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Use of bird-borne radar to examine shearwater interactions with legal and illegal fisheries

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Abstract

Seabirds interact with fishing vessels to consume fishing discards and baits, sometimes resulting in incidental capture (bycatch) and the death of the bird, which has clear conservation implications. To understand seabird–fishery interactions at large spatiotemporal scales, researchers are increasing their use of simultaneous seabird and fishing vessel tracking. However, vessel tracking data can contain gaps due to technical problems, illicit manipulation, or lack of adoption of tracking monitoring systems. These gaps might lead to underestimating the fishing effort and bycatch rates and jeopardize the effectiveness of marine conservation. We deployed bird-borne radar detector tags capable of recording radar signals from vessels. We placed tags on 88 shearwaters (*Calonectris diomedea*, *Calonectris borealis*, and *Calonectris edwardsii*) that forage in the northwestern Mediterranean Sea and the Canary Current Large Marine Ecosystem. We modeled vessel radar detections registered by the tags in relation to gridded automatic identification system (AIS) vessel tracking data to examine the spatiotemporal dynamics of seabird–vessel interactions and identify unreported fishing activity areas. Our models showed a moderate fit (area under the curve >0.7) to vessel tracking data, indicating a strong association of shearwaters to fishing vessels in major fishing grounds. Although in high-marine-traffic regions, radar detections were also driven by nonfishing vessels. The tags registered the presence of potential unregulated and unreported fishing vessels in West African waters, where merchant shipping is unusual but fishing activity is intense. Overall, bird-borne radar detectors showed areas and periods when the association of seabirds with legal and illegal fishing vessels was high. Bird-borne radar detectors could improve the focus of conservation efforts.

KEYWORDS
AIS, biologging, fisheries, Global Fishing Watch, IUU, Mediterranean Sea, seabirds, West Africa

INTRODUCTION

Overfishing and fishery discards are major threats to seabirds from fishing vessel activity (Dias et al., 2019; Furness, 2003). On the one hand, one third of fish stocks worldwide are overexploited (Branch et al., 2011), which reduces prey availability and compromises viability of seabird populations (Cury et al., 2011; Karpouzi et al., 2007). On the other hand, fishery discards provide a predictable food resource to scavenging seabirds but induce dependency on human-provided food subsidies, causing ecological changes with some downsides. That is, fishery discards might be energetically poor, trigger predation on threatened species when provisioning is interrupted, or promote incidental bycatch in fishing gear (Anderson et al., 2011; Grémillet et al., 2008; Lewison et al., 2014; Votier et al., 2004). Indeed, it is thought that incidental bycatch is driving the decline of many seabird populations worldwide (Clay et al., 2019). Thus, in the last 2 decades, increasing the knowledge of seabird–fishery interaction has become an important goal in marine conservation (Lewison et al., 2012).

Seabird–fishery interactions can be assessed using different approaches. At-sea surveys by observers on board fishing vessels can provide a local view of seabird–fishery interactions and quantify bycatch rates (Barcelona et al., 2010; Cabezas et al., 2012). At a broader spatiotemporal scale, the dynamics of seabird–fishery interactions can be studied by tracking seabirds and overlapping their movements with vessel positions obtained from various tracking systems, such as the automatic identification system (AIS) (Le Bot et al., 2018). The AIS is an unencrypted system used in collision avoidance, coastal surveillance, and traffic management by shipping, cruise, and industrial fishing vessels (Robards et al., 2016). However, AIS data may have gaps for several reasons, such as technical problems (e.g., saturation of the system when traffic density is high or faulty equipment), illicit manipulation (e.g., deliberate deactivation to cover illegal operations [Ford et al., 2018; Welch et al., 2022]), and poor enforcement (e.g., AIS not mandatory in some countries). The latter 2 reasons include illegal, unreported, and unregulated (IUU) fishing activities, which are widely practiced among global fisheries, especially in countries with poor governance (Agnew et al., 2009; Selig et al., 2022; Welch et al., 2022). Such fishing activities are challenging but crucial to assess because they are unlikely to follow the best bycatch mitigation strategies and compromise the reliable assessment of fish catches and bycatch rates, limiting the effectiveness of conservation efforts (Lewison et al., 2014; Pauly et al., 2002).

