three discrete behavioral states (see Torres *et al.* 2017). Therefore, we followed Torres *et al.* (2017), who recommended a radius equal to half the product of the mean transit speed and the sampling interval. We calculated mean transit speed (mean ± standard deviation (SD) transit speed = 6.7 ± 4.0 $m \cdot s^{-1}$) as the mean of all ground speeds greater than one meter per second and where tortuosity was less than the median tortuosity. (Tortuosity is defined as the ratio of distance traveled ± five points to net distance traveled ± five points.) Therefore, with a GPS sampling rate of 300 s^{-1}, we calculated an RST radius of 1005 m. Although diving (indicative of foraging) could potentially occur during any of the three RST classifications, it was impossible to know exactly when foraging behavior occurred based on GPS data. We found that, for PFSH, the RST behavioral classification of Torres *et al.* (2017) had the potential to classify locations where birds were floating, resting,
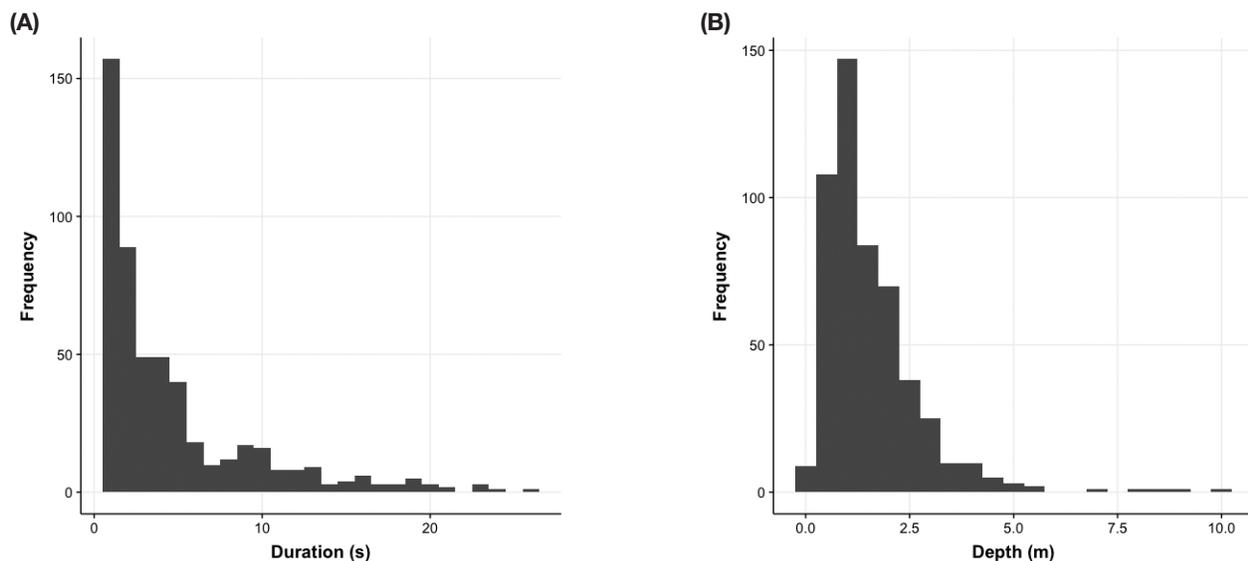
Fig. 3. Frequency distributions of Pink-footed Shearwater (A) dive durations (s) and (B) maximum dive depths (m). *n* = 6 birds, 7 trips, 515 dives.

or foraging while on the water as "searching" behavior (e.g., area-restricted search); therefore, we modified the results of the RST by manually setting all locations with speeds of < 1 m·s^{-1} to "resting/foraging" behavior. Hereafter, results are reported as mean ± 1 SD, unless otherwise noted.

RESULTS

Six PFSHs with GPSs and TDRs completed seven foraging trips spanning 35°30′S to 39°54′S (> 500 km of linear coastline) and lasting 4.2 ± 2.5 d (Table 1, Fig. 2A). The maximum range from Isla Mocha was 334 km (mean 175 ± 100 km), and the cumulative track length per trip (mean 889 ± 673 km) corresponded positively with trip duration (Table 1). Despite variations in trip duration (± 2.5 d), trips displayed similar temporal proportions among individuals, with low variances among the three movement-behavior classifications: 62% ± 6% "resting/searching", 16% ± 4% "searching", and 20% ± 5% "transiting" (Table 1).

