



RESEARCH ARTICLE

Overlap of Pink-footed Shearwaters and central Chilean purse-seine fisheries: Implications for bycatch risk

Ryan D. Carle,^{1*} Jonathan J. Felis,² Rodrigo Vega,³ Jessie Beck,¹ Josh Adams,² Verónica López,¹ Peter J. Hodum,^{1,4} Andrés González,³ Valentina Colodro,¹ and Tiare Varela¹

¹ Oikonos Ecosystem Knowledge, Valparaíso, Región de Valparaíso, Chile

² U.S. Geological Survey, Western Ecological Research Center, Santa Cruz, California, USA

³ Instituto de Fomento Pesquero, Valparaíso, Región de Valparaíso, Chile

⁴ University of Puget Sound, Tacoma, Washington, USA

* Corresponding author: ryan@oikonos.org

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ABSTRACT

Understanding susceptibility of seabirds to fisheries bycatch requires quantifying overlap of seabird at-sea habitat with fisheries' distribution and effort. Pink-footed Shearwaters (*Ardenna creatopus*) are vulnerable seabirds that breed only in Chile. Recently, high rates of Pink-footed Shearwater bycatch (i.e. >1,500 observed mortalities 2015–2017) were documented by observers in central Chilean purse-seine fisheries. We present analysis of Pink-footed Shearwater at-sea movements and overlap with central Chilean purse-seine fleets targeting common sardine (*Strangomera bentincki*), Peruvian anchoveta (*Engraulis ringens*), and Chilean jack mackerel (*Trachurus symmetricus*). To determine overlap during 2015–2017, we paired locations from 49 Pink-footed Shearwaters rearing nestlings at Isla Mocha, Chile, with locations and number of observed purse-seine sets in central Chile. Pink-footed Shearwaters typically visited waters ≤30 km offshore throughout central Chile. Foraging trip durations varied interannually, with longer trips in 2016, but all years revealed persistent foraging hotspots near Valdivia, the Gulf of Arauco, and Isla Mocha, Chile. Greatest overlap between Pink-footed Shearwaters and fisheries occurred with the sardine/anchoveta fleet near Valdivia (artisanal and industrial) and the Gulf of Arauco (artisanal); overlap with the jack mackerel fleet was minimal. Given Pink-footed Shearwater bycatch documented in these fisheries, this overlap may indicate risk of bycatch for these birds, although we did not directly quantify shearwater–fisheries interaction. Our results can inform further fishery monitoring efforts, as well as collaboration among scientists, managers, and fishers to identify, quantify, and reduce fisheries bycatch of Pink-footed Shearwaters within Chile and internationally.

Keywords: *Ardenna creatopus*, at-sea distribution, endangered species, foraging trip, GPS tracking, Peruvian anchoveta, seabird conservation, seabird–fishery interaction

Traslape de zonas de alimentación de *Ardenna creatopus* y pesquerías de cerco de la zona central de Chile: Implicancias para el riesgo de captura incidental

RESUMEN

El entendimiento de la susceptibilidad de las aves marinas a captura incidental en pesquerías requiere cuantificar la sobreposición del hábitat marino de las aves con la distribución y el esfuerzo pesquero. *Ardenna creatopus* es un ave marina vulnerable que anida solamente en islas de Chile. Recientemente, se han reportado altas tasas de captura incidental de fardela blanca (i.e. >1.500 aves muertas entre 2015–2017) en pesquerías de cerco en Chile central. En el presente trabajo, presentamos un análisis de los movimientos de *A. creatopus* en el mar y su sobreposición con pesquerías de cerco que pescan sardina común (*Strangomera bentincki*), anchoveta peruana (*Engraulis ringens*), y jurel (*Trachurus symmetricus*) en Chile central. Para determinar sobreposición durante 2015–2017, superpusimos la distribución de 49 *A. creatopus* que se encontraban en el periodo de cría en Isla Mocha, Chile, con la posición y el número de lances de cerco en Chile central. *A. creatopus* usaron principalmente zonas ubicadas a ≤30 km del continente a lo largo de Chile central. La duración de los viajes de alimentación variaron interanualmente con viajes más largos en 2016, no obstante, se identificaron “hotspots” de alimentación persistentes cerca de Valdivia, el Golfo de Arauco, e Isla Mocha. La mayor sobreposición entre *A. creatopus* y las pesquerías ocurrió con las flotas de sardina/anchoveta cerca de Valdivia (artesanal e industrial) y el Golfo de Arauco (artesanal). Las altas tasas de captura incidental de *A. creatopus* documentadas en estas flotas y el nivel de sobreposición observada, posiblemente indican un elevado riesgo de captura incidental, sin embargo, en este estudio no cuantificamos interacciones entre *A. creatopus* y pesquerías directamente. Nuestros resultados apoyan el aumento de esfuerzos de monitoreo de pesquerías, la colaboración entre científicos, administradores de recursos y pescadores para identificar, cuantificar, desarrollar medidas de mitigación y reducir la captura incidental de *A. creatopus* en Chile e internacionalmente.

Palabras clave: anchoveta peruana, *Ardenna creatopus*, conservación de aves marinas, distribución de aves marinas, especies en peligro, GPS, interacciones aves marinas-pesquerías, viajes de alimentación

INTRODUCTION

Worldwide, mortality from fisheries bycatch has caused population declines among many seabird species (Hall et al. 2000, Melvin and Parrish 2001, Anderson et al. 2011). However, significant data gaps remain regarding extent and magnitude of seabird bycatch, and identification of specific fisheries that pose risks to birds due to habitat overlap and behavior at sea (Lewison et al. 2004, Anderson et al. 2011). A critical preliminary step to inform future fisheries observation programs and mitigate risk of seabird bycatch includes quantifying overlap of seabird at-sea habitat use with the distributions and efforts of fisheries (Phillips et al. 2006, Tuck et al. 2011, Waugh et al. 2016).

The Pink-footed Shearwater (*Ardenna creatopus*) has a breeding range restricted to 3 Chilean islands and a global breeding population currently estimated at ~60,000 individuals (Muñoz 2011, Hodum et al. 2016). Despite research on many species of shearwaters, few studies describe the ecology of the Pink-footed Shearwater (Guicking et al. 1999, 2001, 2004). This may be due to the species' remote breeding locations in South America and a global geographical bias among at-sea studies of seabirds toward the northern hemisphere and countries with high GDPs (Mott and Clarke 2018). About 30% of the Pink-footed Shearwater global breeding population nests on the Juan Fernández Archipelago, Chile (33.640°S, 78.850°W; 670 km offshore), and 70% nests on Isla Mocha, Chile (38.383°S, 73.900°W; 30 km offshore; Guicking et al. 1999, Muñoz 2011, Hodum et al. 2016). After breeding during austral summer, most Pink-footed Shearwaters undertake a trans-equatorial migration (about April–May) to the Pacific coast of North America (Guzman and Myres 1983, Felis et al. 2019). Due to threats on breeding colonies (Guicking et al. 1999, Hinojosa and Hodum 2007, Carle et al. 2016) and at sea (Suazo et al. 2014), the Pink-footed Shearwater is listed as endangered by Chile (Hinojosa and Hodum 2007), threatened by Canada (Hodum et al. 2008), vulnerable by IUCN (Birdlife International 2017), and under Annex 1 of the Agreement on the Conservation of Albatrosses and Petrels (ACAP 2013).

Little is known about at-sea overlap of Pink-footed Shearwaters with fisheries, but mortality from fisheries bycatch has been documented in Chile (Suazo et al. 2014, Vega et al. 2018), Peru, Ecuador (Mangel 2012, Mangel et al. 2012), Guatemala (Davila Perez et al. 2009), Mexico (E. Velarde, Universidad Veracruzana, personal communication), and the United States (Gladics et al. 2017, Jannot et al. 2018). Based on interviews with fishers, Mangel et al. (2012) estimated mortality of ~1,000 Pink-footed Shearwaters annually in Chilean gill-net, purse-seine, and long-line fisheries. Bycatch of Pink-footed Shearwaters in central Chilean purse-seine fisheries occurs mainly when

birds are trapped as the net is being hauled in, leading to death from drowning or trauma in the net or intake system (Suazo et al. 2016, 2017; D. Soto, personal communication). Based on on-board observations, 500–1,000 Pink-footed Shearwaters die annually in Peruvian gill-net, drift-net, and long-line fisheries (Mangel et al. 2012). In central Chilean purse-seine fisheries from 2015 to 2017, government fisheries observers documented bycatch mortality of 1,510 Pink-footed Shearwaters during 1,630 observed sets targeting Peruvian anchoveta (*Engraulis ringens*; hereafter “anchoveta”), common sardine (*Strangomera bentincki*; a clupeid that is not a true sardine; hereafter “sardine”), and Chilean jack mackerel (*Trachurus symmetricus*; hereafter “jack mackerel”; Vega et al. 2018). Pink-footed Shearwater was the most frequently documented seabird species captured in both the government observer program (Vega et al. 2018) and a small-scale, trial observer study (Suazo et al. 2014) of central Chilean artisanal and industrial sardine/anchoveta purse-seine fisheries. Documented fisheries bycatch of Pink-footed Shearwaters appears lower in the U.S. fisheries (Jannot et al. 2018); few data exist on bycatch in Mexico, Peru, Ecuador, and other countries.