Recently developed bird-borne marine radar detectors (hereafter radar detectors) (Weimerskirch et al., 2018) offer new opportunities to assess seabird–vessel interactions without fishing data, such as AIS tracking. Radar detectors measure radio signals from the X band frequencies of marine radar devices on vessels used for navigation safety. In combination with GPS tags, radar detectors have been used to detect the presence of vessels along albatross (*Diomedea amsterdamensis* and *Diomedea exulans*) and gannet (*Morus capensis*) movements, contributing to the discovery of IUU fishing in the Southern Ocean (Carneiro, Clark, et al., 2022; Carneiro, Dias, et al., 2022; Corbeau et al., 2019, 2021; Grémillet et al., 2019; Weimerskirch et al., 2018, 2020). But so far, radar detectors have not been used in other species vulnerable to bycatch, such as shearwaters (Rodríguez et al., 2019), or in areas where fishing vessel and IUU activity are high, such as in West African waters (Welch et al., 2022). Indeed, fishing fleets operating in West African waters, among other problems, have poor control of corruption by the vessel's flag state, and these waters are among the most affected by IUU fishing activities (Belhabib et al., 2020; Doumbouya et al., 2017; Selig et al., 2022; Welch et al., 2022).

We deployed radar detector tags on individuals of 3 species of shearwaters breeding in two regions: the northwestern Mediterranean Sea (Scopoli's shearwater [*Calonectris diomedea*]), and the Canary Current Large Marine Ecosystem (CCLME) along West African waters (Cory's shearwater [*Calonectris borealis*] and Cape Verde shearwater [*Calonectris edwardsii*]). Although Scopoli's and Cory's shearwaters are least concern (International Union for Conservation of Nature [IUCN] Red List of Threatened Species [http://www.iucnredlist.org/]), Scopoli's shearwater is decreasing, and the trend for Cory's shearwater is unknown (BirdLife International, 2022). The Cape Verde shearwater is near threatened, and their populations are decreasing (BirdLife International, 2022). Bycatch from fishing activity constitutes the main driver of population decline of Scopoli's shearwater (Genovart et al., 2017). Cory's shearwater adult survival may be decreasing due to incidental bycatch by longline fisheries during the breeding season (Ramos et al., 2012) and is among the seabirds most affected by bycatch on the northeastern Atlantic coast (Calado et al., 2021). However, in the CCLME, seabird bycatch is poorly studied (Belhabib et al., 2020; Pott & Wiedenfeld, 2017), although it is expected to be elevated due to its high seabird abundance and fishing effort (Lewison et al., 2014; Paiva et al., 2015; Ramos et al., 2013).

Our main aim was to demonstrate how combining bird-borne radar detectors and gridded AIS data can help identify interactions between seabirds and fishing vessels and detect potential IUU fishing activities. Obtaining complete AIS trajectories across national boundaries can be challenging and costly. Therefore, we combined data from radar detector tags with daily gridded AIS data from fishing vessels. This information is publicly available from Global Fishing Watch (GFW, 2022; Kroodsma et al., 2018). Because radar detector tags do not provide information about vessel type (i.e., fishing, passenger, tanker, etc.), we also used monthly gridded AIS data from nonfishing vessels. Hence, we expected that radar detections in typical fishing grounds, but not matching daily fishing vessel presence or regular nonfishing vessel transits, would reflect the presence of IUU fishing vessels. Overall, we aimed to provide valuable information for fisheries management to mitigate seabird bycatch and thus improve the sustainability of fishing activities and protect vulnerable seabird populations. By identifying when and where seabird–fishery interactions occur with IUU fishing vessels, we shed light on an aspect often neglected by other approaches to studying seabird–fishery interactions. This knowledge could have significant impacts on seabird conservation and the marine environment.

