Scaling down the analysis of seabird-fishery interactions

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ABSTRACT: Seabird-fishery interactions are currently a major issue in marine conservation management. A common approach to quantifying the extent of interactions is to overlay density maps of seabird and fishing activities derived from point locations. Such large-scale evaluations of overlap can be misleading due to the static representation of birds and vessels that in reality are spatially and temporally dynamic. Additionally, overlap at large scales does not necessarily indicate interaction; overlapping distributions of seabirds and fisheries could reflect coincident use of habitat. Using 4 yr of distribution data, we conducted a fine-scale analysis of overlap between albatrosses and fishing vessels. Results were compared to those derived from large-scale density comparisons. Additionally, we compared overlap versus interaction rates by calculating the proportion of time that birds foraged in close association with a fishing vessel versus independently while within 10 km of a vessel. Results of our fine-scale analysis indicated generally low rates of overlap while foraging and high variability among sexes, years and types of fishery. Changes in overlap rates were attributed to shifts in both albatross and vessel distributions. Albatrosses foraged independently of fishing vessels half the time they were within 10 km of a vessel, indicating that 50% of overlap is due to coincident habitat use rather than vessel interaction. Overlaying of large-scale distribution maps failed to distinguish annual variation in the degree of bird-fishery overlap, and suggested overlap where none was identified at the finer scale. This study illustrates the increased insight derived from fine-scale analyses of seabird-fisheries interactions.

KEY WORDS: Foraging behavior · Scale · Seabird · Distribution · Overlap · Fisheries interaction · GPS tracking · Buller's albatross

INTRODUCTION

Fishing activities are pervasive in the current ocean landscape, and marine megafauna such as seabirds, sharks and dolphins frequently encounter fishing vessels and gear. These interactions between fisheries and animals can benefit or harm the animals involved. Many seabirds have responded to the global proliferation of commercial fishing fleets by exploiting fisheries waste, including offal (Thompson & Riddy 1995, Grémillet et al. 2008), bait (Pierre & Norden 2006) and discarded non-target catch (Bartle

1991, Rindorf et al. 2000). Demonstrated impacts of seabird-fishery associations include direct negative effects on adult survival rates (Brothers 1991, Rolland et al. 2010, Anderson et al. 2011), indirect negative effects on breeding success (Frederiksen et al. 2004), and positive effects on population sizes (Garthe et al. 1996, Furness 2003). The impacts of these interactions on seabird populations and ecology have become high-profile and common conservation and management issues (Lewison et al. 2004, Croxall 2008). A result of this focus on seabird-fisheries interactions is a proliferation of studies attempting to

define the extent of overlap between seabirds and commercial fishing vessels at various scales including large (Hyrenbach & Dotson 2003, Phillips et al. 2006), meso (Xavier et al. 2004, Waugh et al. 2005, Pichegru et al. 2009), and fine (Votier et al. 2010, Granadeiro et al. 2011, Torres et al. 2011).

A common method of identifying areas of overlap between seabirds and fishing activities is to create density maps of birds and boats from point locations and overlay these outputs (Phillips et al. 2006, Petersen et al. 2008, Fischer et al. 2009, Okes et al. 2009). The resulting density maps are produced in a variety of ways and include kernel density plots, utilization distributions, density grids, or animal home-ranges. Essentially all density maps provide a probability index, either as contours or grids, and indicate the relative proportion of the distribution of seabirds or fishing activities within a particular area. These density plots are created by converting distribution points that had associated timing information into static illustrations of distribution patterns that no longer reflect the temporal component (other than season or year). However, neither the seabirds nor the fishing activities are static. Rather, both are spatially and temporally dynamic and respond to a multitude of factors including environmental variability, short-term climatic conditions, prey/target species availability, market demand (fisheries), and life history stage (seabirds). Therefore, an overlay of density maps typically only provides a coarse-scale evaluation of overlap; broad spatial areas are subsequently outlined as static boundaries of overlap between seabird and fisheries over wide temporal periods. However, effective conservation strategies, that simultaneously minimize burden on the fishing industry, should be dynamic enough to recognize and incorporate the high spatial and temporal variation in overlap between fishing vessels and marine predators.

Moreover, areas in which high densities of birds and boats coincide are frequently considered to be areas where rates of interaction or association between seabirds and fishing vessels are particularly high, and therefore where there is greatest susceptibility of birds to bycatch (Tuck et al. 2003, Cuthbert et al. 2005, Petersen et al. 2008, Copello & Quintana 2009, Fischer et al. 2009, Delord et al. 2010). However, static spatial overlap, as identified by densities alone, does not necessarily indicate interaction. At large (>100 km) and meso (10–100 km) scales, it is likely that seabirds and fisheries target similar productive areas with abundant prey (Freeman et al. 2001, Karpouzi et al. 2007). Furthermore, some birds and fishing vessels compete for the same prey/target species (Montevecchi & Myers 1995, Furness 2002, Okes et al. 2009). Therefore, overlap between seabirds and fisheries could reflect the coincident use of the same habitat or resources, rather than a dedicated foraging strategy to interact with fishing activities. Teasing these behavior patterns apart requires the examination of overlap at very fine scales (<10 km).

The scale adopted in overlap analyses is typically determined by the scale of bird distribution and fisheries data. Recently, fine-scale studies of overlap between seabirds and fishing vessels have utilized distribution data that were highly resolved both spatially and temporally (Votier et al. 2010, Granadeiro et al. 2011, Torres et al. 2011). All 3 studies found high individual variability in overlap rates with fishing vessels, including many birds that rarely or never overlapped with fishing vessels. Each of these studies used GPS data from tracked seabirds and vessel monitoring system (VMS) data. Although the temporal resolution of seabird tracks was high (<14 min), the 3 studies adopted different methods and definitions of overlap to compensate for the less resolved temporal scale of the VMS data (positions every 1 to 3 h). Votier et al. (2010) assessed overlap using 2 methods: (1) aggregated VMS data across 4 years in 5 km^2 cells and assumed minimal spatial variation, (2) assessed the presence/absence of fishing vessels within 2 h and 5 km for each bird GPS location. Granadeiro et al. (2011) interpolated points between VMS locations linearly and defined overlap to be within 3.5 km at a temporal scale of 3 s. Torres et al. (2011) generated scaled buffers around VMS data and linearly interpolated points; the GPS location of a bird was defined as overlapping when within these spatial buffers and 3 min. These studies demonstrate the advantage of fine-scale analysis of seabird-vessel overlap compared to broad scale methods. However, they did not assess inter-annual variability in overlap, which limits interpretation of results, and, like previous studies, failed to distinguish overlap from interaction.