Pink-footed Shearwaters may interact with central Chilean artisanal and industrial purse-seine fisheries because fishing activities concentrate prey. Although little is known about Pink-footed Shearwater diet, sardine and anchoveta likely are important prey (P. Hodum, personal observation; C. Suazo, Birdlife International, personal communication); the importance of jack mackerel as prey is unknown. In central Chile, seasonal abundances of sardine, anchoveta, and jack mackerel are influenced by environmental conditions (Arcos et al. 2001, Cubillos et al. 2001), including seasonally high primary productivity due to upwelling (September–March) in the Humboldt Current (Morales et al. 1996, Cubillos and Arcos 2002). Sardine and anchoveta are abundant over the shelf break during austral summer (Cubillos et al. 2001), whereas jack mackerel typically occur farther offshore (Arcos et al. 2001, Bertrand et al. 2004).

Sardine, anchoveta, and jack mackerel fisheries are economically important to central Chile (Castillo and Dresdner 2013). Fishing effort for sardine and anchoveta increased during the early 1990s to late 2000s, averaging annual landings of 700,000 tons (Cubillos et al. 2012). Landing composition of sardine and anchoveta has recently shifted toward sardine (Aranis et al. 2018). Jack mackerel annual take declined from 4,000,000 tons in the mid-1990s to an average of 225,000 tons from 2012 to 2017, due to declining stocks and new regulations (Arcos et al. 2001, Aranis et al. 2018).

Given Pink-footed Shearwater bycatch reported in central Chilean purse-seine fisheries, and the lack of information on at-sea distribution of Pink-footed Shearwaters, better understanding of where shearwaters and fisheries

overlap within Chilean waters is important for informing bycatch mitigation and at-sea conservation measures for the species (Hinojosa and Hodum 2007, ACAP 2013). Our goal was to track breeding Pink-footed Shearwaters from Isla Mocha during the chick-rearing period to (1) quantify at-sea distribution and foraging areas within Chile during the breeding season and (2) identify spatial overlap of Pink-footed Shearwaters with central Chilean purse-seine fishing effort.

METHODS

Shearwater Tracking

During March 17–28, 2015, February 18–March 5, 2016, and February 19–March 5, 2017, we used global positioning system (GPS) tags to determine foraging habitat use of adult Pink-footed Shearwaters breeding at Isla Mocha, Chile. We studied breeding birds during the chick-rearing period because we expected them to have greater nest-site fidelity during this stage, facilitating higher recapture rates to recover GPS tags. In addition, fishing effort for artisanal and industrial sardine/anchoveta and jack mackerel fleets (Vega et al. 2018) coincided with the Pink-footed Shearwater chick-rearing period (February–April; Hodum and Wainstein 2003).

We captured birds by hand when they left their burrows after chick provisioning and deployed GPS tags (modified i-gotU GT-120 GPS loggers, Mobile Action Technologies, New Taipei City, Taiwan) to record at-sea locations during foraging trips. We stripped the loggers from their housings and sealed them within 2:1 low-shrink-temperature, polyolefin heat-shrink tubing to create a lightweight, waterproof housing (final tag mass = 17 g). We attached tags to several central back feathers using 4 strips of tape (Tesa 4651, Norderstedt, Germany). Tag mass was 2.4% of the mean mass of adult Pink-footed Shearwaters measured on Isla Mocha (703 g, males and females combined; Guicking et al. 2004), and within the 3% body-mass maximum recommended for devices attached to procellariiform seabirds (Phillips et al. 2003). GPS loggers collected location data every 5 min to achieve a maximum expected duration of 10–14 days. During recapture, we blocked burrow entrances and recaptured birds outside burrows, removed tags, and returned birds to their burrows.

For analyses, we defined unique foraging trips as excursions beyond a 1.5-km radius around the colony. Pink-footed Shearwaters always depart and arrive at the colony nocturnally; we excluded trips when birds left and returned during the same night, because visual inspection of these trips indicated nocturnal circling of the colony. To examine interannual variability in at-sea behaviors, we calculated mean annual trip duration, distance traveled, and maximum range for all foraging trips. For each foraging trip metric, we tested the effect of year using ANOVAs and

tested differences between years with post-hoc Student's *t*-tests, with *P*-values adjusted for multiple comparisons using the sequential Bonferroni method (Holm 1979). We used the statistical package JMP (SAS Institute, Cary, North Carolina, USA) for all statistical tests. Statistical significance was defined as $P \leq 0.05$.

Fisheries Effort and Overlap

We evaluated Pink-footed Shearwater locations in relation to spatial fishing effort data from a government observer program administered by the Chilean Instituto de Fomento Pesquero (IFOP; Vega et al. 2018). Fishing effort data included observed set locations and target species captured from 2015 to 2017 for artisanal and industrial purse-seine fisheries operating in central Chile between approximately 35°S and 40°S (from Chilean Region V [Valparaíso] to Region XIV [Los Ríos]). During 2015–2017, the industrial purse-seine fleet (vessels >18 m in length; Castillo and Dresdner 2013) was composed of 25–28 vessels operating out of the ports of Coronel, San Vicente, and Lota in Region VIII (Biobío) of Chile (Aranis et al. 2018). Industrial vessels switched between targeting either sardine/anchoveta or jack mackerel. The artisanal purse-seine fleet in this region primarily fished for sardine/anchoveta and the number of vessels ranged from 472 to 506 during 2015–2017 (Aranis et al. 2018). The main ports of landing for this artisanal fleet are Talcahuano and Coronel (Region VIII), near Concepción to the north of Isla Mocha, and Corral, just west of Valdivia (Region XIV) to the south of Isla Mocha (Aranis et al. 2018). Although officially referred to as “artisanal” in Chile (vessels ≤18 m; Castillo and Dresdner 2013), by global standards most vessels in this heterogeneous fleet would be considered “semi-industrial.” We refer to this fleet hereafter as “artisanal.” Chilean law prohibits the industrial fleet from operating ≤10 km offshore; artisanal vessels may fish within and beyond that boundary (Castillo and Dresdner 2013).

Annual observer coverage of trips during 2015–2017 was 15.8–23.1% in the industrial sardine/anchoveta fishery, 11.6–12.2% in the industrial jack mackerel fishery and 1.3–2.1% in the artisanal sardine/anchoveta fishery (IFOP and Servicio Nacional de Pesca y Acuicultura [SERNAPESCA], personal communication). Fishing effort described here should be regarded as a minimum as it only covers observed sets. The sardine/anchoveta industrial and artisanal fisheries are closed each year from late December to early March during the fish recruitment season, with fishing typically beginning in late March (Aranis et al. 2018). Fishing activity is lower in the second half of the year, including closure from August to October during the fish species' reproductive seasons (Aranis et al. 2018). During 2015–2017, the industrial jack mackerel fleet fished throughout the year, except for September and October (Vega et al. 2018). Despite official seasonal closures, during 2015–2017

observers recorded artisanal sardine/anchoveta sets during all months of the year, and industrial sardine/anchoveta sets during all months except September, December, and January (Vega et al. 2018). Officially open fisheries overlapped with the Pink-footed Shearwater breeding season during October–December (prospecting/incubation) and March–April (chick rearing).

To quantify overlap of Pink-footed Shearwaters and fishing effort, we limited our spatial analysis by latitude (35–40°S) and distance offshore (≤170 km) according to the measured extent of overlap between Pink-footed Shearwater foraging trips from Isla Mocha and fishing effort, both from this study. Using ArcGIS (Environmental Systems Research Institute, Redlands, California, USA), we created a 10 × 10 km grid-cell network in this region and conducted all analyses on a per-grid-cell basis. We used this grid-cell size because 10 km was slightly greater than the distance a Pink-footed Shearwater could travel during the GPS sampling interval (5 min) at the mean maximum observed speed per trip (27 m s⁻¹), thus, a location point likely occurred in any cell crossed. We calculated Pink-footed Shearwater area use at sea in 2 ways: (1) the mean annual proportion of time spent by all tracked individuals in each cell for each study year (P_i) and (2) the mean annual proportion of tracked individuals that entered each cell for any amount of time for each study year (P_t). For fishing data, we calculated the mean annual proportion of total sets by each fishery in each cell during February–April (S). We restricted fishery analyses to February 1–April 30, 2015–2017, coincident with the Pink-footed Shearwater chick-rearing period. We calculated fishery-specific relative spatial overlap indices (FO) for each cell using the following equations for the 2 different shearwater-use metrics (P_i and P_t):

$$FO_i = \frac{P_i \times S}{A} \text{ and } FO_t = \frac{P_t \times S}{A}$$

where A = grid cell area, and FO_i is overlap based on P_i and FO_t is overlap based on P_t . For both metrics, we calculated FO as a per-unit-area metric by dividing by grid cell area because grid cells intersecting the coastline represented less physical area than those entirely at sea. We classified FO into 4 categories based on the quartiles of the distribution of all cell values to map the spatial distribution of FO for each fishery. Areas with no overlap were not included in overlap calculations.