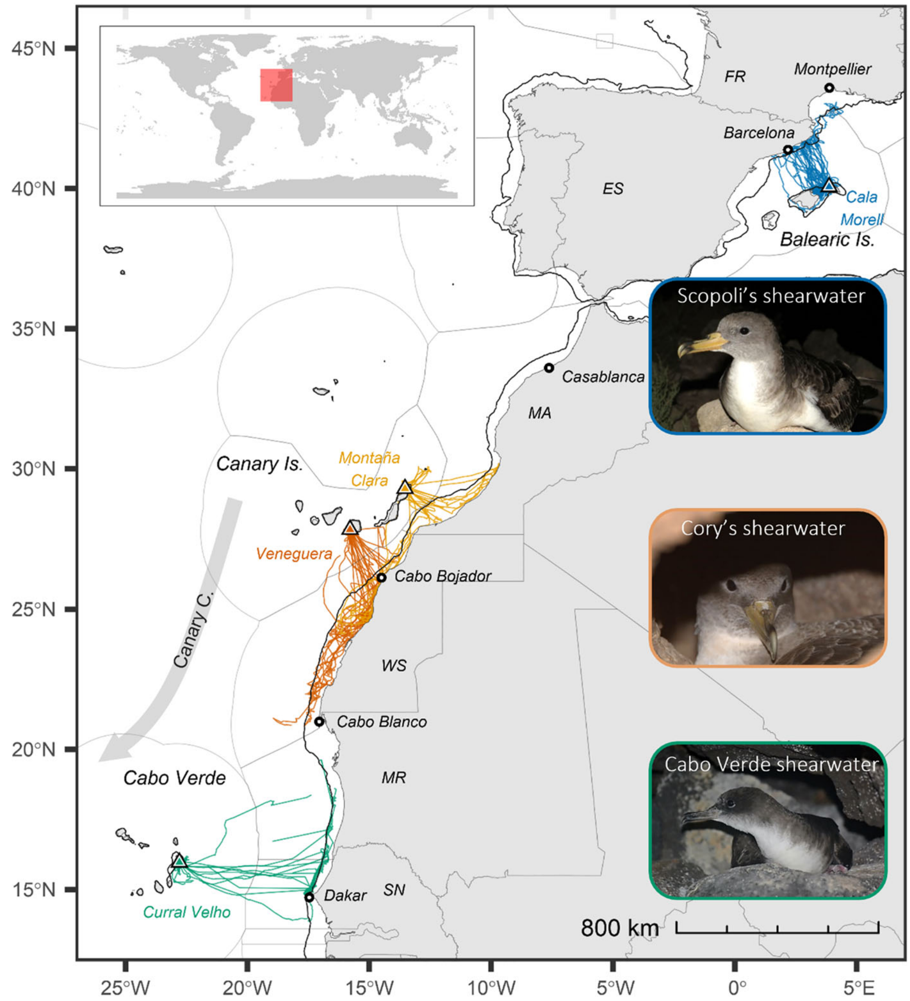

FIGURE 1 Foraging trips of *Calonectris* shearwaters tracked from 2018 to 2020 with radar detector tags (red square, study area; triangles, breeding colony locations; gray lines, boundaries of Exclusive Economic Zones and countries; black lines, isobath at 200 m). Birds were from breeding populations in Balearic Islands (blue lines) (Scopoli's shearwaters breeding in Cala Morell), Canary Islands (gold lines) (Cory's shearwaters breeding in Montaña Clara), Veneguera (orange lines), and Cabo Verde archipelago (green lines) (Cape Verde shearwaters breeding in Curral Velho). Photographs by Montserrat Vanerio (Scopoli's shearwater) and Jacob González-Solís (Cory's and Cape Verde shearwater).