In this study, we use 4 years of data to assess variation in fine-scale foraging behavior of the Buller's albatross *Thalassarche bulleri* relative to inter-annual variability of fishing activities, and address whether coincident use of the same area by birds and boats is due to the presence of vessels or is independent, reflecting a natural foraging strategy. The Buller's albatross is an annual breeder, endemic to New Zealand. The main breeding site is The Snares, lying within the sub-tropical frontal zone. Colonies on The Snares have been studied irregularly since

1948, and annually since 1992. Demographic data collected during this long-term project allow us to assign sex and minimum age to tracked birds. During their breeding season (January-September), Buller's albatrosses forage along the continental shelf and slope of New Zealand and Tasmania (Stahl & Sagar 2000) and are known to interact with fishing vessels (Bartle 1991). Squid are an important natural prey item of many albatrosses including the Buller's albatross (Croxall & Prince 1996, James & Stahl 2000) and are also targeted by local fisheries. We tracked albatross distribution during a time of year (brood-guard) when their energy demands are relatively high and adults are spatially constrained because of the need to return to the colony to feed the chick. We use fine-scale tracking of Buller's albatross foraging trips and fisheries data to assess overlap at a scale of <10 km and <2 min. We examine variation in overlap while foraging by sex, age, year, and fishery, and we compare our results to those derived from overlaying large-scale density maps. Finally, we attempt to distinguish overlap from interaction by assessing the proportion of time an albatross foraged in association with a fishing vessel when given the opportunity to do so.

MATERIALS AND METHODS

Field methods

This study was conducted in April of 4 consecutive years (2008 to 2011) on breeding adult Buller's albatrosses from 2 colonies at The Snares, New Zealand (48.02° S, 166.61° E). In all years, tracking occurred during the guard stage of the breeding cycle (when parents brood the chick in alternate shifts while the other feeds at sea) (Table 1), to eliminate differences in foraging patterns among years due to breeding phase.

We captured banded birds at the nest by hand, and attached GPS loggers to dorsal feathers using waterproof Tesa® tape. Each deployment took ~5 min to complete, and all birds were returned to their nest pedestal where they continued to brood their chick. The sex of each bird was determined from measurements of minimum bill depth (B) and tarsus width (T) (both in mm) using the discriminant function (DF):

$$DF = 0.981 \times B + 1.556 \times T - 50.648$$

with negative values of DF indicating females and positive values males. This equation is estimated to classify 99% of birds correctly (Sagar et al. 1998).

The minimum age of birds not banded as chicks was estimated using the time elapsed since their banding as a breeding bird plus 10 yr, the average age of first breeding (Francis & Sagar 2012).

'GPSlog' loggers (Earth & Ocean Technologies) weighing 65 g, or ~2% of body mass, were deployed in 2008, and the second generation of these tags, the 'miniGPSlog', weighing 34 g and ~1% of the bird's body mass, were deployed in 2009 to 2011. All GPS tags were programmed to acquire a GPS point every 2 min; 90% of fixes were estimated to be within 19 m of the true location (Earth & Ocean Technologies unpubl. data).

In 2010, archival loggers equipped with light and immersion sensors (3.65 g, Mk17 tags, British Antarctic Survey) were simultaneously deployed on the legs of 20 of the 23 birds with GPS loggers. The loggers recorded the time of every change between a wet and dry state that lasted ≥6 s. Before deployment, clocks on immersion and GPS loggers were synchronized, allowing us to determine whether the bird was flying or on the water at the time of each GPS fix.

GPS track analysis and fine-scale overlap analysis

This study examined the annual variation in overlap between foraging Buller's albatrosses and fishing vessels. Therefore, the first step in GPS track analysis was to identify foraging. First, flight characteristics — speed, path straightness and residence — were derived for each point along each track. Speed was calculated as the ratio of distance travelled to the time elapsed since the previous point (km h⁻¹). Path straightness was determined for each point over a 20 min window (±5 GPS points) as the ratio of the straight-line distance between the points and the along-path distance. Residence is a measure of area restricted search and was calculated by considering all track segments within a virtual circle of a constant radius (Barraquand & Benhamou 2008, Torres et al. 2011). We applied a 1 km radius using spatial segments of 100 m and a threshold of 5 steps. The use of these parameters was arbitrary but maintained a fine-scale level of analysis. These 3 flight metrics were used successfully in previous studies to characterize albatross behavior (Weimerskirch et al. 2002, Torres et al. 2011). GPS points with residence values greater than 2× the standard deviation for that particular track were considered to be outliers. These points and points at the start and end of gaps in tracks from 2010 (see 'Results') were excluded from analyses.

Based on these flight characteristics, GPS points were classified into one of 3 behavior states: drift, transit, and foraging. Drift characterizes points when the bird was likely resting on the water for a period of 1 h or more. Drift points were defined based on a 1 h window (±15 points) as having high mean path straightness values (≥0.9), low mean speeds (≤4.25 km h^{-1}), and short mean distances travelled (≤0.15 km). While these cut-off values may be subjective, they were applied successfully to classify drift points from GPS tracks of white-capped albatrosses *Thalassarche steadi* (Torres et al. 2011). We are confident that this methodology correctly identified drift behavior in this study because immersion loggers deployed in 2010 recorded a 'wet' state during 98% of GPS points identified as drift. We assumed that drift and foraging states were mutually exclusive. Therefore, all points identified as drift were excluded from further analyses because they were not considered to denote foraging behavior. Additionally, all points within 5 km of the colony were removed because albatrosses are known to 'bathe' in nearby areas before or after foraging trips.

All remaining points within each track were defined as transit or foraging based on residence, speed and path straightness values over a 20 min window (±5 points). Residence and straightness had highly skewed distributions. Therefore, percentiles of residence and path straightness for each track were calculated and used to classify behavioral state. Transit points were identified as having low residence (in the lower 50th percentile), high path straightness values (in the upper 50th percentile), and high speed (>20 km h^{-1}). Foraging points were identified as having high residence (in the upper 50th percentile) and low speed (<20 km h^{-1}). Path straightness was not used to define foraging points because the birds frequently travel in a relatively straight line when they forage behind vessels, following the path of the vessel (Torres et al. 2011). Although points labeled transit and forage are mutually exclusive, there were some unclassified points that were neither transit nor forage. Therefore, this method of identifying transit and forage points was conservative.

Methods developed by Torres et al. (2011) to detect GPS track points that overlapped a fishing vessel were applied here. Vessel monitoring system (VMS) data were supplied by the New Zealand Ministry of Fisheries, and included records of the movements of every fishing vessel over 28 m, and all foreign vessels in New Zealand waters. Vessel monitoring systems on each vessel accurately recorded location every 1 to 2 h. Vessel monitoring system data analyzed for overlap with albatross tracks were limited to points within the same temporal period as the tracking data for each year, and a consistent spatial area that covered the maximum extent of all 4 yr of tracking data. This large spatial extent was assumed to be the region in which the birds can exploit prey at this time of year, and so was applied for between-year comparisons throughout the analysis. Circular spatial buffers were generated along each VMS track between points at 2 min intervals, the same interval as the bird GPS locations. These circular buffers had increasing radii size with increasing distance from each VMS point to account for increased uncertainty in vessel location (see Torres et al. 2011). Any albatross GPS point that fell within the spatial buffers and within a 2 min window of each vessel location was considered to indicate overlap. These methods allowed us to identify possible vessel-bird associations at a fine scale. Any albatross GPS point beyond a buffer radius of 10 km from a vessel location was considered non-overlapping. Due to the difference in sample size between years and sexes, and gaps in recorded tracks (see 'Results'), overlap and foraging characteristics were quantified as *rates*. The overlap rate was calculated as the ratio of track points identified as foraging and overlapping a VMS track to the total number of points identified as foraging. Therefore, the rate of foraging while overlapping a fishing vessel was calculated.