We recorded a total of 1 791 FastLog "landing events" that included 520 potential dives, 515 of which were confirmed as valid dives using our QAQC method (mean = 74 dives per trip, range = 6–209 dives per trip, *n* = 7 trips from six individuals; Table 1, Figs. 2A, B). Diving occurred throughout the full extent of the foraging area (Fig. 2A), but occurred most frequently within continental shelf waters (depth < 200 m) to the north of Valdivia, Chile (39°49′S); four of the six shearwaters performed 79% of all dives in this region (~15 000 km^2; Fig. 2B). Other regions where diving behavior occurred were within ~20 km of Isla Mocha, and north of Isla Mocha from Lebu to north of Talcahuano (Figs. 2A, B). Mean dive duration was 4.7 ± 4.8 s (range = 1–26 s; Fig. 3A), and the overall distribution of dive durations was skewed, with the majority of dives lasting < 6 s (Fig. 3A).

The proportion of dives associated with movement behaviors was similar to the time spent in the three classified behaviors (see above); the majority of dives (60% ± 12%) were associated with "resting," followed by "searching" (22% ± 21%) and "transiting" (16% ± 10%; Table 1). Mean dive depth was 1.6 ± 1.2 m (range = 0.5–10.1 m), and the overall distribution was skewed, with most recorded dives < 2.5 m in depth (Table 2, Fig. 3B). Individuals

infrequently engaged in prolonged bout diving (1.7 ± 1.4 dives per bout, Table 2). Diving occurred throughout day (*n* = 317; 62% of dives), night (*n* = 115; 22% of dives), and twilight (*n* = 83; 16% of dives), with peak frequencies observed during midday, twilight, and after midnight. A moderate peak also occurred at 02h00, and diving was relatively infrequent between 23h00 and dawn (Fig. 4). PFSHs performed 0.10 ± 0.03 dives per hour during the day, 0.16 ± 0.05 dives per hour during the night, and 0.39 ± 0.11 dives per hour during twilight. There were approximately four times more dives during evening twilight than during morning twilight (Fig. 4).

DISCUSSION

This study involved only six chick-provisioning PFSHs, which were tracked for a relatively short duration during the chick-rearing
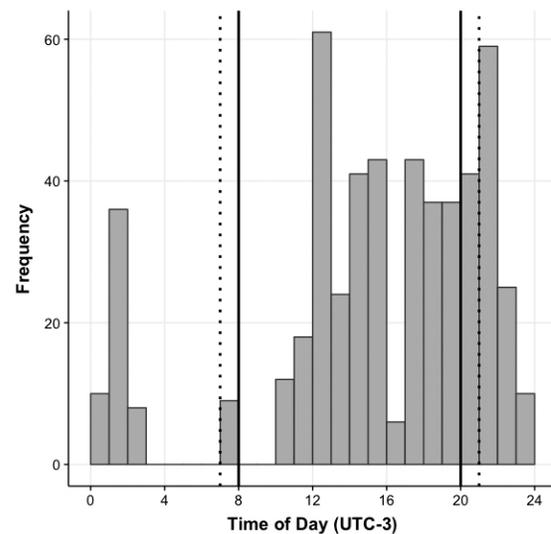
Fig. 4. Frequency distribution of Pink-footed Shearwater dives (*n* = 6 birds, 7 trips, 515 dives), based on local time (UTC −03h00). Daytime dives are between the solid lines (08h00–20h00), nighttime dives are outside the dotted lines (21h00–07h00), and twilight dives are contained between solid and dotted lines (07h00–08h00 and 20h00–21h00).

TABLE 1
Summary of GPS tracking (*n* = 6 birds, 7 trips), behavioral RST classifications (resting/foraging, searching, transiting), and percentage of dives in each classification (in parentheses) for breeding Pink-footed Shearwaters tracked from Isla Mocha during March 2015

ID-Trip	Date	Trip summaries			RST classifications (% of total dives by behavior)		
		Duration (d)	Track length (km)	Max dist. (km)	% Resting/foraging	% Searching	% Transiting
696-1	19–24 Mar	4.6	901	258	62 (17)	18 (67)	19 (17)
701-2	19–22 Mar	2.7	545	132	59 (63)	18 (23)	23 (13)
701-5	22–23 Mar	0.7	87	18	69 (50)	15 (10)	12 (30)
702-1	19–28 Mar	8.6	2183	334	61 (62)	12 (16)	26 (22)
703-1	20–26 Mar	5.9	1185	170	57 (57)	21 (19)	22 (24)
706-1	20–23 Mar	2.9	451	139	72 (93)	11 (4)	17 (4)
708-1	20–24 Mar	3.7	870	177	57 (81)	20 (13)	23 (5)
Average[a]		4.2 ± 2.5	889 ± 673	175 ± 100	62 ± 6 (60 ± 24)	16 ± 4 (22 ± 21)	20 ± 5 (16 ± 10)

[a] Average includes overall mean ± SD.

season at Isla Mocha, Chile. Nevertheless, we recorded complete foraging trips lasting up to eight days with high spatial and temporal resolution (GPS data at five-minute intervals), and we were able to describe behavior above and below the surface of the water.