Finally, we created a metric of relative shearwater-fishery overlap directly comparable across fisheries by identifying all grid cells in the study area where fishing effort and tagged Pink-footed Shearwaters co-occurred. We calculated the sums of P_i and S that occurred within those cells and graphed them against each other to visualize the degree of cumulative overlap between tagged Pink-footed Shearwaters and each fishery. All results are reported as means ± SD.

RESULTS

Pink-footed Shearwater Tracking

We recovered GPS tags with usable tracking data from 18 Pink-footed Shearwaters in 2015 (25 deployed, 19 recovered), 16 in 2016 (23 deployed, 16 recovered), and 15 in 2017 (25 deployed, 22 recovered). In total, we documented 83 unique foraging trips by 47 individuals. Across all years, mean trip duration, maximum range, and distance traveled were 93.7 ± 72.5 hr (3.9 ± 3.0 d), 164.7 ± 137.4 km, and 909.8 ± 872.0 km, respectively (Table 1). Across all foraging trips recorded, year had a significant effect on trip duration ($F_{2,79} = 9.50$, $P \leq 0.001$), maximum trip range ($F_{2,80} = 7.08$, $P = 0.002$), and distance traveled ($F_{2,79} = 12.20$, $P \leq 0.001$; Table 1). Mean trip duration and distance traveled were significantly greater during 2016 than during either 2015 (duration $t_{79} = 4.13$, $P \leq 0.001$, distance $t_{79} = 4.77$, $P \leq 0.001$) or 2017 (duration $t_{79} = 3.42$, $P = 0.002$, distance $t_{79} = 3.68$,

TABLE 1. Mean ± SD duration, maximum range, and distance travelled of foraging trips (excluding intra-night trips) made by Pink-footed Shearwaters breeding on Isla Mocha, February–April 2015–2017. “Short” foraging trips were <30 hr duration (spanning a single day between nocturnal visits) and “long” foraging trips were ≥30 hr duration (with at least one night spent away from the colony). Some trips are from the same individuals because some birds were tracked for more than one trip

Trip type		Birds	Trips	Duration (hr)	Range (km)	Distance travelled (km)
Short	2015	8	13	19.0 ± 3.3	28.2 ± 17.3	122.6 ± 47.6
	2016	4	5	18.3 ± 2.5	17.1 ± 7.1	98.9 ± 40.7
	2017	3	4	17.8 ± 3.1	15.2 ± 7.7	69.8 ± 32.6
	Short total	15	22	18.6 ± 3.0	23.3 ± 15.1	107.6 ± 46.8
Long	2015	18	24	100.7 ± 41.6	159.4 ± 70.4	858.7 ± 453.5
	2016	16	18	179.4 ± 82.6	303.3 ± 167.6	1,989.4 ± 1,078.8
	2017	13	19	90.2 ± 26.5	203.8 ± 87.4	878.8 ± 326.6
	Long total	47	61	121.2 ± 65.9	215.7 ± 125.6	1,203.9 ± 845.7
All trips	2015	18	37	72.0 ± 51.7	113.3 ± 85.4	600.1 ± 509.0
	2016	16	23	144.3 ± 99.4	241.1 ± 190.5	1,578.4 ± 1,239.1
	2017	15	23	77.1 ± 37.3	171.0 ± 107.7	731.7 ± 434.2
	Grand total	49	83	93.7 ± 72.5	164.7 ± 137.4	909.8 ± 872.0

$P \leq 0.001$). The 2015 and 2017 trip duration and distances did not significantly differ (duration $t_{79} = 0.29$, $P = 0.78$, distance $t_{79} = 0.63$, $P = 0.53$; Table 1). Trip range was significantly greater during 2016 vs. 2015 ($t_{80} = 3.75$, $P \leq 0.001$) but did not differ 2016 vs. 2017 ($t_{80} = 1.85$, $P = 0.13$) or 2015 vs. 2017 ($t_{80} = 1.69$, $P = 0.09$; Table 1).

Pink-footed Shearwaters demonstrated a bimodal foraging pattern of either short trips (<30 hr long; spanning only one day between two nocturnal visits; 27% of trips) or long trips (≥ 30 hr; at least one full night spent at sea away from colony; 73% of trips; Figure 1). We summarized trip metrics separately for short and long trips (Table 1). Across all years, means of trip duration, maximum range, and distance traveled of long trips were at least 5 times greater than those of short trips (Table 1).

In 2015 and 2017, Pink-footed Shearwaters used near-shore (≤ 30 km from coast) waters and ranged from near Valdivia in the south to 150 km north of Concepción in the north (Figure 2A, 2C). During 2016, Pink-footed Shearwaters ranged farther (up to 680 km from Isla Mocha) to both the north and south, from near Isla Chiloé in the south to near the port of San Antonio in the north (33.833–44.500°S; Figure 2B). The longest trip recorded during any year was 13 days in 2016. Pink-footed Shearwaters also traveled farther offshore in 2016 than in other years (often >100 km, and up to 170 km, offshore), with 50% of Pink-footed Shearwaters traveling to deep waters over submarine canyons and the Atacama Trench, in addition to widespread use of nearshore waters (Figure 2B).

Across all tracking years combined there were 2 distinct regions that we qualitatively considered hotspots, based on >70% of tagged Pink-footed Shearwaters visiting them in at least 1 study year (Figure 3). The most prominent

interannual hotspot was south of Isla Mocha in an off-shore area north of the city of Valdivia (approximately 39.0–39.5°S; hereafter, “Valdivia hotspot”; Figure 3). Ninety percent of tracked Pink-footed Shearwaters visited the Valdivia hotspot in 2015, 100% in 2016, and 30% in 2017 (Figure 2). Although tagged individuals traveled much farther north, south, and offshore in 2016 compared with other years, the principal area used was the Valdivia hotspot (Figure 2B). A second hotspot was throughout a larger coastal region to the north of Isla Mocha, from ~37.600°S north to Concepción (36.817°S), including the Gulf of Arauco (hereafter, “Gulf of Arauco hotspot”; the Gulf of Arauco is an obvious coastal feature located just north of the town of Arauco; Figures 2 and 3). The Gulf of Arauco hotspot was secondary to the Valdivia hotspot in 2015 and 2016 (30–40% of birds), but during 2017 it was the primary area visited (70–80% of birds; Figure 2). In all years, a smaller percentage of birds also used waters north of the latitude of Concepción, and there was consistent use of waters surrounding Isla Mocha in all years (Figure 2). Areas of greatest use were consistent when analyzed as the proportion of tracked individuals visiting a grid cell (P_i) vs. proportion of bird time spent in each cell (P_t ; Figure 3); however, in analysis based on P_t , the Valdivia and Gulf of Arauco hotspots and around Isla Mocha were prominent, with little time spent elsewhere (Figure 3B).

Fisheries Effort

During February–April 2015–2017, artisanal sardine/anchoveta purse-seine fishery activity occurred primarily 10–20 km offshore (Figure 4). Regions with greatest artisanal fishing effort were near Valdivia (~39.167–39.833°S), from the Gulf of Arauco to the north of Concepción (~36.333–37.167°S), and around Isla Mocha (Figure 4A). A total of 417 artisanal sardine/anchoveta sets occurred in the study area, representing 100% of observed sets recorded by observers in this fishery anywhere during those months (Figure 4A). Industrial sardine/anchoveta purse-seine fishery sets ($n = 190$) occurred 10–30 km offshore, exclusively in the Valdivia region (~38.167–40.000°S; Figure 4B), representing 100% of observed sets recorded by observers in this fishery anywhere during the study period. The industrial jack mackerel fishery operated farther from the coast, with most sets ranging from 40 to several hundred kilometers offshore (Figure 4C). Within the study area, industrial jack mackerel sets ($n = 237$) represented 42% of observed sets recorded anywhere by observers in this fishery during the study period (most sets occurred beyond 170 km from the coast and outside our study area boundary). The jack mackerel fishery was more dispersed than the industrial and artisanal sardine/anchoveta fisheries, with few sets occurring in any single grid cell (Figure 4C).

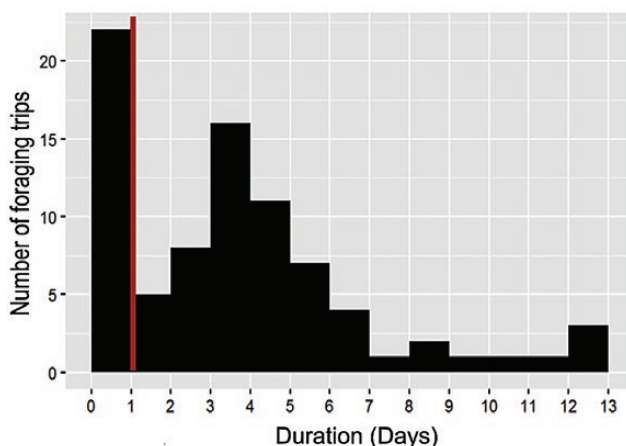


FIGURE 1. Pink-footed Shearwater foraging trip durations (days) from Isla Mocha, 2015–2017 (excluding intra-night trips; $n = 83$ foraging trips, 47 birds). The red line distinguishes short trips (<30 hr) and long trips (≥ 30 hr with at least one night spent at sea away from colony).