GPS track points identified as foraging and overlapping a vessel were then cross-referenced to a catch effort dataset also provided by the New Zealand Ministry of Fisheries (Ministry of Fisheries 2006). The catch effort dataset includes all start locations and times of fishing events by all commercial fishing vessels in New Zealand (regardless of size), and the target species, fishing method and catch weight of each event. Overlap points were cross-referenced with this dataset based on a unique vessel identification code that was constant between the VMS and catch effort datasets. This approach identified the target species and fishing method used by the vessel of interest. With this information, the rates of foraging while overlapping particular fisheries (e.g. squid trawl) were quantified as the ratio of the number of points identified as foraging and overlapping a fishery to the total number of foraging points. ANOVA was used to test for difference in overlap rates among sexes and years. Correlation tests were used to detect possible relationships between albatross age and overlap rate.

Seabird attraction to fishing vessels occurs at scales <10 km (Skov & Durinck 2001). Therefore, it is assumed that an albatross can perceive fishing vessels within 10 km and subsequently chooses to forage independently of the vessel (no defined overlap) or in association with the vessel (overlap defined). The number of bird locations within 10 km of a fishing vessel that were previously identified as foraging and/or overlapping a vessel while foraging were tallied for each track. The percentage of foraging points within 10 km of a vessel that overlapped a fishing vessel was calculated for each track as the ratio of the number of overlapping foraging points (always within 10 km of a vessel) to the total number of foraging points within 10 km of a fishing vessel (whether overlapping or not). This reflects the proportion of time that a bird forages in association with a vessel when the opportunity is available (within 10 km of a fishing vessel).

Circular statistics and rose diagrams were used to compare the distribution patterns of male and female albatrosses, and fishing vessels (based on VMS data) within and among years. The bearing from the colony at The Snares was calculated for all foraging points of each tracked bird, and for VMS points within the spatial extent of the tracked birds in all years. Rose diagrams were generated to illustrate the angular distribution patterns of foraging activity relative to the colony. Next, the circular statistics package (Lund & Agostinelli 2007) was implemented in R (www.r-project.org/) to perform Watson's 2-sample test, a non-parametric procedure to test the null hypothesis of no difference between 2 circular distributions (Zar 1999). We used this test to assess whether males and females foraged in similar directions from the colony, and for comparison of foraging activity by sex and year relative to the distribution of vessels (VMS dataset).

Large-scale overlap analysis

For comparison with results from the fine-scale overlap analysis, albatross tracking and fisheries data were analyzed at a large scale. Kernel densities were created (ArcGIS version 10, Spatial Analyst tools) from albatross GPS points and from the start locations of all fishing events in each year (from the catch effort datasets). Each density plot was classified into 5 equal interval groups of density, ranked (1 = <20% through to 5 = >80%), and converted to polygons. The intersect tool in ArcGIS was used to coalesce yearly polygons of bird and boat density

into one layer. For each resulting polygon, the product of bird and boat density rank was calculated. Polygon layers were symbolized by this product, which could range from 1 to 25.

Characterizing yearly fishing activity

Using the catch effort dataset, the number of fishing events by target species and fishing method was counted for each year. Additionally, the catch per unit effort (CPUE) for all trawl events (bottom and mid-water) was calculated as the total catch (kg) per minute of each tow. CPUE for squid jiggers was calculated as the total catch weight (kg) per number of squid jig events.

To compare the fisheries distributions and catches among years, density plots were generated (ArcGIS version 10, Spatial Analyst tools) using start locations and associated catch weights provided for each fishing event in the catch effort dataset. Fishing events were grouped by fishery and year. A density plot, weighted by catch weight (kg), was made for each group using 1000 m cell size and 50 km search radius.

RESULTS

Foraging trips were tracked at high resolution for 77 birds. The youngest bird tracked was 10 and the oldest bird was at least 29 yr old. Forty-three trips were performed by males and 34 trips by females (Table 1). The fewest foraging trips were recorded in 2008 (n = 11); more tracks were recorded in 2009 (n = 23), 2010 (n = 25), and 2011 (n = 18). The duration of foraging trips was 0.5 to 4 d, with a mean of 41.5 h. All but 3 tracks from 2010 included periods when no GPS data were acquired, typically of 1 h, and

Table 1. *Thalassarche bulleri.* Details of GPS logger deployment on Buller's albatrosses

| Year | Date range | Number of recorded trips | | | Age range[a] (yr) |
		Male	Female	Total	
2008	4–8 April	5	6	11	12–28
2009	6–11 April	13	10	23	11–28
2010	8–14 April	13	12	25	12–29
2011	8–13 April	12	6	18	10–24
Total		43	34	77	10–29

[a]Upper bound of age range is a minimum estimate (see 'Materials and methods')

occasionally longer (maximum 8 h). These gaps accounted for 19.4% of time spent at sea by tracked birds in 2010, and restricted our ability to compare trip length among years, sexes and ages. Over all years, the tracks covered 759 000 km^2, extending from 42.3° S to 51.1° S (Fig. 1). In all years, the birds dispersed from the colony in all directions except southwest. The tracks overlapped a variety of habitats, but there was a concentrated use in all years of waters over the 200 m shelf break to the east and southeast of the colony (Fig. 1).

During the 4 yr of tracking, 93 fishing vessels were active within the area used by the albatrosses. Ves-