METHODS

Fieldwork

We conducted our study during the breeding season (end of June to end of August) of 3 shearwater populations: Scopoli's shearwaters from the Balearic Islands population (Cala Morell colony, northwestern Mediterranean Sea, 2018–2020); Cory's shearwaters from Canary Islands population (Montaña Clara and Veneguera colonies, northeastern central Atlantic [CCLME, 2019–2020]); and Cape Verde shearwaters from Cabo Verde population (Curral Velho islet colony, southeastern central Atlantic [CCLME, 2018–2019]) (Figure 1). Breeding individuals were caught at night in their burrows by hand or with the help of a pole with a nested loop. Individuals were fitted with a radar detector sealed with a shrinking tube (18–20 g; Sextant Technology) attached to dorsal feathers with waterproof tape (Tesa). In general, radar detectors were recovered at least 5 days after deployment, though 9 were recovered earlier due problems in the field. The weight of the tag was below the rule of 5% of bird body mass (Croll et al., 1992): Scopoli's shearwater (mean [SD] = 3.2% [0.3%] of body mass; mean [SD] = 621.8 g [56.6] body mass) and Cory's shearwater (mean [SD] = 2.7% [0.3%] of body mass; mean [SD] = 761.3 g [92.0] body mass). However, for Cape Verde shearwater (mean [SD] = 4.5% [0.4%] of body mass; mean [SD] = 444.7 g [38.8] body mass), the rule of 5% of the bird's body mass was not accomplished on one individual (5.3%). We evaluated the radar detector weight's impact on Cape Verde shearwater as the lightest study species. To do so, we included a group of individuals that carried common lightweight GPS tags (16–18 g) (Perthold Engineering). We compared hatching and breeding success and found no differences among 3 groups of breeding pairs: those that never carried a tag (20 breeding pairs), that carried lightweight GPS tags (17 breeding pairs), and that carried a radar detector tag (16 breeding pairs). Furthermore, in comparison with individuals carrying lightweight GPS tags, individuals carrying radar detectors during the incubation period did not differ in trip duration, although they gained less weight during their foraging trip. Although the difficulties faced by Cape Verde shearwaters to gain weight are concerning, we sought to reveal, for the first time, the association of these birds with fishing vessels with data from radar tags. This is a crucial step toward the conservation of the species. Further details on the models performed to analyze the impact of carrying radar detectors on Cape Verde shearwater and their results are in Appendix S1.

Individuals were handled for <20 min, and we alternated tag fitting between the members of a pair to minimize impact on breeding success. Fieldwork protocols were approved by Conselleria de Medi Ambient, Agricultura i Pesca from Govern de les Illes Balears (permits: ANE 27/2018, ANE 22/2019, and ANE 19/2020); Consejería de Transición Ecológica, Lucha contra el Cambio Climático y Planificación Territorial del Gobierno de Canarias (permits: 2016/9887 and 2020/10835); and Direção Nacional do Ambiente de Cabo Verde (permits: 72/2017 and 91/2018). We adhered to the recommendations of the guidelines for the Use of Animals in Research approved by the Ethics Committee and the Animal Care Committee.

Seabird tracking data analyses

To optimize the tag battery life, the sampling frequency of radar detector tags was configured according to previous information on foraging trip duration (generally <5 days on average for the Balearic Islands population and >5 days on average for the CCLME populations). Accordingly, we configured radar detector tags to record GPS fixes every 5 min for the Balearic Islands population and 15 min for the CCLME populations. Using the SDLfilter R package (Shimada et al., 2012), we removed near-duplicate GPS fixes (fixes that occurred ≤2 min after the previous fix due to technical errors) and those that fell on land or registered unrealistic flight speeds (over 90 km/h). After that, we resampled all trajectories at 5-min intervals with linear interpolation with the move R package (Kranstauber et al., 2020) to harmonize data sets between species and fill in occasional gaps in data. We removed consecutive interpolated GPS locations lasting more than 1 h because they are considered large GPS gaps that may result in inaccuracies. Finally, because multiple trips per individual could be monitored, we split GPS trajectories into foraging trips (at-sea consecutive GPS fixes from departure to return to the colonies) with the track2KBA R package (Beal, Oppel, et al., 2021).