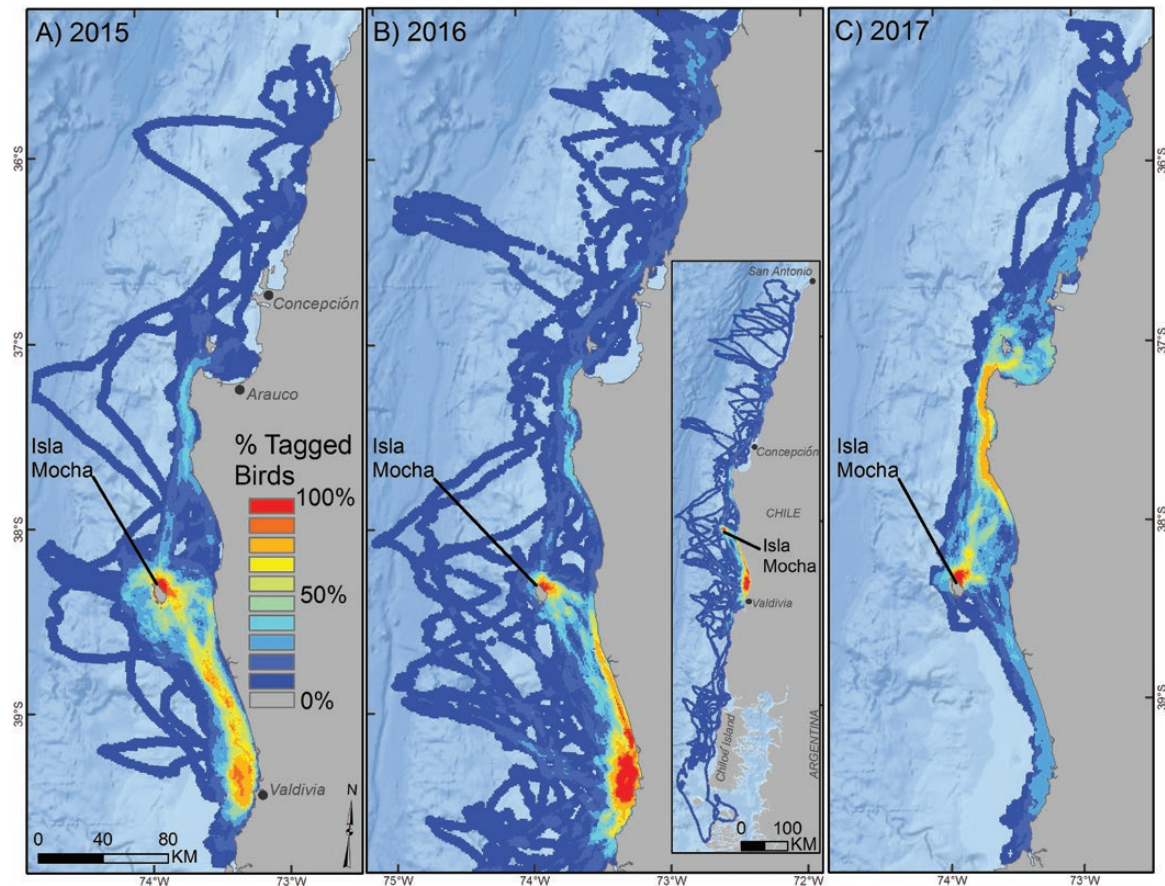


FIGURE 2. At-sea habitat use by Pink-footed Shearwaters tracked from Isla Mocha during **(A)** 2015 (March 17–25; $n = 18$ birds), **(B)** 2016 (February 18–March 5; $n = 16$ birds), and **(C)** 2017 (February 19–March 5; $n = 15$ birds). Heat map indicates percentage of tracked individuals (cell size = 1 km, search radius = 3 km). Inset on **(B)** map shows full extent of 2016 tracking data.

Overlap of Pink-Footed Shearwaters with Fisheries

Nearly all Pink-footed Shearwater locations were within the fisheries overlap study area ($35.0\text{--}40.0^\circ\text{S}$, ≤ 170 km offshore) except for the most distant locations of several long trips in 2016 ($<10\%$ of birds; we excluded these locations from analysis). Although the relative spatial distribution of shearwater-use metrics P_i and P_t differed somewhat (Figure 3), overlap locations and relative spatial magnitudes of indices FO_i and FO_t , calculated using P_i and P_t , respectively, were similar, so we only report overlap results based on FO_i .

Areas with the greatest overlap (FO_i) of Pink-footed Shearwaters with artisanal sardine/anchoveta fisheries occurred in the Valdivia hotspot, from the Gulf of Arauco to the north of Concepción, and around Isla Mocha (Figure 5A). No cell >50 km offshore registered FO_i with artisanal fisheries (Figure 5A). Pink-footed Shearwaters overlapped with industrial sardine/anchoveta fisheries exclusively at the Valdivia hotspot, and all grid cells with FO_i were ≤ 30 km from shore (Figure 5B). Areas of greatest overlap with the industrial jack mackerel fishery were scattered

throughout the study area, with greatest overlap around Isla Mocha and offshore of the Gulf of Arauco (Figure 5C). It is important to note that each fishery is scaled relative to its own effort (S), so that FO_i values are not directly comparable among fisheries. When comparing the cumulative shearwater–fishing overlap, a metric directly comparable across fisheries, 19% of Pink-footed Shearwater time (P_t) overlapped with 100% of industrial sardine/anchoveta fishing effort (S), 45% of P_t overlapped with 99% of artisanal sardine/anchoveta fishing S , and 6% of P_t overlapped with 68% of industrial jack mackerel fishing S .

DISCUSSION

During 2015–2017, Pink-footed Shearwaters breeding on Isla Mocha used waters off central Chile from 33.833°S to 44.500°S , with interannually persistent hotspots in areas ≤ 30 km offshore near Valdivia, the Gulf of Arauco, and Isla Mocha (Figure 3). Throughout this range, tagged Pink-footed Shearwaters overlapped extensively with industrial and artisanal purse-seine fisheries targeting sardine and

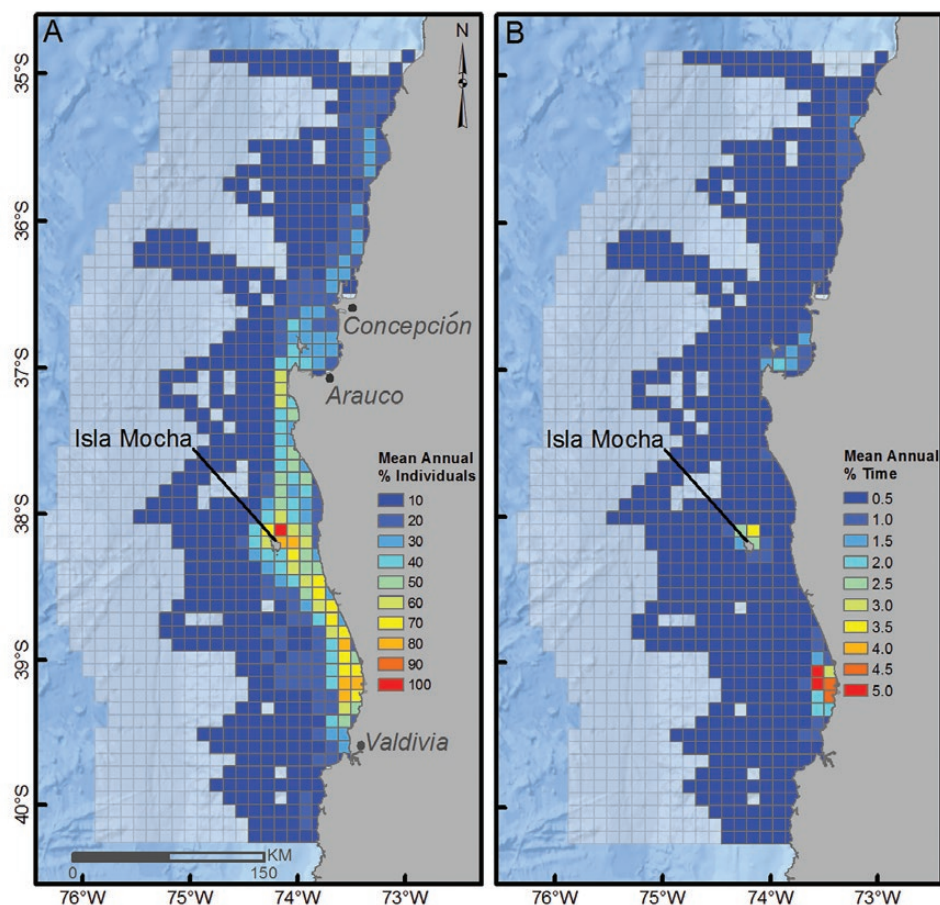


FIGURE 3. Mean annual percentages of habitat use of Pink-footed Shearwaters tracked from Isla Mocha during 2015–2017 (see sample sizes in Figure 2 caption), in 10×10 km grid cells. (A) shows percentages of tracked individuals (P_i) that visited each cell and (B) shows percentages of total tracked bird time (P_t) in each cell. Gray cells had no bird use.

anchoveta (Figure 4), which are known to have Pink-footed Shearwater bycatch and mortality (Suazo et al. 2014, Vega et al. 2018).