sels targeted 31 different species, using 7 different fishing methods, yet squid trawls (targeting arrow squid *Nototodarus gouldi* and *N. sloani*) dominated fishing effort in all years (73% of all fishing events), followed by hoki (*Macruronus novaezelandiae*) trawls, barracouta (*Thyrsites atun*) trawls, and squid jiggings (targeting arrow squid *Nototodarus gouldi* and *N. sloani*). Fishing methods included bottom trawls (n = 1556), mid-water trawls (n = 226), squid jiggings (n = 49), set nets (n = 50), bottom longline (n = 29), and surface longline (n = 1). Although squid trawls dominated effort in all years, fishing effort and catch per unit effort (CPUE) was variable among
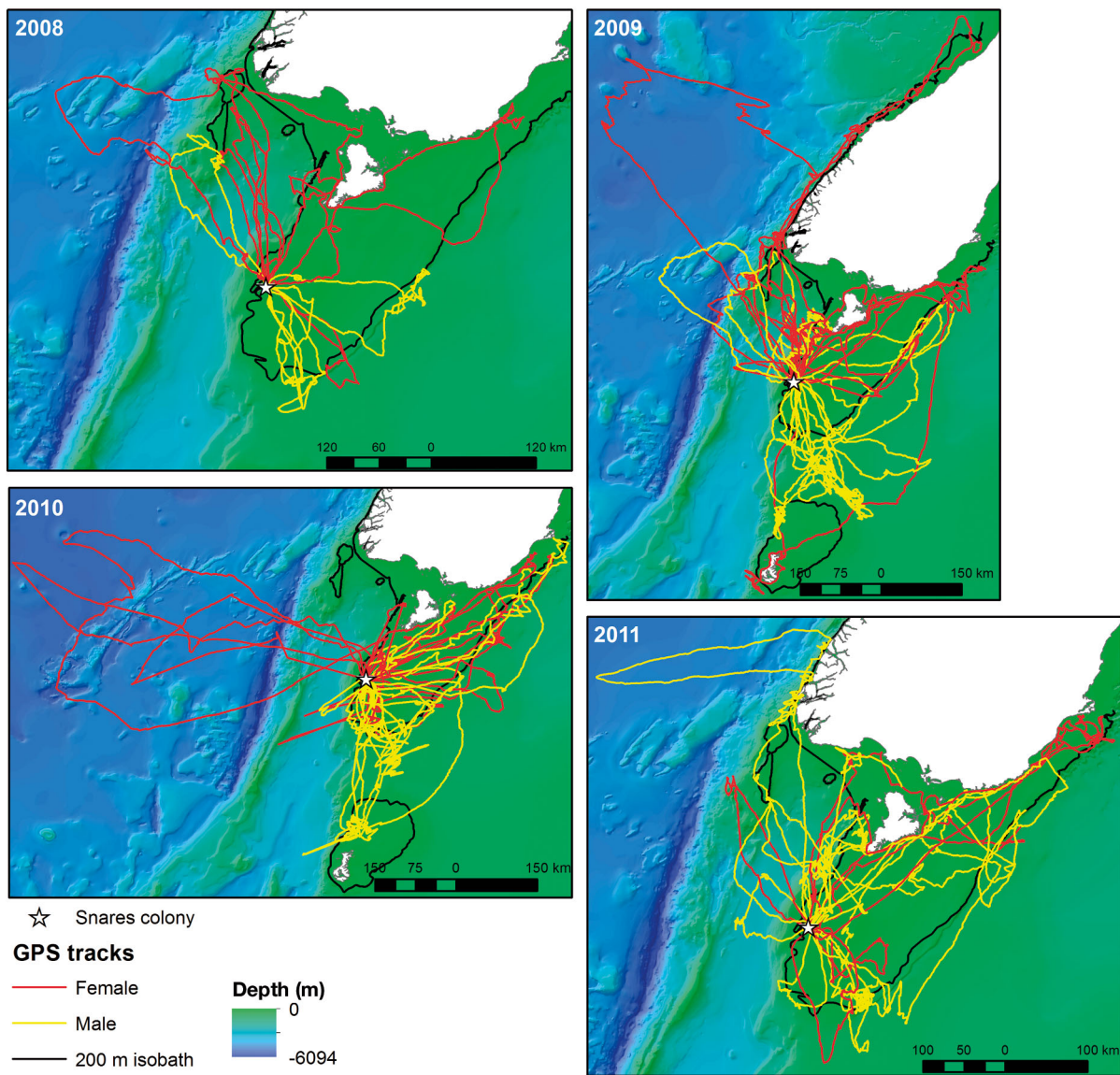

Fig. 1. *Thalassarche bulleri*. Tracks of Buller's albatross fitted with GPS loggers in 2008 to 2011, south of New Zealand. All birds were tagged at The Snares (☆). Note that the map scales vary

years (Fig. 2). Both fewest fishing events and lowest CPUE occurred in 2010, caused mainly by the sharp decline in squid trawl CPUE. There was minimal hoki trawl effort in 2008, but effort and CPUE were higher in 2009 and 2010. Trawls for barracouta (BAR) increased in 2010, with increased CPUE. There was only one event targeting silver warehou *Seriolella punctata* (SWA) and jack mackerel *Trachurus declivis* (JMA) in 2009, and no targeting of these species in 2010. CPUE for SWA and JMA was highest in 2011. Squid jigging effort and CPUE were relatively constant across all years. Note that individual fishing vessels can rapidly switch fishing methods and targets.

The large-scale analysis of overlap between yearly kernel densities of fishing event start locations and albatross track GPS points indicated potential interaction between seabirds and fishing activities at numerous locations (Fig. 3). In all years, medium to high levels of overlap were identified along the shelf break, particularly along the southern portion of the shelf break. Additionally, in all years, overlap that

varied in intensity from low to high was identified along the southeast coast of mainland New Zealand. High levels of overlap were indicated just north of the Auckland Islands in 2009 and 2010, and near the colony in 2010 and 2011. Medium to low levels of overlap were identified along the entire south coast of mainland New Zealand in 2008 and 2011. These spatial comparisons of yearly fishing effort and albatross distributions illustrate overlap over a broad range at variable intensities.

The fine-scale analysis of overlap revealed that in all years, several birds never overlapped a fishing vessel while foraging (2008: 55%; 2009: 57%; 2010: 20%; 2011: 56%). The rates of foraging while overlapping a fishing vessel were highest in 2010, with double the rate of overlap for females and both sexes combined compared to other years (Table 2). In 2010, 22.7% of foraging effort by males overlapped a fishing vessel, including 14.0% of foraging effort with squid trawl vessel and 4.6% with hoki trawls. The overall rate of overlap by females while foraging in 2010 was 14.5%, with 6.1% attributed to hoki trawls and 4.2% attributed to barracouta trawls. No overlap between female albatrosses and these fisheries was determined in any other year. The lowest overall rate of overlap while foraging was in 2008, although minimal overlap by females while foraging was detected in 2009. Males spent 7.1% and 7.5% of their foraging effort in 2009 overlapping squid and hoki trawls, respectively. The elevated rate of foraging by females while overlapping in 2011 is mainly attributed to overlap with squid jig events (5.0% of foraging effort).

In a multi-way ANOVA, there was a significant effect of year ($F = 4.18$, p = 0.009, df = 3) on the rate of overlap while foraging. The mean rate of overlap while foraging was higher in 2010 ($\bar{x} = 17\%$, SD = 14.5%) than 2008 ($\bar{x} = 6\%$, SD = 11%), 2009 ($\bar{x} = 6\%$, SD = 13%), and 2011 ($\bar{x} = 7\%$, SD = 11%). Rates of overlap while foraging were not significantly affected by sex ($F = 2.45$, p = 0.122, df = 1), and there was no interaction between year and sex ($F = 1.06$, p = 0.371, df = 3). Moreover, there were no significant differences between sexes in the rates of overlap while foraging in the different fisheries (squid trawl: $F = 2.14$, p = 0.148; hoki trawl: $F = 1.64$, p = 0.204; barracouta trawls: $F = 0.03$, p = 0.863; squid jig: $F =$
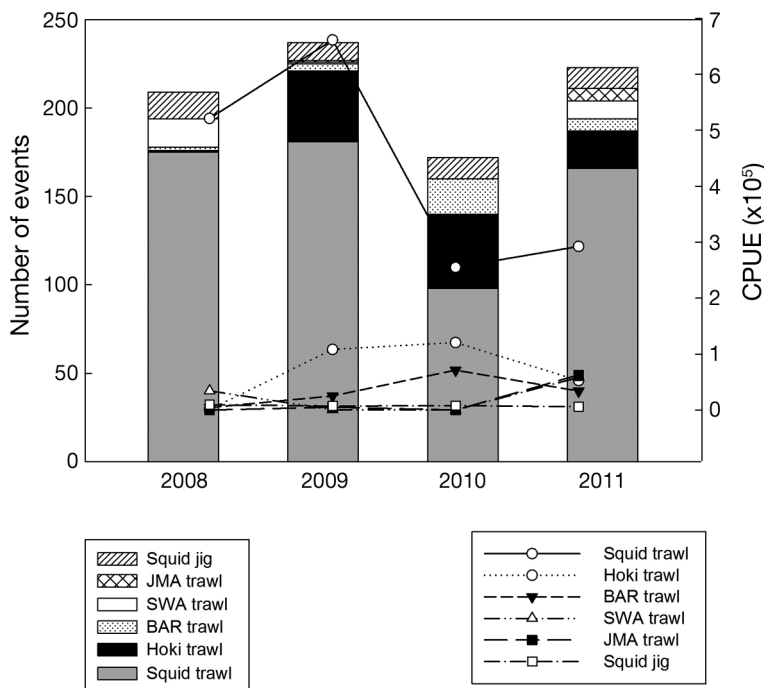