To detect vessels, the tag scanned marine radar emissions in a radius of 5 km (based on Weimerskirch et al., 2018) for a duration of 2 min every 5 min. Thus, time stamps (hereafter radar scan) were registered with information about the presence (hereafter radar detections) or absence of vessel radar emissions detected. Then, the coordinates of each radar scan were assigned by linearly interpolating the preceding and following GPS fixes with the move R package (Kranstauber et al., 2020). We considered radar scan interpolated positions unrealistic when they were interpolated to more than 1 h from a GPS fix (we chose a wide interval of 1 h to keep as much radar scan information as possible despite GPS gaps). We grouped successive radar detections (separated by 15-min intervals at most) to define seabird–vessel interactions (hereafter, radar events, composed of 1 or more radar detections).

Vessel tracking data

Though seabirds interact mainly with fishing vessels, nonfishing vessels (also equipped with marine radars) are also recorded by a radar detector. Therefore, we used 2 different space–time aggregated gridded products derived from satellite AIS data, one representing the density of nonfishing vessels (i.e., passenger, cargo, tanker, service, and unspecified vessels) and the other representing the density of fishing vessels (i.e., drifting longlines, fixed gear, set longlines, set gillnets, pots and traps, seiners, trawlers, squid jigger, and unspecified gear type).

First, we calculated nonfishing vessel activity as the number of nonfishing vessel transits per unit area and month (0.25° cell, June and July of 2019 and 2020) (exactEarth gridded data gathered from March, Metcalfe, et al., 2021). Vessels were classified as merchant (i.e., passenger, cargo, and tanker) or other vessels (i.e., recreational, service, or unspecified vessels).

Second, we gathered data on fishing vessel activity at 0.01° cell and daily resolution measured by GFW. Specifically, we used gridded data provided by GFW that includes the number of hours vessels were present, number of fishing hours, and absence or presence of fishing vessels. We also used fishing vessel activity from the GFW data set at the same spatial grid and time scale of nonfishing vessel data. To do so, we aggregated the number of hours vessels were present and the number of fishing hours separately from 0.01° to 0.25° cell. To capture typical fishing vessel activity, we averaged these data by month. Thus, we could detect patterns of fishing vessel activity that might go unnoticed on a daily basis, particularly in the context of unreported fishing operations.

Vessel detection in seabird movements

We quantified the number of radar events in shearwater core areas to determine the degree of overlap between the most common areas used by birds and vessel activity. To do so, we calculated the percentage of radar events per individual that occurred in the core area of its species (considering that the Canary Islands population core area contains 2 colonies), from which we obtained the mean and standard deviation at the population level. A radar event was considered to be in the core area if at least one radar detection occurred in the core area. We identified the 50% kernel contours of GPS fixes as core areas with the adehabitatHR R package (Calenge, 2006). We estimated the kernel bandwidth at the colony level with Worton's (1989) ad hoc method. We tested whether individuals in the colony reuse sites more than expected by chance (Kolmogorov–Smirnov test

>0.5) and estimated the percentage of the core areas used by each population captured by the sample size (Appendix S2). For these analyses, we used indEffectTest and repAssess functions from track2KBA R package, respectively (Beal, Oppel, et al., 2021).