Our Pink-footed Shearwater tracking results were consistent with small samples of previously tracked chick-rearing Pink-footed Shearwaters from Isla Mocha (Guicking et al. 2001) and the Juan Fernández Archipelago (Hodum and Wainstein 2003), which visited areas from the Gulf of Arauco to north of Concepción (~ 36.0 – 37.0° S). However, the importance of the Valdivia hotspot to Pink-footed Shearwaters was undocumented prior to this study. Furthermore, simultaneously deployed time–depth recorders on a subset of 6 GPS-tagged Pink-footed Shearwaters (this study) during 2015 indicated diving behavior (i.e. foraging) occurred most frequently near Valdivia followed by the Gulf of Arauco and around Isla Mocha (Adams et al. 2019). With a greater number of GPS tagged Pink-footed Shearwaters in this study, the Valdivia hotspot proved to be the most frequently used foraging area for chick-rearing shearwaters at Isla Mocha ($\sim 70\%$

of the world breeding population), with 90% and 100% of tagged birds visiting it in 2015 and 2016, respectively.

Valdivia, the Gulf of Arauco, and Isla Mocha are associated with major upwelling centers on the central Chilean coast between Concepción and Valdivia (Atkinson et al. 2002). We suggest that Pink-footed Shearwaters from Isla Mocha may visit these areas to take advantage of increased prey availability in reliably productive waters. Foraging hotspots near Valdivia, the Gulf of Arauco, and Isla Mocha were persistent across years (based on both P_i and P_t metrics), with the relative importance of each area varying interannually (Figure 2). For example, the Valdivia hotspot was visited by tagged birds in all years but had much greater use in 2015 and 2016 than in 2017, when birds more often traveled north to the Gulf of Arauco (Figure 2). Foraging trips with significantly longer durations and greater distances traveled during 2016 (Table 1, Figure 2B) coincided with a strong El Niño oceanographic event in the Humboldt Current during March 2015–April 2016 (Kogan and Guo 2017). El Niño events are characterized by reduced

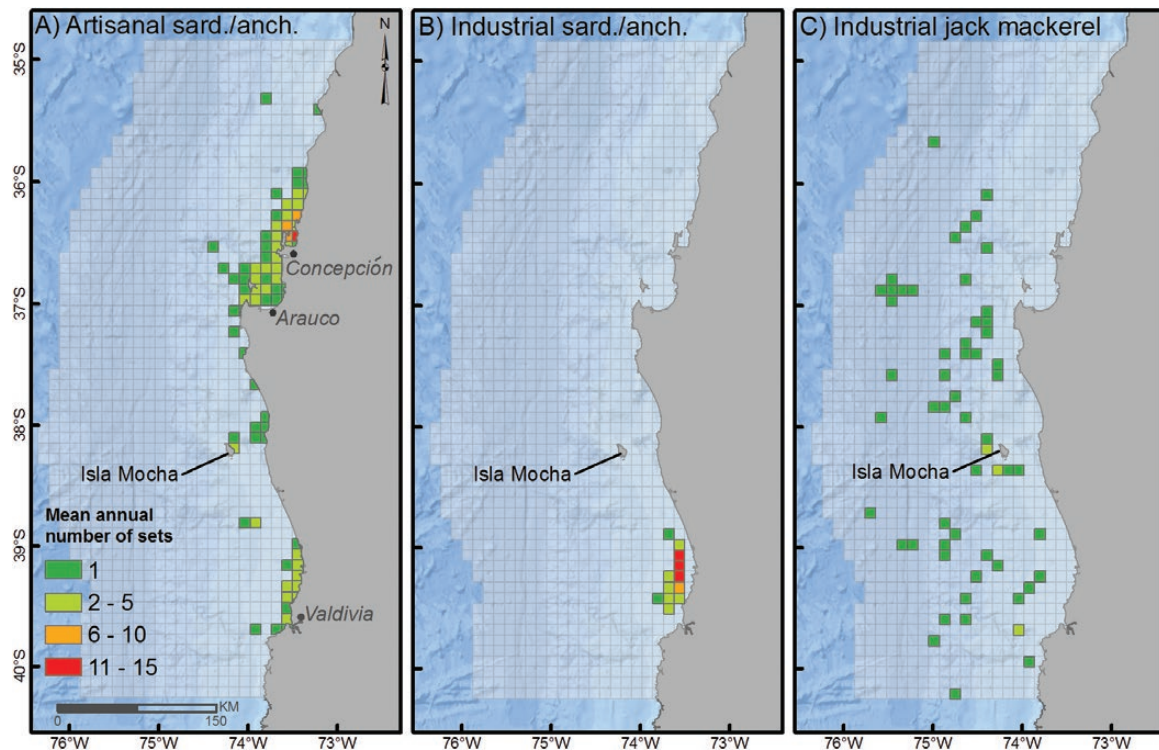


FIGURE 4. Effort of (A) artisanal sardine/anchoveta, (B) industrial sardine/anchoveta, and (C) industrial jack mackerel purse-seine fisheries in the fisheries overlap study area, February–April 2015–2017 ($n = 417$ artisanal sardine/anchoveta sets, 190 industrial sardine/anchoveta sets, and 237 industrial jack mackerel sets). Fishing effort (S) was summarized as mean annual number of sets in each 10×10 km grid cell ($n = 1,498$ cells). Gray cells had no sets.

primary productivity and decreased availability of forage fish (Barber and Chavez 1983, Espinoza-Morriberon et al. 2017), which might partially explain different movements of Pink-footed Shearwaters during 2016. However, central Chilean fishery landings did not indicate a major decline in abundance or shift in distribution of forage fishes during 2016, except for the jack mackerel fishery moving farther offshore (Aranis et al. 2018).

The distribution of Pink-footed Shearwater foraging trip durations was bimodal (Figure 1) similar to that described for other shearwaters (e.g., Weimerskirch 1998, Congdon et al. 2005, Magalhães et al. 2008) and albatrosses (e.g., Weimerskirch et al. 1997, Hyrenbach et al. 2002). Long-duration foraging trips outnumbered short-duration trips and averaged much greater distances and ranges (Table 1). However, Pink-footed Shearwater long foraging trips were relatively short (average annual distance traveled 858.7 ± 453.5 km to $1,989.4 \pm 1,078.8$ km; Table 1) compared with some *Ardenna* shearwaters, especially those breeding far from high-productivity waters, including Great Shearwaters (*A. gravis*; $9,257 \pm 3,249$ km; Schoombie et al. 2018), Short-tailed Shearwaters (*A. tenuirostris*; annual averages $>10,000$ km; Berlincourt and Arnould 2015), and Sooty Shearwaters (*A. grisea*; range of 4,500–12,700 km; Shaffer et al. 2009). Pink-footed Shearwater foraging

trips from Isla Mocha were more similar to those of their closest relative, Flesh-footed Shearwaters (*A. carneipes*), breeding at Lord Howe Island, Australia (“long” trips 724 ± 193 km; Thalmann et al. 2009). Although Pink-footed Shearwaters could have made trips longer than our study effort without being recaptured, 78% of all tags deployed were recovered, indicating longer trips may be infrequent. Nearby productive foraging areas associated with upwelling centers (Atkinson et al. 2002) may benefit Pink-footed Shearwaters breeding at Isla Mocha by allowing them to expend less foraging effort than those breeding at the oceanic Juan Fernández Archipelago (670 km offshore). For example, Pink-footed Shearwaters from the Juan Fernández Archipelago occasionally traveled much greater distances to reach the same relatively nearshore foraging grounds offshore of the Concepción area used by the birds we tracked from Isla Mocha (Hodum and Wainstein 2003). Not only could this result in differences in reproductive success between the 2 colonies but it may indicate different exposure to fisheries overlap.

We identified areas of overlap between Pink-footed Shearwaters and central Chilean purse-seine fisheries that can be used to focus and inform further fisheries observing efforts and eventual bycatch mitigation efforts. The foraging range from Isla Mocha and aggregation in