The maximum dive depth (10.1 m) and overall mean maximum depth among individuals (4.6 ± 2.8 m) that we observed for PFSH are anomalously less than what would be predicted allometrically compared with several diving shearwaters—that is, PFSH diving ability seems more similar to the *Calonectris* shearwaters than to the *Ardenna* shearwaters (e.g., Burger 2001, Shoji *et al.* 2016). For example, the PFSH mean diving depths (1.6 ± 1.2 m, max = 10.1 m) and durations (4.7 ± 4.8 s, max = 26 s) we recorded were shallower than those for Short-tailed Shearwater (short trips: mean = 13 m, max = 30 m; long trips: mean = 58 m, max = 71 m; Weimerskirch & Cherel 1998) and Sooty Shearwater (short and long trips: 15.9 ± 10.8 m; Shaffer *et al.* 2009). Instead, we observed that PFSH dives were more similar to those of Flesh-footed Shearwaters (early breeding season: 4.8 ± 8.7 m; western North Pacific: 2.4 ± 2.6 m, Rayner *et al.* 2011), Great Shearwater (mean = 3.3 m, max = 18.9 m; mean duration 7.9 s, max duration 40 s; Ronconi *et al.* 2010), Streaked Shearwater *C. leucomelas*, 96% of dives < 3 m, max depth = 6 m; Matsumoto *et al.* 2012), Scopoli's Shearwater *C. diomedea*, depth = 0.0–5.4 m; duration = 5.6–14.0 s; Grémillet *et al.* 2014), and Cory's Shearwater *C. borealis* (mean max depth = 4.9 m, mean duration = 17 s; Paiva *et al.* 2010). Clearly, diving capacity among shearwaters varies according to species, but in general, most foraging occurs at shallower depths. The shallow, short-duration diving exhibited by PFSH partitions vertical foraging habitats among co-occurring shearwaters at sea (e.g., Sooty and PFSH; see Table 3 in Briggs *et al.* 1987, Ainley *et al.* 2009). This may reflect a greater reliance of PFSHs on subsurface predators (e.g., predatory fishes, cetaceans, and seabirds) to make prey more available to them near the surface (Martin 1986, Ainley *et al.* 2009).

PFSHs displayed diel variability in diving frequency (Fig. 4). Studies of other shearwater species have shown peak foraging-related behaviors associated with early morning and evening, with less diving activity during mid-day and little to no diving late at night (e.g., Great Shearwater, Ronconi *et al.* 2010; Flesh-footed Shearwater, Rayner *et al.* 2011; Sooty Shearwater, Shaffer *et al.* 2009). Although PFSH diving was generally less frequent at night than during the day, the moderate peak corresponding with the night (Fig. 4; 53 dives from 00h00 to 03h00) represented the activity of

three individuals, with one bird accounting for 40 of 53 dives (75%) that occurred during this period on one night. Our tracking period corresponded with the late chick-rearing period and coincided with a relatively dark phase of the moon (early waxing crescent). Chick-provisioning trips by Scopoli's Shearwater have been reported to be significantly longer during the full moon than around the new moon or during waxing/waning periods (Rubolini *et al.* 2015). Furthermore, Streaked Shearwaters spend more time flying and perform more frequent water landings during their non-breeding season (Yamamoto *et al.* 2008). Dias *et al.* (2012) suggested that individual Cory's Shearwaters display flexibility in their foraging strategies, depending on location and environmental conditions during the non-breeding season: birds were observed to be more diurnal in the warmer and shallower Benguela, Agulhas, and Brazilian currents, and more nocturnal in colder and deeper waters of the central-south and northwest Atlantic; this may be related to diel vertically migrating prey. It remains to be determined whether the diel patterns observed for PFSH in this study are consistent throughout the breeding season (i.e., during brighter periods at sea with more moonlight) or if they differ during the non-breeding season.

Adults provisioning chicks at Isla Mocha concentrated their diving behavior mostly within ~20 km of the coast north of Valdivia (Fig. 2B), which is consistent with results from a 2015–2017 study involving a larger sample of PFSHs outfitted with only GPS trackers (R. Carle *et al.* unpubl. data). This indicates that this region is an important foraging area for PFSHs, though its full significance remains to be characterized.