Fig. 2. Variation in fishing effort (stacked bars) and catch per unit effort (CPUE; lines) among years in the area used by Buller's albatross *Thalassarche bulleri* during the tracking periods. CPUE for trawl fisheries calculated as the sum of the ratio of catch weight per duration of tow for each event. CPUE for squid jig in each year calculated as the sum of the ratio of catch weight per fishing event. Squid = *Nototodarus gouldi* and *N. sloani*; hoki = *Macruronus novaezelandiae*; BAR = barracouta *Thyrsites atun*; SWA = silver warehou *Seriolella punctata*; JMA = jack mackerel *Trachurus declivis*
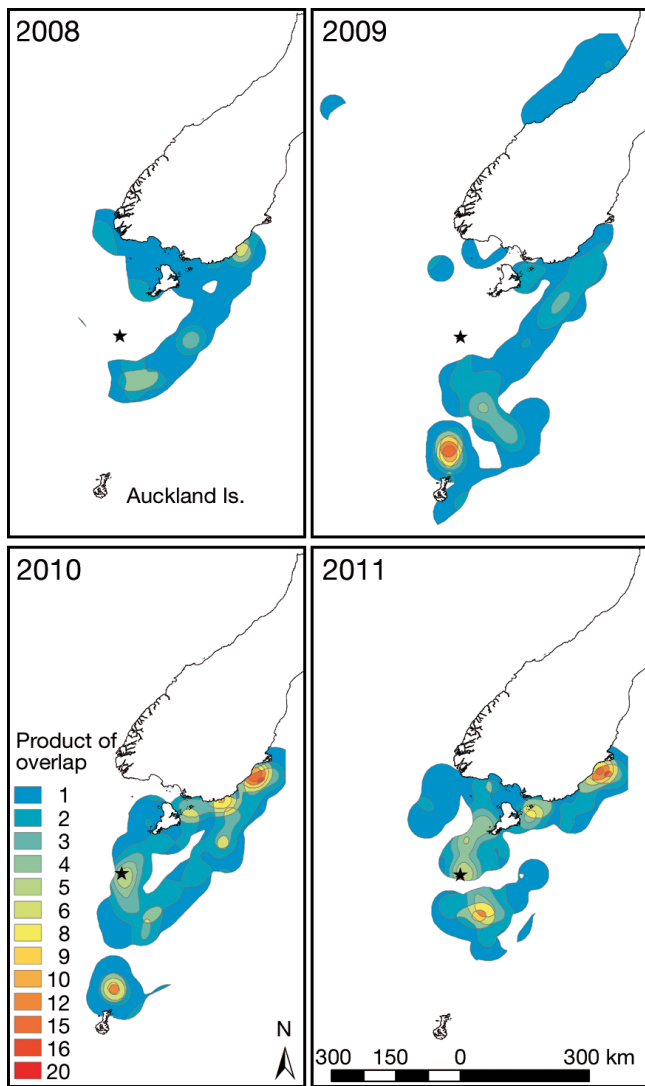
0.14, p = 0.705; df = 1 for all tests). There was no correlation detected between age and rate of overlap while foraging (ρ = 0.09, p = 0.4613).

Circular statistics comparing angle from the colony indicated highly significant differences (p < 0.001) in distributions between male and female albatrosses, and fishing vessels. Comparisons of test statistics from Watson's tests (Tables 3 & 4) confirmed the trends that are evident in the rose diagrams (Fig. 4). Between-year comparisons of vessel bearings from the colony suggested consistent distribution of fishing effort in all years (Table 3) (low test statistic values), except in 2010 when higher values for test statistics indicated a slightly different distribution of fishing vessels. The rose diagrams confirm this annual consistency, and show a slight shift northeast of fishing vessels in 2010. Female albatrosses consistently foraged to the north of the colony, with a strong preference for habitat toward the northeast in 2010 and 2011. Male albatrosses foraged more frequently to the south of the colony, although some foraged to the north and east, especially in 2011. There was a significant difference between males and females in the bearings from the colony of foraging points in all years (Table 4), although this was least

Fig. 3. Spatial intersection of yearly density plots of tracked Buller's albatrosses *Thalassarche bulleri* and fishing event start locations. Plots are standardized across years according to the product of bird and boat density rank (see 'Materials and methods') as symbolized by legend displayed: 1 (blue) = low intensity overlap through 20 (red) = high intensity overlap. (★): Snares colony

Table 2. *Thalassarche bulleri*. Comparison by year and sex of recorded GPS foraging points and rates of overlap with vessels while foraging. F = female; M = male; squid = *Nototodarus gouldi* and *N. sloani*; hoki = *Macruronus novaezelandiae*; BAR = barracouta *Thyrsites atun*; SWA = silver warehou *Seriolella punctata*; JMA = jack mackerel *Trachurus declivis*

Year; sex	Points classified as foraging (n)	Foraging points over-lapping with vessels (n)	Rate of overlap						
			While foraging: all fisheries (%)	With squid trawl (%)	With hoki trawl (%)	With BAR trawl (%)	With squid jig (%)	With SWA trawl (%)	With JMA trawl (%)
2008	2991	110	3.68	2.37	0.00	0.00	0.00	1.30	0.00
F	1739	44	2.53	2.53	0.00	0.00	0.00	0.00	0.00
M	1252	66	5.27	2.16	0.00	0.00	0.00	3.12	0.00
2009	5540	456	8.23	4.04	4.17	0.00	0.02	0.00	0.00
F	2474	6	0.24	0.20	0.00	0.00	0.04	0.00	0.00
M	3066	450	14.68	7.14	7.53	0.00	0.00	0.00	0.00
2010	7554	1379	18.26	8.09	5.40	3.03	1.73	0.00	0.00
F	4083	590	14.45	3.06	6.10	4.19	1.10	0.00	0.00
M	3471	789	22.73	14.00	4.58	1.67	2.48	0.00	0.00
2011	6463	417	6.45	1.83	0.00	0.82	1.69	1.30	0.82
F	1973	146	7.40	0.46	0.00	0.00	5.02	0.00	1.93
M	4490	271	6.04	2.43	0.00	1.18	0.22	1.87	0.33

Table 3. *Thalassarche bulleri*. Results from Watson's 2-sample tests comparing the circular distributions of foraging locations between years by male and female Buller's albatrosses and fishing vessels (from vessel monitoring system [VMS] data). Test statistics (F) given with p in parentheses; all 0 values indicate p < 0.0001

Group	2008 vs. 2009	2009 vs. 2010	2008 vs. 2010	2008 vs. 2011	2009 vs. 2011	2010 vs. 2011
Female	174 (0)	519 (0)	1226 (0)	761 (0)	214 (0)	41 (0)
Male	2.44 (0.12)	122 (0)	156 (0)	729 (0)	973 (0)	2812 (0)
VMS	13.07 (0.0003)	259 (0)	153 (0)	27.2 (0)	77 (0)	53 (0)

Table 4. *Thalassarche bulleri*. Results from Watson's 2-sample tests comparing the circular distributions of foraging locations of male and female Buller's albatrosses and fishing vessels (from vessel monitoring system [VMS] data) in different years. Test statistics (F) given with p in parentheses; all 0 values indicate p < 0.0001

	Males vs. females	Males vs. VMS	Females vs. VMS
2008	2411 (0)	720 (0)	7912 (0)
2009	1537 (0)	773 (0)	6655 (0)
2010	1966 (0)	22.8 (0)	1745 (0)
2011	14.06 (0.0002)	4299 (0)	3594 (0)

apparent in 2011 when males foraged less often to the south. Higher test statistics in the comparisons between female and vessel bearings from the colony, relative to comparisons between male and vessel bearings, indicated that females foraged more frequently in a different direction from the colony relative to vessels. In 2010, test statistics indicated greater similarity between foraging locations of males and VMS points ($F = 23$) and between foraging locations of females and VMS points ($F = 1745$), indicating greater coincident use of the same areas by birds and boats.