Modeling seabird–vessel interactions

We fitted a generalized additive mixed model (GAMM) per population to analyze general spatial and temporal drivers of radar detections to examine when and where birds are exposed to fishing activity. Accordingly, we fitted GAMMs with binomial family with the gamm4 R package (Wood & Scheipl, 2020). To minimize the effect of spatiotemporal autocorrelation, radar detections were binned hourly and recoded as a binomial response (present, at least one radar detection, or absent). The model included 2 temporal fixed predictors: light effect (day vs. night) and weekday effect (weekdays, Monday through Friday; weekends, Saturday and Sunday). The latter was included because Scopoli's shearwater from the northwestern Mediterranean Sea is more likely to interact with fisheries during weekdays and daylight (Cortés et al., 2018; Soriano-Redondo et al., 2016). Day and night periods were defined after estimating sunrise and sunset hours with the maptools R package (Bivand & Lewin-Koh, 2020). Spatiotemporal fixed predictors included number of hours of fishing vessel presence (from GFW, all gear types pooled) and nonfishing vessel transit density (merchant and other vessels separately). We used values at monthly resolution and 0.25° cell within 5 km (extent of radar detection [Weimerskirch et al., 2018]). The number of hours of fishing vessel presence, merchant vessel transit density, and other vessels transit density were uncorrelated for Scopoli's and Cory's populations. However, for the Cape Verde population, other vessel transit density was excluded from the model because of its high correlation (Spearman correlation >0.7) with the number of hours of fishing vessel presence. To include these variables in the model as smooth predictor variables, we transformed them with a $\log(x + 1)$ function and then scaled them with z scoring. Finally, the year and the trip nested within the individual were included in the model as random variables. We generated a full model set per population with the combination of all fixed-effect terms with the MuMIn R package (Barton, 2020). We selected the most parsimonious model as the model with the lowest Akaike information criterion (AIC). We measured the predictive performance of the model by calculating the area under the curve (AUC) with 5-fold cross-validation with the presenceabsence R package (Freeman & Moisen, 2008). To account for the repeated-measures structure derived from telemetry data, we incorporated a block factor in the cross-validation process (March, Drago, et al., 2021; Roberts et al., 2017). Thus, we randomly split data into 5 balanced parts (folds) while keeping all data from an individual in the same fold. Four parts were used to fit the model, and the last was used to test the model accuracy. We repeated this process 5 times and estimated an average AUC value. An AUC >0.9 was considered good model accuracy, 0.7–0.9 was considered moderate, and 0.5–0.7 was considered low based on the assumption that an AUC = 0.5 indicates the model's performance is equal to a random prediction (Fielding & Bell, 1997).

Unmasking IUU fishing activity

We identified potential seabird–fishing vessel interactions by measuring the presence or absence of fishing vessels (based on the daily GFW database at 0.01° cell) from radar events. To do so, we determined whether a fishing vessel was present within 5 km (Weimerskirch et al., 2018) of each radar event and identified the potential gear types and flag states. To search for potential IUU events, we analyzed radar events from June and July (i.e., when both GFW and nonfishing vessel data were available). We hypothesized that a radar event not matching concurrent AIS data (i.e., GFW on a daily basis) and occurring in an area with high fishing activity but low nonfishing activity suggests the presence of IUU fishing. Thus, we assessed vessel density within 5 km (Weimerskirch et al., 2018) of each radar event not matched with daily GFW data sets. To do so, we calculated densities from fishing (i.e., fishing hours, all gears pooled) and nonfishing vessels (i.e., vessel transits) in the study area per grid cell (0.25° × 0.25°) and month. To define an IUU index, we first selected those cells in 3 bounding boxes per population, limited by the minimum and maximum coordinates of its GPS fixes. Then, after visualizing that both fishing and nonfishing densities had a log-normal distribution over the cells, we classified each cell as low (<5% percentile), medium (≥55% and <95% percentiles), or high density (≥95% percentile) (Coro et al., 2022). Finally, we defined a composite IUU risk index that accounted for all combinations between classes and considered that radar events occurring in areas with high or medium fishing density and low nonfishing density were likely to indicate IUU activity.