During the season of our study, this region of the Humboldt Current System is characterized oceanographically by persistent southwesterly winds that transport warmer surface waters offshore (Shaffer *et al.* 1999, Sobarzo *et al.* 2007). This transport drives upwelling of cooler, deoxygenated, nutrient-rich Subsurface Equatorial Waters of the Peru-Chile Undercurrent (Morales *et al.* 1996). Enhanced primary productivity off south-central Chile (30–40°S) supports an abundance of primary and secondary consumers (e.g., schooling fishes; Escribano *et al.* 2007) that likely are important prey for PFSHs. Although very little is known specifically about the food habits of PFSHs, they have been observed feeding on northern anchovy *Engraulis mordax* and market squid *Doryteuthis opalescens* (Baltz & Morejohn 1977; J. Adams, pers. obs.) while frequenting the California Current

TABLE 2
Summary of mean diving behavior (± SD) of Pink-footed Shearwaters tracked on seven trips
from Isla Mocha during March 2015, measured using time-depth recorders

ID-Trip	Dives	Bouts	Max depth (m)	Max duration (s)	Descent rate (m·s⁻¹)[a]	Ascent rate (m·s⁻¹)
696-1	6	6	1.4 (1.0 ± 0.3)	2.5 (1.8 ± 0.7)	0.56 ± 0.24	0.70 ± 0.11
701-2	52	35	2.2 (1.0 ± 0.5)	12.6 (2.5 ± 2.8)	0.59 ± 0.54	0.76 ± 0.61
701-5	20	12	4.5 (1.0 ± 0.9)	4.0 (1.5 ± 0.9)	0.73 ± 0.34	0.60 ± 0.23
702-1	109	62	5.3 (1.3 ± 0.9)	24.1 (4.8 ± 4.7)	0.44 ± 0.34	0.56 ± 0.43
703-1	209	120	10.1 (2.1 ± 1.5)	25.7 (5.9 ± 5.5)	0.52 ± 0.33	0.74 ± 0.36
706-1	28	23	4.4 (1.6 ± 1.1)	19.8 (8.3 ± 5.4)	0.45 ± 0.43	0.35 ± 0.24
708-1	91	44	4.3 (1.2 ± 0.6)	16.5 (2.7 ± 2.7)	0.57 ± 0.35	0.71 ± 0.29
Total and average	515	302	4.6 ± 2.8 (1.6 ± 1.2)	15.0 ± 9.2 (4.7 ± 4.8)	0.52 ± 0.37	0.67 ± 0.40

[a] Excluded outlier values from three dives with descent rates > 2.5 m·s⁻¹ and one dive with ascent rate > 2.5 m·s⁻¹ (i.e., "plunge errors").

during the non-breeding season. At Isla Mocha we observed adult chick-provisioning birds regurgitating unidentified fishes during capture at their colony. Direct observations of shearwaters foraging in association with pelagic purse seine operations off Chile (C. Suazo, unpubl. data) indicate that Sooty Shearwaters dive on average for longer duration (range = 2–8 s, mean = 4.95 ± 1.48 s, *n* = 24) than PFSHs (range = 1–6 s, mean = 2.82 ± 1.48 s, *n* = 29) when feeding in association with nets. While these net-associated PFSH dives are of slightly shorter mean duration than what we observed (4.7 ± 4.8 s), we have no way of knowing whether the short-duration dives that we measured were associated with fishing activity. This information, together with observed PFSH interactions with anchoveta *E. ringens* fisheries and feeding on sardines *Sardinops sagax* during purse seining in Chile (Suazo *et al.* 2014, C. Suazo, pers. obs.), suggests that schooling forage fishes in general are important prey for PFSH.

Recent concern regarding PFSH bycatch associated with purse seine fisheries targeting sardine and anchoveta off Chile (Suazo *et al.* 2014) may be better informed from the results of our study. Fishing activities pose several threats to shearwaters, and attraction to fishing vessels by increased seabird activity or enhanced food availability will increase risks associated with gear strikes, entanglement, hooking, and fouling (Robertson 1998, Lewison & Crowder 2003, Bull 2009). Risk of bycatch among the closely related, and behaviorally similar, Flesh-footed Shearwater has been implicated as one of the reasons for declines in its abundance in New Zealand (Priddel *et al.* 2006).