The distribution and intensity of fisheries varied within the same spatial extent and similar period (second week of April) during the 4 yr of albatross tracking (Fig. 5). The distribution of the squid trawl fishery was the most consistent across all years, with the majority of events to the south of the colony, north of the Auckland Islands, and along the shelf break to the east and southeast of the colony. Despite a high density of squid trawls around the Auckland Islands in all years, no tracked albatross foraged in this area in 2008 and 2011. The distribution of the hoki fishery changed dramatically among years. In 2008, only one hoki trawl occurred to the east of the colony. Many more hoki trawls occurred in both 2009 and 2010, but the distribution of events was predominantly to the southeast of the colony in 2009, and predominantly to the east and northeast

in 2010. In 2011, the distribution of hoki trawls shifted back to the southeast of the colony. However, unlike 2009, no bird location identified as foraging occurred in the high density hoki trawl area. Although the barracouta trawl fishery was relatively minor in 2008 and 2009, the distribution of events shifted close to the colony and catch weight was greater in 2010. In 2011, the fishery shifted back to the south of the colony, and catch weight increased. Foraging albatrosses overlapped with the distribution of barracouta trawl events near the colony in 2010 and 2011. The distribution of silver warehou trawls concentrated along the shelf break in 2008, was limited to one event in 2009, none in 2010, and was concentrated just to the south of the colony in 2011.The jack mackerel fishery operated within a short distance to the southeast of the colony in 2009 and 2011; no vessel targeted jack mackerel in 2008 and 2010.