We compared our IUU risk index for each radar event with 2 complementary AIS-based data sets and found good agreement. First, we obtained raw AIS trajectories of both fishing and nonfishing vessels from CLS (Collecte Localisation Satellites) for the CCLME region. Radar events identified as high risk of IUU fishing did not have any corresponding raw AIS locations. This indicated that the vessel detected in the vicinity of the bird had not activated its AIS transmitter. Second, we examined a global data set of suspected AIS disabling events by fishing vessels (Welch et al., 2022) from 2017 to 2019. We associated 16% of these radar events identified as high risk of IUU fishing with 2 vessels that deactivated their AIS transmitter. One of these vessels had disabled its AIS transmitter for a period longer than the recommended 2 weeks for reliable allocation, as suggested by Welch et al. (2022). Despite this, by utilizing data on long-term AIS disabling events (2017–2019) lasting for at least 2 weeks, we determined that these radar events identified as high risk of IUU fishing coincided with areas of concurrent AIS disabling events. Details on both methods and their results are in Appendices S3–S7.

All analyses were performed with R 4.0.3 (R Core Team, 2020), and the R code is available at https://github.com/LeiaNH/Bird-borne-radar-detection and https://zenodo.org/records/10479979. We assumed a significance level of $p < 0.05$.

RESULTS

Description of radar detections in seabird movements

Of the 104 tags deployed, 7 were lost at sea, and 36 did not record data due to technical problems. Overall, 61 tags recorded data correctly and were used (Appendix S8). We obtained 122 trips, of which 36 were incomplete due to the tag running out of battery before the individual returned to its colony (Appendix S8). Both GPS and radar sensors worked correctly a mean (SD) of 95.2% (13.4%) of the time between the first and last GPS location of each trip. On average, radar tags worked better on the northwestern Mediterranean Sea (Balearic Islands population, mean = 97.0% [9.0%]) than on the CCLME area (i.e., the foraging area of the birds from the Canary Islands and Cabo Verde populations, mean of 93.7% [16.0%]).

Nearly one half of the trips from each population registered radar detections (50.0%, 46.9%, and 57.9% from the Balearic Islands, Canary Islands, and Cabo Verde populations, respectively) (Table 1; Appendix S8). Over one half of radar events were in the core areas for all 3 populations (mean [SD] = 51.6% [40.4%], 59.3% [33.2%], and 80.3% [27.6%] of the Balearic Islands, Canary Islands, and Cabo Verde populations, respectively) (Table 1; Figure 2; Appendix S8). When we broke down seabird–fishing interactions per population, 60%, 29%, and 81% of radar events from the Balearic Islands, Canary Islands, and Cabo Verde populations, respectively, matched the presence of fishing vessels at a daily level (Table 1). Most of the radar events that matched with fishing vessels (80%) in all 3 populations overlapped with the trawling fleet, followed by the purse seiner fleet in the Balearic and Canary Islands populations (Table 1). The longline fleet was present in 6.5% of radar events only for the Canary Island population (Table 1). Balearic Islands population used mainly Spanish waters, so radar events primarily matched with the presence of Spanish vessels (Figure 1; Appendix S9). In addition to Spanish waters, the Canary Islands population frequented Morocco and Western Sahara waters, and its radar events matched with several Moroccan and European vessel flags (Figure 1; Appendix S9). The Cabo Verde population used Mauritanian and Senegal waters, and close to 90% of radar events matched with the presence of Senegalese vessels (Figure 1; Appendix S9).

Drivers of radar detections

The most parsimonious GAMM models for radar detections had moderate accuracy (AUC > 0.7) for all 3 populations (Table 2; Appendix S10). Fishing vessel density had a positive effect on the probability of a shearwater detecting radar

TABLE 1 Summary of trips of shearwaters equipped with radar detectors and vessel radar detections at 3 locations.