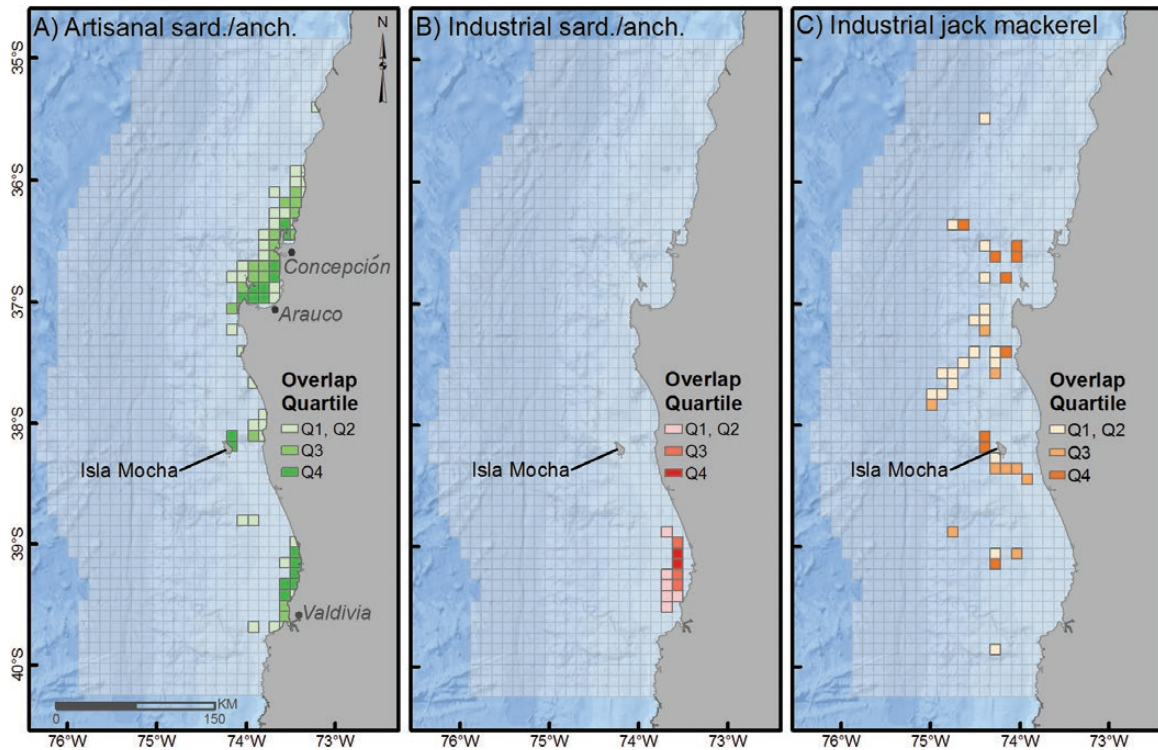


FIGURE 5. Relative overlaps (FO) of Pink-footed Shearwaters (average percentage of tracked individuals per cell P) with fishing sets of (A) artisanal sardine/anchoveta, (B) industrial sardine/anchoveta, and (C) industrial jack mackerel purse-seine fishery effort (S) during February–April 2015–2017. Heat map categories indicate quartiles (Q1–Q4) for each value, with Q4 being greatest overlap and Q1 being least overlap. Cells where shearwaters and fishing effort did not co-occur (gray) had no overlap and were not included in calculations of FO_i quartiles. Note that quartiles of each fishery are scaled relative to that fishery’s effort and are not directly comparable across fisheries.

nearshore areas resulted in overlap with sardine/anchoveta fisheries (Figures 5), especially near Valdivia (industrial and artisanal fleets) and the Gulf of Arauco (artisanal fleet only; Figure 5A, 5B). Overlap with the industrial jack mackerel fishery was much less extensive but did occur near Isla Mocha and the Gulf of Arauco (Figures 5C). The industrial sardine/anchoveta fishery had the greatest overlap with tagged Pink-footed Shearwaters (Figures 5B). It is notable that data from the observer program coincident with our study (all months of 2015–2017) indicated that the industrial sardine/anchoveta fishery had the greatest bycatch rate of Pink-footed Shearwaters of observed purse-seine fleets, with 5.5 birds caught per set (Vega et al. 2018), vs. 2.1 birds per set in the artisanal sardine/anchoveta fishery (Vega et al. 2018). Observer coverage was variable in these fisheries, with greater coverage of trips per year in the industrial sardine/anchoveta fishery (15.8–23.1%) and jack mackerel fishery (11.6–12.2%) than in the artisanal sardine/anchoveta fisheries (1.3–2.1%). Given the relatively low observer coverage of the artisanal fishery, results of the spatial extent of that fishery and overlap with Pink-footed Shearwaters should be interpreted cautiously. Nevertheless, tagged Pink-footed Shearwaters frequently

used waters ≤ 10 km offshore, in the exclusive fishing zone of the artisanal fleet.

Whereas the importance of the Valdivia hotspot for tagged Pink-footed Shearwaters during 2015 and 2016 may indicate increased potential exposure to the industrial sardine/anchoveta fishery, during 2017 they overlapped more with the artisanal sardine/anchoveta fishery at the Gulf of Arauco hotspot. Trips ranging farther offshore during 2016 could have resulted in greater exposure to the jack mackerel fishery, which had relatively low bycatch rates of Pink-footed Shearwaters during 2015–2017 (0.02 birds caught per set; Vega et al. 2018). Likewise, longer-distance foraging trips during 2016 may have exposed shearwaters to 4 additional fisheries not analyzed here: an artisanal purse-seine fishery targeting Falkland sprat (*Sprattus fuegensis*) based in the Port of Calbuco (41.77°S, 73.13°W) near Isla Chiloé, anchoveta and jack mackerel purse-seine fisheries in northern Chile, a long-line swordfish (*Xiphias gladius*) fishery operating far offshore, and a trawl fishery targeting Chilean hake (*Merluccius gayi gayi*) in south-central Chile.

Pink-footed Shearwater foraging areas and overlap with fisheries may vary seasonally depending on phenology-specific shearwater movement patterns. Foraging behavior

during chick-rearing is not necessarily representative of shearwater pre-breeding or incubation periods. For instance, Cory's Shearwaters (*Calonectris borealis*) made more "short" trips during chick-rearing than during incubation, resulting in an overall decrease in home range (Paiva et al. 2010), whereas the foraging range of Great Shearwaters was much greater during chick-rearing than incubation (Schoombie et al. 2018). In addition, intra-annual and interannual, and vessel-specific variability in fishing locations and effort, which we did not analyze, could influence the degree of overlap and/or bycatch of Pink-footed Shearwaters. For example, in various systems changes in seabird bycatch have been linked to interannual variability in fishing fleet effort and location (Torres et al. 2013), poor seabird foraging conditions associated with environmental variability (Gilman et al. 2016), and the practices of individual vessels with consistently high or low bycatch rates year to year (Weimerskirch et al. 2000, Dietrich et al. 2009); indeed, the effects of these factors on bycatch rates could be synergistic and interrelated (Barbaud et al. 2012). Additional tracking or dietary analysis during pre-breeding and incubation coupled with detailed analysis of interannual and intra-annual fisheries activity would improve understanding of year-round overlap between Pink-footed Shearwaters and Chilean purse-seine fisheries (e.g., Waugh et al. 2018).

Because of the limited nature of available data on fishing effort, we could not directly assess the amount of interaction between Pink-footed Shearwaters and fishing vessels. It is possible that seabirds and fishing boats using overlapping areas interact minimally or not at all (e.g., Torres et al. 2013). Nevertheless, Pink-footed Shearwaters attended vessels during purse-seine gear deployment, resulting in fisheries interactions (Suazo et al. 2014), and industrial and artisanal central Chilean purse-seine fleets caught >1,500 Pink-footed Shearwaters as bycatch during 2015–2017 (Vega et al. 2018). Similarly, the greatest amount of Pink-footed Shearwater bycatch during 2015–2017 in the industrial and artisanal sardine/anchoveta fleet occurred at the Valdivia and Gulf of Arauco hotspots (Vega et al. 2018), where we identified the greatest overlap between tagged Pink-footed Shearwaters and fisheries. Although we stress that the overlap indices presented here indicate spatial overlap only, and not necessarily risk of interaction or bycatch, indices can be useful for targeting continued monitoring of fisheries interactions within Chile by focusing effort on the geographical areas where Pink-footed Shearwaters and purse-seine fisheries overlap.

Given the current degree of observer coverage in central Chilean purse-seine fisheries, greater observer effort in areas with the greatest overlap with Pink-footed

Shearwaters would provide meaningful insight about temporal and spatial dynamics of fisheries and the risks of bycatch. Current annual observer coverage of the industrial sardine/anchoveta fishery (15.8–23.1% of trips; Vega et al. 2018) is close to or within the range of 20–33% minimum observer coverage threshold recommended for accurate bycatch estimation in purse-seine fisheries (Lennert-Cody 2001), although precision of bycatch estimates may depend on species-specific factors (Amande et al. 2012). Current annual observer coverage of the artisanal sardine/anchoveta fishery and jack mackerel fisheries (1.3–2.1%, and 11.6–12.2% of trips; Vega et al. 2018) may be useful for identifying the existence of seabird bycatch, but <20% observer coverage is considered inadequate to document particular species' interaction rates in both purse-seine and longline fisheries (Lennert-Cody et al. 2001, Amande et al. 2012, reviewed in Debsky et al. 2016). Furthermore, if a seabird species is infrequently captured but caught in large numbers at those times, as may be the case for Pink-footed Shearwaters in central Chile (R. Vega, personal observation), higher levels of coverage may be required to achieve satisfactory levels of precision (Debsky et al. 2016). In addition to fisheries observer programs, further study documenting seabird beach-stranding events, some of which have been linked to discarded fisheries bycatch in Chile (Simeone et al. 1999, Portflitt-Toro et al. 2018), would help reveal the spatial extent and magnitude of seabird bycatch in Chile.