Additional information on the diving capacity of PFSHs may assist in designing and evaluating gear modifications, updating net and line deployment protocols (i.e., time of sets), and improving net and line designs (e.g., to increase sinking rates for purse seine nets and baited longlines; Robertson *et al.* 2006). For comparison, our measured descent rate for PFSH (0.52 m·s^{-1}) was about half that of Great Shearwater (1.14 m·s^{-1}, Ronconi *et al.* 2010) and approximately double the sink rate of modified longline gear (0.20 m·s^{-1}); these modifications have been shown to reduce bycatch for White-chinned Petrels *Procellaria aequinoctialis* and Sooty Shearwaters (Robertson *et al.* 2006). When commercial longline fisheries off Chile switched to a new system that increased sink rates five-fold (from 0.15 m·s^{-1} to 0.80 m·s^{-1}), seabird mortality was reduced to zero because fast-sinking, baited hooks were no longer available to shallow-diving species (Robertson *et al.* 2014).

Purse seine operations also present risks for diving seabird entanglement (Suazo *et al.* 2014). The factors affecting the risk of bycatch for an unfurling seine net are different from those affecting a baited longline. Whereas increasing the sinking rate or depth of deployment during longlining directly reduces the time that a baited hook is available to a foraging shearwater, the hazardous zone of a seine net (i.e., ceiling and folds, as described by Suazo *et al.* 2017) will be present for an extended duration as it sinks from the surface. Faster deployment of purse seine gear would reduce the amount of time in which birds can be entangled in netting near the surface. Other factors influencing the hazardousness of seine nets include the mesh size, the color of the top panel, and the net angle at the surface. If the float line is allowed to drift toward the center of the set, the net angle will increase, and the net will create a partial barrier at the surface surrounding the net curtain. In this scenario, shearwaters that are foraging underwater face the risk of drowning as they attempt to surface into the top of the overhanging net (Suazo *et al.* 2016).

Whereas our results have contributed new information on the foraging behavior of PFSHs raising chicks on Isla Mocha, additional research involving more individuals or individuals from other breeding colonies (such as the more oceanic Juan Fernández Archipelago), would improve estimates associated with variability in movements and diving behaviors. Likewise, future TDR and GPS deployments could span a greater portion of the breeding season and years with contrasting oceanographic conditions (e.g., El Niño Southern Oscillation). Continued assessment of certain fishing activities is currently being matched with assessments of the distribution and movements of PFSHs at sea (Carle *et al.*, unpubl. data) for a more comprehensive evaluation of fisheries overlap. Together with our results, these efforts are important because they enable fisheries managers to implement effective methods for minimizing potential impacts (including competition for food resources (Daunt *et al.* 2008)) to PFSHs, whether through gear modifications, revised fishing methods, flexible spatial closures, or limited fishing during the PFSH breeding period (c.f. Hyrenbach *et al.* 2000, Grantham *et al.* 2008).

REFERENCES

ACAP (Agreement on the Conservation of Albatrosses and Petrels). 2013. *Listing of New Species – Pink-footed Shearwater* Puffinus creatopus. Seventh Meeting of the Advisory Committee, 06–10 May 2013. AC7 Doc 24 Rev 1, Agenda Item 14. La Rochelle, France: ACAP.

ADAMS, J., SCOTT, D., MCKECHNIE, S., BLACKWELL, G., SHAFFER, S.A. & MOLLER, H. 2009. Effects of geolocation archival tags on reproduction and adult body mass of sooty shearwaters (*Puffinus griseus*). *New Zealand Journal of Zoology* 36: 355–366.

AINLEY, D.G., DUGGER, K.D., FORD, R.G. ET AL. 2009. Association of predators and prey at frontal features in the California Current: Competition, facilitation, and co-occurrence *Marine Ecology Progress Series* 389: 271–294.

BALTZ, D.M. & MOREJOHN, G.V. 1977. Food habits and niche overlap of seabirds wintering on Monterey Bay, California. *The Auk* 94: 526–543.

BRIGGS, K.T., TYLER, W.B., LEWIS, D.B. & CARLSON, D.R. 1987. *Bird communities at sea off California: 1975 to 1983*. Studies in Avian Biology No. 11. San Diego, CA: Cooper Ornithological Society.

BROOKE, M. DE L. 1987. *The Birds of the Juan Fernández Islands, Chile.* Cambridge, UK: International Council for Bird Preservation.

BROWN, R.G.B., BOURNE, W.R.P. & WAHL, T.R. 1978. Diving by shearwaters. *The Condor* 80: 123–125.

BULL, L.S. 2009. New mitigation measures reducing seabird by-catch in trawl fisheries. *Fish and Fisheries* 10: 408–427. doi:10.1111/j.1467-2979.2009.00327.x

BURGER, A.E. 2001. Diving depths of shearwaters. *The Auk* 118: 755–759.