Forty-seven tracks had foraging points identified within 10 km of a fishing vessel, and 30 tracks had no foraging points within 10 km of a fishing vessel. For these 47 tracks, a mean of 51% of foraging points within 10 km of a fishing vessel were identified as overlapping (using the radius buffer method; see 'Materials and methods'). This relationship, between albatrosses foraging near (within 10 km) a fishing vessel and foraging while overlapping a fishing vessel, revealed that albatross perception of a fishing vessel does not inevitably result in overlap or association with the fishing vessel (Fig. 6). On around half (49%) of the occasions that albatrosses spent foraging within 10 km of a fishing vessel, the bird was foraging independently. Tracks with extreme values of percent foraging points within 10 km of a vessel that overlapped a vessel (close to 0 or 100%; left side of *x*-axis in Fig. 6) were also those tracks with few foraging points within 10 km of a vessel. In 2009 and 2010, there was an apparent skew toward a greater tendency for overlap when within 10 km of a vessel, whereas the opposite applied in 2008 and 2011, i.e. there was a reduced tendency for overlap when within 10 km of a vessel.
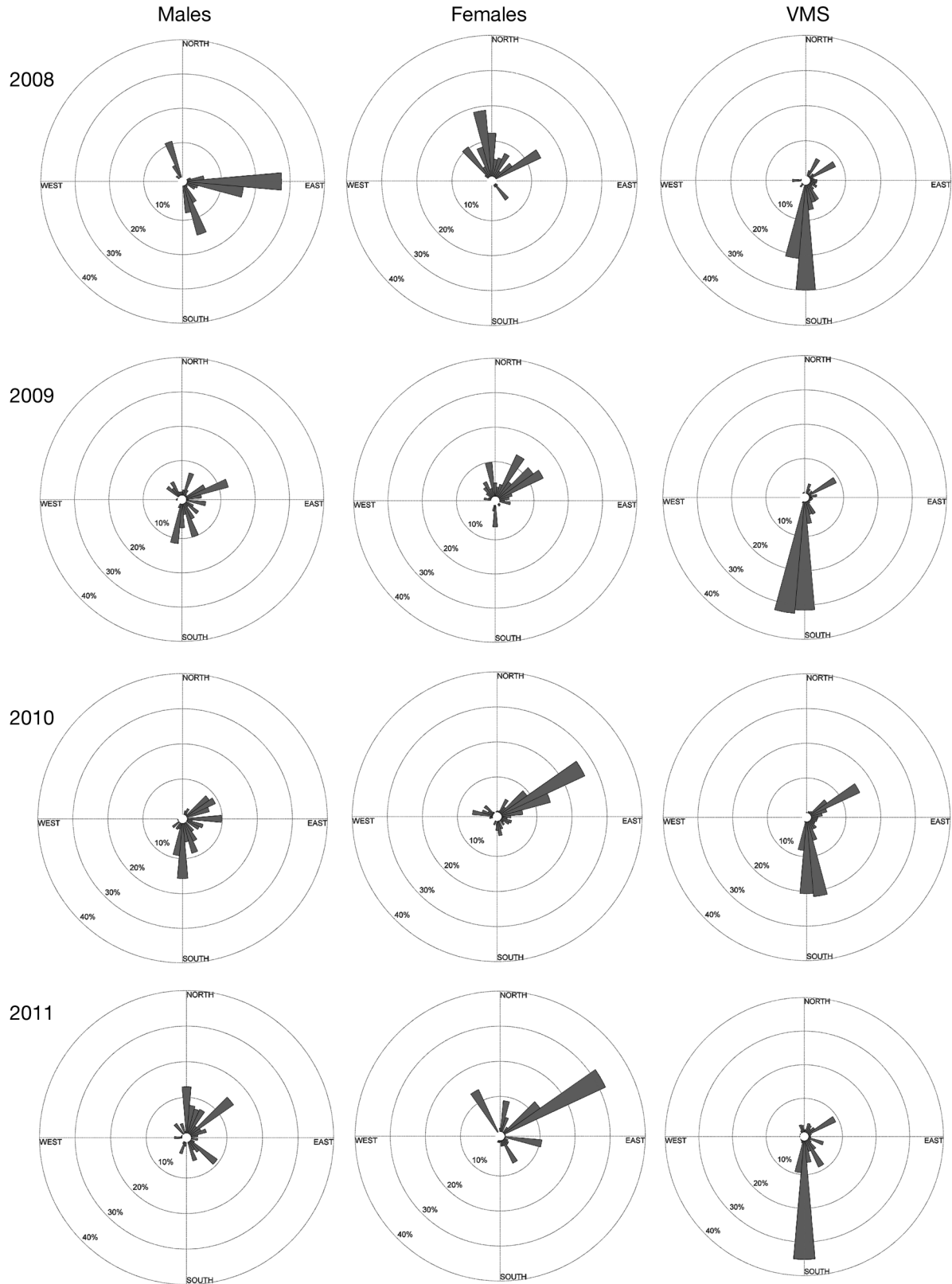
Fig. 4. *Thalassarche bulleri.* Rose diagrams indicating the angular distribution from the colony of foraging locations of tracked male and female Buller's albatrosses and vessel locations (VMS points) within the same spatial extent and time period. The center of each rose diagram represents the colony location, and length of each wedge reflects the number of points in that direction. All rose diagrams have a consistent scale that extends to 40%, with each ring representing 10% of points
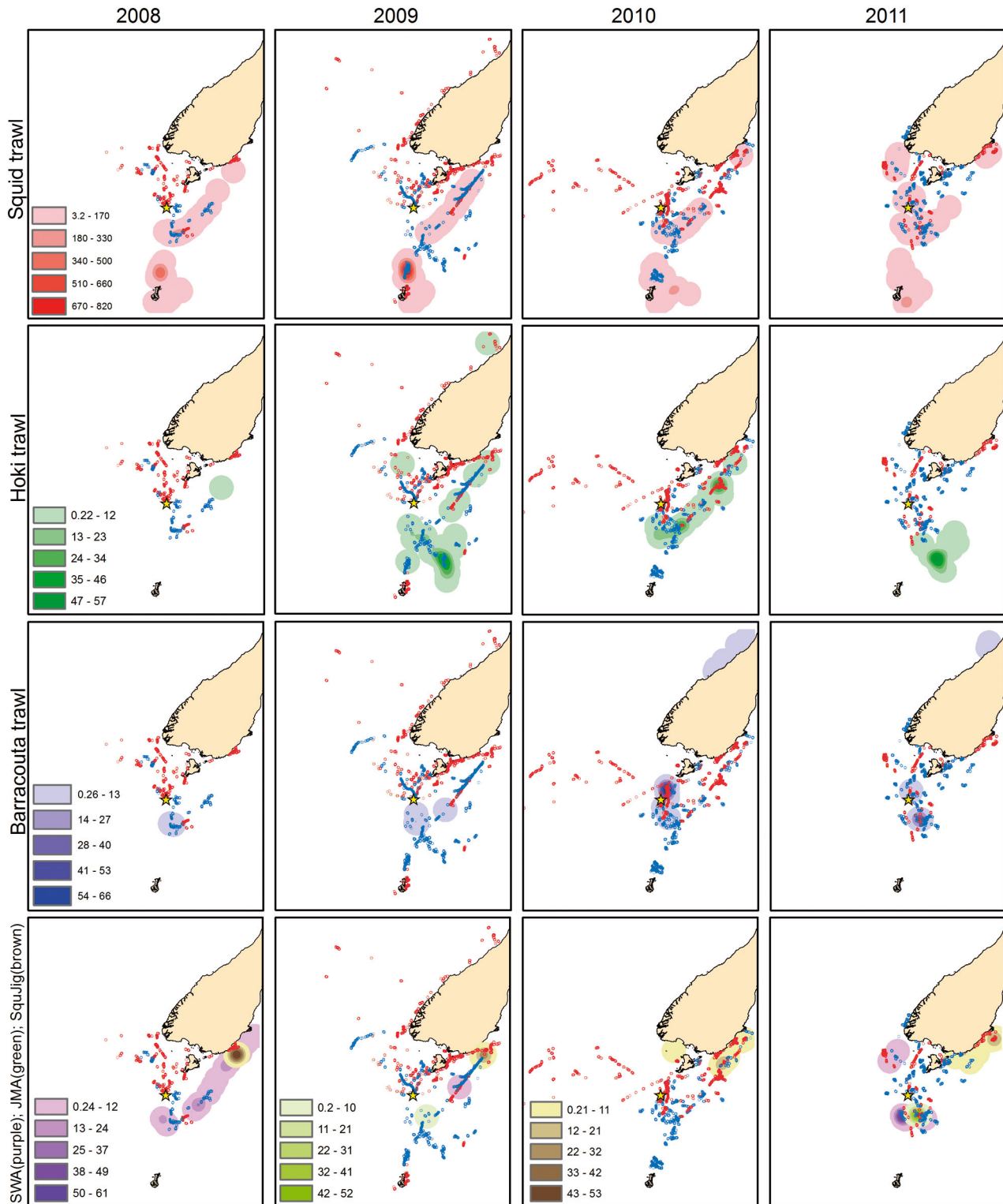
Fig. 5. *Thalassarche bulleri.* Variation in the distribution of fisheries among years with Buller's albatross foraging locations overlaid (male = blue dots; female = red dots). (★) The Snares. Density plots for each fishery created from start locations of fishing events, weighted by catch weight (tons) of the event. The scale of plots for each fishery is standardized across all years, so that each fishery color bar reflects the relative weight of catch (t) in to every year. The bottom row of plots includes density plots of 3 fisheries. Squid = *Nototodarus gouldi* and *N. sloani*; hoki = *Macruronus novaezelandiae*; barracouta = *Thyrsites atun*; SWA = silver warehou *Seriolella punctata*; JMA = jack mackerel *Trachurus declivis*; SquJig = squid jig
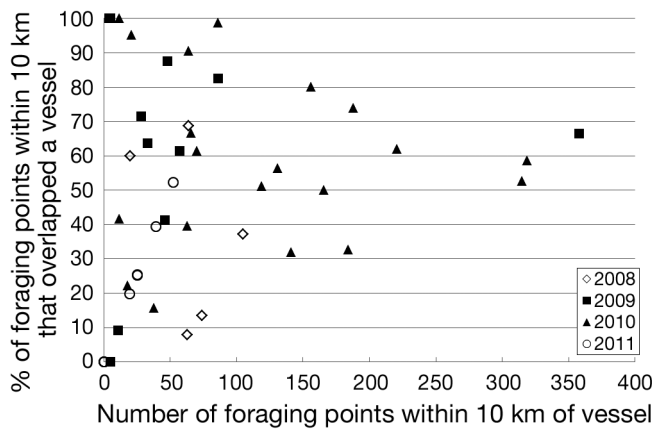
Fig. 6. *Thalassarche bulleri.* Relationship between Buller's albatrosses foraging near (within 10 km) a fishing vessel and foraging while overlapping a fishing vessel (identified using radius buffer method; see 'Materials and methods'). The number of foraging points from 47 Buller's albatross tracks that foraged within 10 km of a fishing vessel (*x*-axis) is plotted relative to the percent of foraging points within 10 km of a vessel that were identified as overlapping a vessel (*y*-axis). The 30 tracks with no identified foraging points within 10 km of a fishing vessel are not included in this figure

DISCUSSION

Seabird interactions with fishing vessels are generally considered in the context of seabirds being attracted to boats in order to scavenge on fisheries discards and catch (Arcos & Oro 1996, Skov & Durinck 2001). However, our study demonstrates that this is not always the default foraging strategy, even when birds and vessels occur in the same area. We found that Buller's albatrosses forage independently about half of the time they are within 10 km of a fishing vessel. Thus, use of the same area by albatrosses and vessels is due, at least half the time, to coincidence rather than the deliberate tactic of targeting vessels for feeding opportunities. Additionally, we demonstrate temporal and spatial variability in albatross foraging locations across 4 yr. Despite the relatively static distribution of the squid trawl fishery, overlap rates while foraging by tracked birds were relatively low in 2008 and 2011, indicating flexible foraging patterns and use of areas irrespective of the presence of squid trawl vessels. Moreover, it appears that the dramatic increase in rates of vessel overlap while foraging by females in 2010 was due to shifts in fishing effort rather than changes in bird distribution. In 2010 the hoki trawl fishery moved north into the areas used by females, and the barracouta trawl fishery was very active in close proximity to the colony.