Our results may also be useful for informing eventual efforts for mitigation, including promotion of gear modifications that may reduce purse-seine bycatch (Suazo et al. 2016, 2017), especially among vessels operating at fishing ports closest to Pink-footed Shearwater–fisheries overlap hotspots such as Corral (Valdivia hotspot) and Coronel (Gulf of Arauco hotspot). Additional research that could potentially help reduce Pink-footed Shearwater fisheries interactions includes analysis of Pink-footed Shearwater overlap, interaction, and bycatch in other Chilean fisheries. For example, bycatch of Sooty Shearwaters and unidentified *Ardenna* shearwaters has been documented in purse-seine fleets targeting anchoveta off northern Chile (Vega et al. 2018), and Pink-footed Shearwater bycatch has been reported in Chilean gill-net, longline, and trawl fisheries (Mangel et al. 2012, Suazo et al. 2014). Further assessment of fisheries overlap and bycatch rates in waters of countries used by Pink-footed Shearwaters during post-breeding dispersal (Felis et al. 2019), especially Peru, Ecuador, Mexico, the United States, and Canada, also would be required to better understand the global extent of the bycatch threat. Lastly, collaborative efforts among scientists, fisheries managers, and fishers will help identify, quantify, and reduce fisheries bycatch of Pink-footed Shearwaters within Chile and internationally.

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Author contributions: RC, JF, RV, JA, JB, and PH wrote the paper. RC, JF, RV, JB, VL, and TV conducted the research; JA, VC, PH, and RV conceived the ideas; JF, JA, RV, RC, PH, and JB developed methods; JF, RV, RC, and AG analyzed the data; JA, VC, and TV contributed substantial resources.

LITERATURE CITED

- Adams, J., J. J. Felis, M. Czupanskiy, R. D. Carle, and P. Hodum (2019). Diving behavior of Pink-footed Shearwaters *Ardenna creatopus* rearing chicks on Isla Mocha, Chile. *Marine Ornithology* 47:17–24.
- [ACAP] Agreement on the Conservation of Albatrosses and Petrels (2013). Listing of new species—Pink-footed Shearwater *Puffinus creatopus*. In: Seventh meeting of the Advisory Committee, Document 24, Agenda Item 14. ACAP Secretariat, Hobart, Australia.
- Amande, M. J., E. Chassot, P. Chavance, H. Murua, A. D. de Molina, and N. Bez (2012). Precision in bycatch estimates: The case of tuna purse-seine fisheries in the Indian Ocean. *ICES Journal of Marine Science* 69:1501–1510.
- Anderson, O. R. J., C. J. Small, J. P. Croxall, E. K. Dunn, B. J. Sullivan, O. Yates, and A. Black (2011). Global seabird bycatch in longline fisheries. *Endangered Species Research* 14:91–106.
- Aranis, A., A. Gómez, K. Walker, G. Muñoz, L. Caballero, C. Eisele, F. Cerna, C. Valero, A. Lopez, C. Machuca, et al. (2018). Informe Final. Convenio de Desempeño, 2017. Programa de Seguimiento de las Principales Pesquerías Pelágicas de la Zona Centro-Sur de Chile, V–XI Regiones, año 2017. Instituto de Fomento Pesquero, Valparaíso, Chile.
- Arcos, D. F., L. A. Cubillos, and S. P. Núñez (2001). The jack mackerel fishery and El Niño 1997–98 effects off Chile. *Progress in Oceanography* 49:597–617.
- Atkinson, L. P., A. Valle-Levinson, D. Figueroa, R. De Pol-Holz, V. A. Gallardo, W. Schneider, J. L. Blanco, and M. Schmidt (2002). Oceanographic observations in Chilean coastal waters between Valdivia and Concepción. *Journal of Geophysical Research: Oceans* 107:18–1–18–13.
- Barbaud, C., V. Rolland, S. Jenouvrier, M. Nevoux, K. Delord, and H. Weimerskirch (2012). Effects of climate change and fisheries bycatch on Southern Ocean seabirds: A review. *Marine Ecology Progress Series* 454:285–307.
- Barber, R. T., and F. P. Chavez (1983). Biological consequences of El Niño. *Science* 222:1203–1210.
- Berlincourt, M., and J. P. Arnould (2015). Breeding Short-tailed Shearwaters buffer local environmental variability in south-eastern Australia by foraging in Antarctic waters. *Movement Ecology* 3:16.
- Bertrand, A., M. A. Barbieri, J. Córdova, C. Hernández, F. Gómez, and F. Leiva (2004). Diel vertical behaviour, predator–prey relationships, and occupation of space by jack mackerel (*Trachurus murphyi*) off Chile. *ICES Journal of Marine Science* 67:1105–1112.
- BirdLife International (2017). *Ardenna creatopus* (amended version of 2016 assessment). The IUCN Red List of Threatened Species 2017: e.T22698195A112079183. <http://dx.doi.org/10.2305/IUCN.UK.2017-1.RLTS.T22698195A112079183.en> (accessed 9 May 2019).
- Carle, R. D., J. N. Beck, V. Colodro, and P. Hodum (2016). Effects of cattle exclusion on the vegetation at a Pink-footed Shearwater (*Ardenna creatopus*) colony on Robinson Crusoe Island, Chile. *Revista Chilena de Ornithología* 22:184–193.
- Castillo, C., and J. Dresdner (2013). Effort optimisation in artisanal fisheries with multiple management objectives, collective quotas and heterogeneous fleets. *Australian Journal of Agricultural Resources and Economics* 57:104–122.
- Congdon, B. C., A. K. Krockenberger, and B. V. Smithers (2005). Dual-foraging and co-ordinated provisioning in a tropical procellariiform, the Wedge-tailed Shearwater. *Marine Ecology Progress Series* 301:293–301.
- Cubillos, L. A., and D. F. Arcos (2002). Recruitment of common sardine (*Strangomera bentincki*) and anchovy (*Engraulis ringens*) off central–south Chile in the 1990s and the impact of the 1997–1998 El Niño. *Aquatic Living Resources* 15:87–94.
- Cubillos, L. A., D. F. Arcos, D. A. Bucarey, and M. T. Canales (2001). Seasonal growth of small pelagic fish off Talcahuano, Chile (37°S, 73°W): A consequence of their reproductive strategy to seasonal upwelling? *Aquatic Living Resources* 14:115–124.
- Cubillos, L. A., H. Trujillo, C. Jiménez, B. Ernst, M. Feltrim, and C. Gatica (2012). Análisis de estrategias de explotación de peces pelágicos pequeños basados en la fuerza de los reclutamientos. Informe Final Proyecto Fondo de Investigación Pesquera.
- Davila Perez, C., P. Velasquez Jofre, and R. Siguenza (2009). Diagnostico de captura incidental de aves marina en el Pacifico de Guatemala, Centro America. Informe Final. Unpublished report to Pacific Seabird Group, Corvallis, OR, USA.
- Debsky, I., J. Pierre, and K. Knowles (2016). Observer coverage to monitor seabird captures in longline fisheries. Western and Central Pacific Fisheries Commission, Scientific Committee 12th Regular Session, Bali, Indonesia.
- Dietrich, K. S., J. K. Parrish, and E. F. Melvin (2009). Understanding and addressing seabird bycatch in Alaska demersal long-line fisheries. *Biological Conservation* 142:2642–2656.