CARLE, R.D., BECK, J.N, COLODRO, V. & HODUM, P. 2016. Efectos de la exclusión de ganado vacuno sobre la vegetación en el área ocupada por una colonia de Fardela Blanca (Ardenna creatopus) en la Isla Robinson Crusoe, Chile. [Effects of cattle exclusion on the vegetation at a Pink-footed Shearwater (*Ardenna creatopus*) colony on Robinson Crusoe Island, Chile.] *La Revista Chilena de Ornitología* 22: 184–193.

CHANG, W., CHENG, J., ALLAIRE, J.J., XIE, Y. & MCPHERSON, J. 2016. *Shiny: Web Application Framework for R.* R package version 0.13. 2, 2016. Boston, MA: RStudio, Inc.

DAUNT, F., WANLESS, S., GREENSTREET, S.P.R., JENSEN, H., HAMER, K.C. & HARRIS, M.P. 2008. The impact of the sandeel fishery closure on seabird food consumption, distribution, and productivity in the northwestern North Sea. *Canadian Journal of Fisheries and Aquatic Sciences* 65: 362–381.

DÁVILA PERÉZ, C.V., VELÁSQUEZ JOFRE, P.M. & SIGÜENZA, R. 2009. Diagnóstico de captura incidental de aves marinas en el Pacífico de Guatemala, Centro América. Corvallis, OR: Pacific Seabird Group. [Available online at: https://www.pacificseabirdgroup.org/GrantReports/SiguenzaDeMicheo.FinalReport.2010.pdf Accessed 12 October 2018.]

DIAS, M.P., GRANADEIRO, J.P. & CATRY, P. 2012. Working the day or the night shift? Foraging schedules of Cory's shearwaters vary according to marine habitat. *Marine Ecology Progress Series* 467: 245–252.

ENVIRONMENT CANADA. 2008. *Recovery strategy for the Short-tailed Albatross (Phoebastria albatrus) and the Pink-footed Shearwater (*Puffinus creatopus*) in Canada.* Species at Risk Act: Recovery Strategy Series. Ottawa: Environment Canada.

ESCRIBANO, R., HIDALGO, P., GONZÁLEZ, H., GIESECKE, R., RIQUELME-BUGUEÑO, R. & MANRÍQUEZ, K. 2007. Seasonal and inter-annual variation of mesozooplankton in the coastal upwelling zone off central-southern Chile. *Progress in Oceanography* 75: 470–485.

FAUCHALD, P. & TVERAA, T. 2003. Using first-passage time in the analysis of area-restricted search and habitat selection. *Ecology* 84: 282–288.

GLADICS, A.J., MELVIN, E.F., SURYAN, R.M., GOOD, T.P., JANNOT, J.E. & GUY, T.J. 2017. Fishery-specific solutions to seabird bycatch in the U.S. West Coast sablefish fishery. *Fisheries Research* 196: 85–95.

GUICKING, D., MICKSTEIN, S. & SCHLATTER, R.P. 1999. Estado de la población de Fardela blanca (*Puffinus creatopus*, Coues, 1864) en Isla Mocha, Chile. *Boletín Chileno de Ornitología* 6: 33–35.

GUICKING, D., RISTOW, D., BECKER, P.H., SCHLATTER, R., BERTHOLD, P. & QUERNER, U. 2001. Satellite tracking of the Pink-footed Shearwater in Chile. *Waterbirds: The International Journal of Waterbird Biology* 24: 8–15.

GUICKING, D., FIEDLER, W., LEUTHER, C., SCHLATTER, R. & BECKER, P.H. 2004. Morphometrics of the pink-footed shearwater (*Puffinus creatopus*): Influence of sex and breeding site. *Journal of Ornithology* 145: 64–68.

GRANTHAM, H.S., PETERSEN, S.L. & POSSINGHAM, H.P. 2008. Reducing bycatch in the South African pelagic longline fishery: The utility of different approaches to fisheries closures. *Endangered Species Research* 5: 291–299.

GRÉMILLET, D., PÉRON, C., PONS, J.-B. ET AL. 2014. Irreplaceable area extends marine conservation hotspot off Tunisia: Insights from GPS-tracking Scopoli's shearwaters from the largest seabird colony in the Mediterranean. *Marine Biology* 161: 2669–2680.

HOWELL, S.N.G. 2012. *Petrels, Albatrosses, and Storm-Petrels of North America: A Photographic Guide.* Princeton, NJ: Princeton University Press.

HYRENBACH, K.D., FORNEY, K.A. & DAYTON, P.K. 2000. Marine protected areas and ocean basin management. *Aquatic Conservation: Marine and Freshwater Ecosystems* 10: 437–458.