Correspondingly, as the hoki fishery moved north in 2010, away from the southern areas used by males, rates of overlap while foraging by male albatrosses and hoki trawls declined.

The fine-scale overlap analysis revealed that across all 4 yr of tracking, the mean rate of overlap with a fishing vessel while foraging was relatively low (10%). This result indicates that the tracked albatrosses foraged independently of fishing vessels for the majority of the time. Even in 2010, when the rate of overlap while foraging increased, the birds still foraged away from vessels for the majority of the time. This result is in contrast to other studies that have documented high rates of albatross bycatch in fisheries (Croxall 2008, Anderson et al. 2011). We consider 3 non-exclusive hypotheses for this incongruity. (1) As a medium-sized albatross species, Buller's albatrosses are outcompeted by larger albatrosses (i.e. white-capped (*Thalassarche steadi*) or Salvin's (*Thalassarche salvini*) albatrosses) for access to foraging opportunities behind fishing vessels. (2) Buller's albatrosses were not particularly attracted to available fishing activities during the temporal period of our tracking work. (3) Fisheries mitigation methods such as Tori lines and offal mincing are properly implemented and effectively deterring interactions with Buller's albatrosses.

Additionally, our results illustrate how overlap rates are subject to the variability in both bird and fishing vessel distributions at fine scales. Both groups search for prey within a highly dynamic ecosystem, which occasionally results in overlapping distributions. The high rate (14%) of overlap while foraging of males and squid trawls in 2010 was likely due to a shift in the distribution of male foraging effort to the east and south (Fig. 4) compared with other years; this distribution over the shelf break and north of the Auckland Islands coincided with a dense concentration of squid trawlers. The explanation for this change in foraging distribution is difficult to ascertain, but further tracking and comparisons with fisheries distributions as well as an assessment of the role of environmental variability may reveal the driving factor(s).

Our results demonstrate the increased precision and value of quantifying seabird-fishery overlap with a fine-scale approach, rather than relying on conventional large-scale analysis typically done through overlays of density plots (Fig. 3). Comparison of results derived from fine and large-scale analyses illustrate that conclusions drawn from overlaid kernel density plots can be misleading. For instance, the kernel density plot in 2010 looks little different from

any other year, yet the fine-scale analysis revealed dramatically higher rates of overlap while foraging. Additionally, in all years, spatial overlap was indicated in areas where no or little foraging behavior was identified through the fine-scale track analysis, including along the south coast of mainland New Zealand. This large-scale overlap approach is also highly susceptible to sampling bias; density plot comparisons do not account for the variable number of tracks recorded in each year, which certainly influences areas identified as overlap. These examples highlight the deficiencies of a simple spatial overlay. Moreover, overlays are often assessed qualitatively through visual evaluations rather than objectively quantified (BirdLife International 2004, Phillips et al. 2006, Copello & Quintana 2009). Spatial comparisons of density plots of birds and boats are an effective broad-scale approach to assessing seabird-fisheries overlap. However, we suggest it would be prudent to resist over-interpreting results and simultaneously recognize that observed patterns are not absolute but rather the starting point for investigations at finer spatial and temporal scales.

Furthermore, access to fine-scale data utilized to create the kernel density plots in Fig. 3 (start locations from fishing events) is typically not available to scientists. Previous studies that compared seabird and fisheries distributions through density overlays have used catch effort datasets at meso-scales (18.6 km^2 or 1° grid cells) with variable temporal scales (Petersen et al. 2008, Copello & Quintana 2009, Pichegru et al. 2009) or data provided by regional fisheries management organizations in 5° grid cells at yearly temporal scales (Weimerskirch et al. 1997, Tuck et al. 2003, Cuthbert et al. 2005, Phillips et al. 2006, Walker & Elliott 2006). Therefore, our attempt at a large-scale comparison of seabird-fisheries overlap can still be considered relatively fine in scale compared to other studies.

The value of multiple years of tracking and analysis is illustrated by the increased overlap rate in 2010 compared with other years. With 4 yr of data and analysis, we demonstrated the temporal variability in rate of vessel overlap while foraging. Single-year analyses would have limited and skewed our understanding of relationships between Buller's albatrosses and fisheries. Additionally, our results highlight the relatively large variability in fishing effort and activity within a comparatively small spatial area and short temporal period.

GPS tracking of Buller's albatrosses during the brood-guard stage revealed a general pattern of sexual segregation. In all years but 2011, males foraged to the south and east of the colony, whereas females consistently foraged to the north and northeast of the colony in all years. There are a number of non-exclusive explanations for sexual segregation in foraging distributions of albatrosses, including size-mediated dominance and competitive exclusion, reproductive role specialization, and niche divergence (Shaffer et al. 2001, Phillips et al. 2004). Although the driver of the different distribution patterns of male and female Buller's albatrosses is unknown, males spent more time foraging near the large squid and hoki trawl fisheries (except in 2010 when the hoki trawl fishery moved north), which were also mainly to the south and east of the colony. However, the lack of a significant difference in rates of vessel overlap while foraging between sexes indicates that males are no more likely to interact closely with fishing vessels than females. The shift to the north and east of the colony of male foraging locations in 2011 illustrates the flexibility in albatross foraging behavior and also highlights the importance of multiple years of tracking data to better understand distribution patterns.

Fishing vessels have become part of the environment of many marine megafauna. Individuals utilize this resource (fisheries discards or target species) if and when it is advantageous, but according to our results, it would be incorrect to assume that this foraging tactic is common for all species (see also Granadeiro et al. 2011). Our results indicate that Buller's albatrosses maintain natural foraging patterns for the majority of the time, despite relatively widespread fishing activity within their at-sea range. Moreover, variable albatross overlap rates with fisheries are not solely a function of seabird and vessel distribution patterns, but also of the distribution and operational characteristics of vessels. To the best of our knowledge, this study represents the first time that more than 2 yr of fine-scale seabird tracking and fisheries distribution data have been assessed at small spatial (<10 km) and temporal (2 min) scales. Our datasets and analyses enabled us to quantify overlap rates by behavior state (limited to foraging), sex, age, year, and fishery, allowing meaningful comparisons among groups and insightful results.

Historically, national and international fisheries bodies have been reluctant to distribute fine-scale data on fishing vessel distribution, and until recently, GPS loggers were too large to deploy on seabirds. Hence, most studies of seabird-fisheries overlap were at relatively large scales (Phillips et al. 2006, Petersen et al. 2008, Fischer et al. 2009). However, access to fine-scale fishing vessel distribution and catch data is increasing, and biologging devices are

now much smaller, which allows much finer-scale analyses of overlap (Votier et al. 2010, Granadeiro et al. 2011, Torres et al. 2011). Therefore, we believe greater insight into fisheries association can be generated by scaling down analyses and examining individual behavior, as demonstrated in our study. This knowledge will also improve our understanding of seabird foraging strategies and help to generate effective conservation management solutions while minimizing regulatory burdens on fisheries operators.

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