- Espinoza-Morriberon, D., V. Echevin, F. Colas, J. Tam, J. Ledesma, L. Vasquez, and M. Graco (2017). Impacts of El Niño events on the Peruvian upwelling system productivity. *Journal of Geophysical Research Oceans* 122:5423–5444.
- Felis, J. J., J. Adams, P. J. Hodum, R. D. Carle, and V. Colodro (2019). Eastern Pacific migration strategies of Pink-footed Shearwaters *Ardenna creatopus*: Implications for fisheries interactions and international conservation. *Endangered Species Research*. In press.
- Gilman, E., M. Chaloupka, J. Peschon, and S. Ellgen (2016). Risk factors for seabird bycatch in a pelagic longline tuna fishery. *PLOS One* 11:e0155477.
- Gladics, A. J., E. F. Melvin, R. M. Suryan, T. P. Good, J. E. Jannot, and T. J. Guy (2017). Fishery-specific solutions to seabird bycatch in the U.S. West Coast sablefish fishery. *Fisheries Research* 196:85–95.
- Guicking, D., W. Fiedler, C. Leuther, R. Schlatter, and P. H. Becker (2004). Morphometrics of the Pink-footed Shearwater (*Puffinus creatopus*): Influence of sex and breeding site. *Journal of Ornithology* 145:64–68.
- Guicking, D., S. Mickstein, and R. P. Schlatter (1999). Estado de la población de fardela blanca (*Puffinus creatopus*) en Isla Mocha, Chile. *Boletín Chileno de Ornitología* 6:35–38.
- Guicking, D., D. Ristow, P. H. Becker, R. Schlatter, P. Berthold, and U. Querner (2001). Satellite tracking of Pink-footed Shearwater in Chile. *Waterbirds* 24:8–15.
- Guzman, J. R., and M. T. Myres (1983). The occurrence of shearwaters (*Puffinus* spp.) off the west coast of Canada. *Canadian Journal of Zoology* 61:2064–2077.
- Hall, M. A., D. L. Alverson, and K. I. Metuzals (2000). By-catch: Problems and solutions. *Marine Pollution Bulletin* 41:204–219.
- Hinojosa Saez, A., and P. Hodum, Editors (2007). Plan Nacional para la Conservación de la Fardela de Vientre Blanco *Puffinus creatopus* Coues, 1864 en Chile. Corporación Nacional Forestal and Comisión Nacional del Medio Ambiente, Santiago, Chile.
- Hodum, P., and M. Wainstein (2003). Biology and Conservation of the Juan Fernández Archipelago Seabird Community. Unpublished report to Corporación Nacional Forestal (CONAF). Juan Fernández Islands Conservancy, Long Beach, CA, USA. <http://oikonos.org/wp-content/uploads/2018/12/2003-Report.pdf> (accessed 9 May 2019).
- Hodum, P., M. Flores, V. Colodro, V. López, H. Gutiérrez, R. Carle, T. Varela, and P. González (2016). Conservation of the Pink-footed Shearwater Final Report 2016. Unpublished report to American Bird Conservancy. Oikonos - Ecosystem Knowledge, Valparaíso, Chile. <http://oikonos.org/wp-content/uploads/2018/12/Oikonos-Pink-footed-Shearwater-final-report-2016.pdf> (accessed 9 May 2019).
- Hodum, P., J. L. Smith, N. R. Parker, K. H. Morgan, L. K. Blight, M. H. Chutter, T. Mawani, and D. Cunningham (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. Environment Canada, Ottawa, Canada.
- Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics* 6:65–70.
- Hyrenbach, K. D., P. Fernández, and D. J. Anderson (2002). Oceanographic habitats of two sympatric North Pacific albatrosses during the breeding season. *Marine Ecology Progress Series* 233:283–301.
- Jannot, J. E., T. P. Good, K. Somers, V. Tuttle, and J. McVeigh (2018). Seabird mortality in U.S. West Coast groundfish fisheries 2002–2016. NOAA Fisheries, NWFSC Observer Program, Seattle, WA, USA.
- Kogan, F., and W. Guo (2017). Strong 2015–2016 El Niño and implication to global ecosystems from space data. *International Journal of Remote Sensing* 38:161–178.
- Lennert-Cody, C. (2001). Effects of sample size on bycatch estimation using systematic sampling and spatial post-stratification: Summary of preliminary results. In *Indian Ocean Tuna Commission Proceedings* 4:48–53.
- Lewison, R. L., L. B. Crowder, A. J. Read, and S. A. Freeman (2004). Understanding impacts of fisheries bycatch on marine megafauna. *Trends in Ecology & Evolution* 19:598–604.
- Magalhães, M. C., R. S. Santos, and K. C. Hamer (2008). Dual-foraging of Cory's Shearwaters in the Azores: Feeding locations, behaviour at sea and implications for food provisioning of chicks. *Marine Ecology Progress Series* 359:283–293.
- Mangel, J. (2012). Interactions of Peruvian small scale fisheries with threatened marine vertebrate species. Ph.D. dissertation, University of Exeter, Devon, UK.
- Mangel, J. C., J. Adams, J. Alfaro-Shigueto, P. Hodum, K. D. Hyrenbach, V. Colodro, P. Palavecino, M. Donoso, and J. Hardesty-Norris (2012). Conservation implications of Pink-footed Shearwater movements and fishery interactions assessed using multiple methods. Unpublished report to American Bird Conservancy, Washington, DC, USA. <http://oikonos.org/wp-content/uploads/2018/12/Mangel-et-al.-2012.pdf> (accessed 9 May 2019).
- Melvin, E. F., and J. K. Parrish, Editors (2001). Seabird Bycatch: Trends, Roadblocks, and Solutions. University of Alaska Sea Grant College Program, Fairbanks, AK, USA.
- Morales, C. E., J. L. Blanco, M. Braun, H. Reyes, and N. Silva (1996). Chlorophyll-*a* distribution and associated oceanographic conditions in the upwelling region off northern Chile during the winter and spring 1993. *Deep Sea Research* 43:267–289.
- Mott, R., and R. H. Clarke (2018). Systematic review of geographic biases in the collection of at-sea distribution data for seabirds. *Emu - Australian Ornithology* 118:235–246.
- Muñoz, D. M. (2011). Áreas de nidificación y densidad de nidos de fardela de vientre blanco, *Puffinus creatopus*, en la Reserva Nacional Isla Mocha. Master's thesis, University of Concepción, Concepción, Chile.
- Paiva, V. H., P. Gerdal, I. Ramírez, A. Meirinho, S. Garthe, and J. A. Ramos (2010). Oceanographic characteristics of areas used by Cory's Shearwaters during short and long foraging trips in the North Atlantic. *Marine Biology* 157:1385–1399.
- Phillips, R. A., J. R. D. Silk, J. P. Croxall, and V. Afanasyev (2006). Year-round distribution of White-chinned Petrels from South Georgia: Relationships with oceanography and fisheries. *Biological Conservation* 129:336–347.
- Phillips, R. A., J. C. Xavier, and J. P. Croxall (2003). Effects of satellite transmitters on albatrosses and petrels. *The Auk* 120:1082–1090.
- Porfitt-Toro, M., D. Miranda-Urbina, and G. Luna-Jorquera (2018). Aves marinas varadas en la bahía de Coquimbo, norte de Chile: ¿Que especies y cuántas mueren? *Revista de Biología Marina y Oceanografía* 53:185–193.
- Schoombie, S., B. J. Dilley, D. Davies, and P. G. Ryan (2018). The foraging range of Great Shearwaters (*Ardenna gravis*) breeding on Gough Island. *Polar Biology* 1:8.

- Shaffer, S. A., H. Weimerskirch, D. Scott, D. Pinaud, D. R. Thompson, P. M. Sagar, H. Moller, G. A. Taylor, D. G. Foley, Y. Tremblay, and D. P. Costa (2009). Spatiotemporal habitat use by breeding Sooty Shearwaters *Puffinus griseus*. *Marine Ecology Progress Series* 391:209–220.
- Simeone, A., M. Bernal, and J. Meza (1999). Incidental mortality of Humboldt Penguins *Spheniscus humboldti* in gill nets, central Chile. *Marine Ornithology* 27:157–161.
- Suazo, C. G., L. A. Cabezas, C. A. Moreno, J. A. Arata, G. Luna Jorquera, A. Simeone, L. Adasme, J. Azócar, M. García, O. Yates, and G. Robertson (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., L. A. Cabezas, and O. Yates (2016). Collaboration on technical innovation towards the reduction of seabird bycatch in purse seine fisheries. Seabird Bycatch Working Group 7, Doc 20 Rev 1. ACAP Secretariat, Hobart, Australia.
- Suazo, C. G., E. Frere, M. Garcia, L. Cocos, and O. Yates (2017). Assessment of the “modified purse seine (MPS)” against ACAP best practice criteria. Seabird Bycatch Working Group 8, Doc 21. ACAP Secretariat, Hobart, Australia.
- Thalmann, S. J., G. B. Baker, M. Hindell, and G. N. Tuck (2009). Longline fisheries and foraging distribution of Flesh-footed Shearwaters in eastern Australia. *Journal of Wildlife Management* 73:399–406.
- Torres, L. G., P. M. Sagar, D. R. Thompson, and R. A. Phillips (2013). Scaling down the analysis of seabird-fishery interactions. *Marine Ecology Progress Series* 473:275–289.
- Tuck, G. N., R. A. Phillips, C. Small, R. B. Thomson, N. L. Klaer, F. Taylor, R. M. Wanless, and H. Arrizabalaga (2011). An assessment of seabird–fishery interactions in the Atlantic Ocean. *ICES Journal of Marine Science* 68:1628–1637.
- Vega, R., L. Ossa, B. Suárez, A. González, S. Henríquez, R. Ojeda, M. A. Jiménez, A. Ramírez, J. Le-Bert, A. Simeone, et al. (2018). Informe Final - Convenio de Desempeño 2017–2018. Programa de observadores científicos 2017–2018. Programa de investigación del descarte y captura de pesca incidental en pesquerías pelágicas. Programa de monitoreo y evaluación de los planes de reducción del descarte y de la pesca incidental 2017–2018. Instituto de Fomento Pesquero, Valparaíso, Chile.
- Waugh, S. M., S. C. Patrick, D. P. Filippi, G. A. Taylor, and J. P. Y. Arnould (2016). Overlap between Flesh-footed Shearwater *Puffinus carneipes* foraging areas and commercial fisheries in New Zealand waters. *Marine Ecology Progress Series* 551:249–260.
- Waugh, S. M., T. A. Poupart, J. W. Griffiths, J. Y. P. Arnould, D. P. Filippi, and K. Rogers (2018). Environmental factors and fisheries influence the foraging patterns of a subtropical seabird, the Westland Petrel (*Procellaria westlandica*), in the Tasman Sea. *The Condor: Ornithological Applications* 120:371–387.
- Weimerskirch, H. (1998). How can a pelagic seabird provision its chick when relying on a distant food resource? Cyclic attendance at the colony, foraging decision and body condition in Sooty Shearwaters. *Journal of Animal Ecology* 67:99–109.
- Weimerskirch, H., D. Capdeville, and G. Duhamel (2000). Factors affecting the numbers and mortality of seabirds attending trawlers and long-liners in the Kerguelen area. *Polar Biology* 23:236–249.
- Weimerskirch, H., Y. Cherel, F. Cuenot-Chaillet, and V. Ridoux (1997). Alternative foraging strategies and resource allocation by male and female Wandering Albatrosses. *Ecology* 78:2051–2063.