IUCN (International Union for Conservation of Nature) 2018. *The IUCN Red List of Threatened Species.* Version 2018-1. [Available online at: http://www.iucnredlist.org/ Accessed 12 October 2018.]

KELLEY, D. & RICHARDS, C. 2015. *oce: Analysis of Oceanographic Data.* R package version 0.9-17.

KURODA, N. 1954. On the classification and phylogeny of the order Tubinares, particularly the shearwaters (*Puffinus*). Tokyo, Japan: Published by the author.

LEWISON, R.L. & CROWDER, L.B. 2003. Estimating fishery bycatch and effects on a vulnerable seabird population. *Ecological Applications* 13: 743–753.

LUQUE, S.P. & FRIED, R. 2011. Recursive filtering for zero offset correction of diving depth time series with GNU R package diveMove. *PLoS One* 6: e15850.

MANGEL, J.C., ADAMS, J., ALFARO-SHIGUETO, J. ET AL. 2013. *Conservation implications of Pink-footed Shearwater (*Puffinus creatopus*) movements and fishery interactions assessed using multiple methods.* Fifth Meeting of the Seabird Bycatch Working Group. 01–03 May 2013. SBWG5 Doc 06, Agenda Item 18, 19. La Rochelle, France: Agreement on the Conservation of Albatrosses and Petrels. [Available online at: http://oikonos.org/papers/SBWG5_Doc_06_Mangel_et_al._pink-footed_shearwater_E_s_f.pdf Accessed 02 August 2018.]

MANGEL, J.C., ALFARO-SHIGUETO, J., BAQUERO, A., DARQUEA J., GODLEY, B.J. & HARDESTY NORRIS, J. 2011. *Seabird bycatch by small-scale fisheries in Ecuador and Peru.* Sixth Meeting of Advisory Committee, 29 August–02 September 2011. SBWG4 Doc 24, Agenda Item 5. Guayaquil, Ecuador: ACAP.

MARTIN, A.R. 1986. Feeding association between dolphins and shearwaters around the Azores Islands. *Canadian Journal of Zoology* 64: 1372–1374.

MATSUMOTO, K., OKA, N., OCHI, D., MUTO, F., SATOH, T.P. & WATANUKI, Y. 2012. Foraging behavior and diet of Streaked Shearwaters *Calonectris leucomelas* rearing chicks on Mikura Island. *Ornithological Science* 11: 9–19.

MINISTERIO SECRETARÍA GENERAL DE LA PRESIDENCIA. 2005. *Reglamento para la Clasificación de Especies Silvestres, 2005.* Decreto Supremo N°75. Santiago, Chile: Ministerio Secretaría General de la Presidencia, Chile. [Available online at: https://www.leychile.cl/Navegar?idNorma=237791 Accessed 02 August 2018.]

MORALES, C.E., BLANCO, J.L., BRAUN, M., REYES, H. & SILVA, N. 1996. Chlorophyll-*a* distribution and associated oceanographic conditions in the upwelling region off northern Chile during the winter and spring 1993. *Deep-Sea Research Part I: Oceanographic Research Papers* 43: 267–289.

PAIVA, V.H., GERALDES, P., RAMÍREZ, I., MEIRINHO, A., GARTHE, S. & RAMOS, J.A. 2010. Foraging plasticity in a pelagic seabird species along a marine productivity gradient. *Marine Ecology Progress Series* 398: 259–274.

PECK, D.R. & CONGDON, B.C. 2006. Sex-specific chick provisioning and diving behaviour in the Wedge-tailed Shearwater *Puffinus pacificus*. *Journal of Avian Biology* 37: 245–251.

PHILLIPS, R.A., XAVIER, J.C. & CROXALL, J.P. 2003. Effects of satellite transmitters on albatrosses and petrels. *The Auk* 120: 1082–1090.

PRIDDEL, D., CARLILE, N., FULLAGAR, P., HUTTON, I. & O'NEILL, L. 2006. Decline in the distribution and abundance of Flesh-footed Shearwaters (*Puffinus carneipes*) on Lord Howe Island, Australia. *Biological Conservation* 128: 412–424.

RAYNER, M.J., TAYLOR, G.A., THOMPSON, D.R., TORRES, L.G., SAGAR, P.M. & SHAFFER, S.A. 2011. Migration and diving activity in three non-breeding Flesh-footed Shearwaters *Puffinus carneipes*. Journal of Avian Biology 42: 266–270.

ROBERTSON, G. 1998. The culture and practice of longline tuna fishing: Implications for seabird by catch-mitigation. *Bird Conservation International* 8: 211–221.

ROBERTSON, G., MCNEILL, M., SMITH, N., WIENECKE, B., CANDY, S., & OLIVIER, F. 2006. Fast sinking (integrated weight) longlines reduce mortality of White-chinned Petrels (*Procellaria aequinoctialis*) and Sooty Shearwaters (*Puffinus griseus*) in demersal longline fisheries. *Biological Conservation* 132: 458–471.

ROBERTSON, G., MORENO, C., ARATA, J.A. ET AL. 2014. Black-browed Albatross numbers in Chile increase in response to reduced mortality in fisheries. *Biological Conservation* 169: 319–333.

RONCONI, R.A., RYAN, P.G. & ROPERT-COUDERT, Y. 2010. Diving of Great Shearwaters (*Puffinus gravis*) in cold and warm water regions of the South Atlantic Ocean. *PLos One* 5: e15508.

RUBOLINI, D., MAGGINI, I., AMBROSINI, R. ET AL. 2015. The effect of moonlight on Scopoli's Shearwater *Calonectris diomedea* colony attendance patterns and nocturnal foraging: A test of the foraging efficiency hypothesis. *Ethology* 121: 284–299.

SHAFFER, G., HORMAZABAL, S., PIZARRO, O. & SALINAS, S. 1999. Seasonal and interannual variability of currents and temperature off central Chile. *Journal of Geophysical Research* 104: 29951–29961.

SHAFFER, S.A., WEIMERSKIRCH, H., SCOTT, D. ET AL. 2009. Spatiotemporal habitat use by breeding Sooty Shearwaters *Puffinus griseus*. *Marine Ecology Progress Series* 391: 209–220.

SHOJI, A., DEAN, B., KIRK, H., FREEMAN, R., PERRINS, C.M. & GUILFORD, T. 2016. The diving behaviour of the Manx Shearwater *Puffinus puffinus*. *Ibis* 158: 598–606.

SOBARZO, M., BRAVO, L., DONOSO, D., GARCÉS-VARGAS, J. & SCHNEIDER, W. 2007. Coastal upwelling and seasonal cycles that influence the water column over the continental shelf off central Chile. *Progress in Oceanography* 75: 363–382.

SUAZO, C.G., CABEZAS, L.A., MORENO, C.A. ET AL. 2014. Seabird bycatch in Chile: A synthesis of its impacts, and a review of strategies to contribute to the reduction of a global phenomenon. *Pacific Seabirds* 41: 1–12.

SUAZO, C.G., CABEZAS, L.A. & YATES, O. 2016. *Collaboration on technical innovation towards the reduction of seabird bycatch in purse seine fisheries.* Seventh Meeting of the Seabird Bycatch Working Group, 02–04 May 2016. SBWG7 Doc 20 Rev 1, Agenda Item 9. La Serena, Chile: ACAP.

SUAZO, C.G., FRERE, E., GARCÍA, M., COCAS, L. & YATES, O. 2017. *Assessment of the "Modified Purse Seine (MPS)" against ACAP best practice criteria.* Eighth Meeting of the Seabird Bycatch Working Group, 04–06 September 2017. SBWG8 Doc 21, Agenda Item 10.1. Wellington, New Zealand: ACAP.

TORRES, L.G., ORBEN, R.A., TOLKOVA, I. & THOMPSON, D.R. 2017. Classification of animal movement behavior through residence in space and time. *PLoS One* 12: p.e0168513.

VEGA, R., OSSA, L., SUÁREZ, B. ET AL. 2018. *Informe Final: Convenio de Desempeño 2017.* Programa de Observadores Científicos, 2017. Valparaíso, Chile: Instituto de Fomento Pesquero.

VELARDE, E., GARCA-ALBERTO, G., GASTELUM-NAVA, E. & ANDERSON, D. 2017. *Seabird bycatch by the purse-seine small pelagic fishery in the central Gulf of California.* 44th Annual Meeting of the Pacific Seabird Group. Tacoma, WA: Pacific Seabird Group. [Available online at: https://pacificseabirdgroup.org/wp-content/uploads/2016/07/PSG_2017_ABSTRACTS.pdf Accessed on 03 November 2017.]

WEIMERSKIRCH, H. & CHEREL, Y. 1998. Feeding ecology of short-tailed shearwaters: Breeding in Tasmania and foraging in the Antarctic? *Marine Ecology Progress Series* 167: 261–274.

YAMAMOTO, T., TAKAHASHI, A., YODA, K. ET AL. 2008. The lunar cycle affects at-sea behaviour in a pelagic seabird, the Streaked Shearwater, *Calonectris leucomelas*. *Animal Behaviour* 76: 1647–1652.