Population location	No. of trips (trips with ≥1 radar event)	Max. distance (km) (SD)[a]	Number of radar detections					
			Total (no. in core area)	GFW[b]	Trawler	Purse seiners	Longliner	Unspecified
Balearic Island	54 (27)	81.3 (80.3)	95 (47)	57	56	14	0	2
Canary Island	49 (23)	284.4 (237.3)	166 (113)	48	43	10	2	2
Cabo Verde	19 (11)	403.3 (308.9)	218 (197)	180	178	5	0	2

[a]Maximum distance from colony calculated per trip.
[b]Number of radar events overlapping with daily fishing vessel from Global Fishing Watch data set for different gear types (trawlers, purse seiners, longliners, and unspecified types of fishing vessels). Diverse fishing gear types can occur in the same grid cell.

TABLE 2 Results of the generalized additive mixed models of radar-equipped shearwater detections of vessels .

Population location and factors							
Balearic Island							
Fixed factors	**Estimate (SE)**	***z***	***p***	**AIC**[a]	**Mean AUC**[b] **(SD)**	**df**	χ^2
Intercept	−2.86 (0.20)	−14.05	<0.001	347.87	0.7 (0.09)		
Night	−0.86 (0.40)	−2.17	<0.05				
Weekend	−0.92 (0.45)	−2.06	<0.05				
Smoothing factors							
Fishing[c]			<0.05			1.00	5.04
Other[d]			<0.05			1.00	4.57
Canary Island							
Fixed factors							
Intercept	−4.06 (0.54)	−7.54	<0.001	489.49	0.7 (0.12)		
Smoothing factors							
Fishing[c]			<0.001			1.00	16.48
Other[d]			<0.1			1.00	3.64
Cabo Verde							
Fixed factors							
Intercept	−2.26 (0.49)	−4.64	<0.001	716.56	0.9 (0.05)		
Night	−2.17 (0.22)	−9.69	<0.001				
Smoothing factors							
Fishing[c]			<0.001			4.66	41.41

[a] Akaike's information criterion.
[b] Area under the curve obtained from *k*-fold cross-validation.
[c] Monthly average of the numbers of fishing vessel hours.
[d] Monthly average of the number of other vessel transits.

in all 3 populations. Other vessels had a positive effect on the Balearic Islands population (Table 2; Figure 3). We also found an increase in the probability to detect a radar during daylight in the Balearic Islands and Cabo Verde populations. The weekday effect was only significant for the Balearic Islands population, which had a lower probability of radar detections on weekends (Table 2).

Unraveling potential unregulated fishing activity

Overall, 27.7% of the radar events (14, 41, and 31 from Balearic Islands, Canary, and Cabo Verde populations, respectively) did not overlap with any reported fishing vessel on a daily basis in June and July of 2019 and 2020. Though radar events occurred mainly in areas of low and medium risk overlap with the fishing fleet, 31 of these radar events (2 and 29 from Canary Islands and Cabo Verde populations, respectively) were found in areas of high risk of IUU (usual areas with high or medium fishing vessel density and low nonfishing vessel density) mainly around waters from Senegal and Mauritania (Figure 4).

DISCUSSION

Our results showed the utility of using radar detector tags to assess seabird–fishery interactions at the interspecific level on 3 species of shearwaters breeding across a large geographical scale. We provided the first spatiotemporal assessment between shearwaters and fisheries in the CCLME (West African waters). This spatiotemporal information can be used to manage bycatch risk in the CCLME. More importantly, we identified an area in the CCLME where IUU fishing activity is likely to occur, putting at risk conservation efforts in this biodiversity hotspot.

Shearwaters from all 3 species frequently interacted with vessels, mostly fishing vessels, throughout their foraging distribution. Moreover, we delineated daily and weekly spatiotemporal dynamics of the interactions between shearwaters and vessels. Regarding the diurnal cycle of seabird–vessel interaction, vessel interactions were more likely to happen during daylight for all 3 species but also during the night in the case of Cory's shearwater. This pattern was expected because the studied species forage mainly during the day or at crepuscular hours, although they can also be active at night or, for example, when the moon is full (Dias et al., 2012; Zango et al., 2019). Overall, these results reinforce the suitability of setting longlines at night as an effective

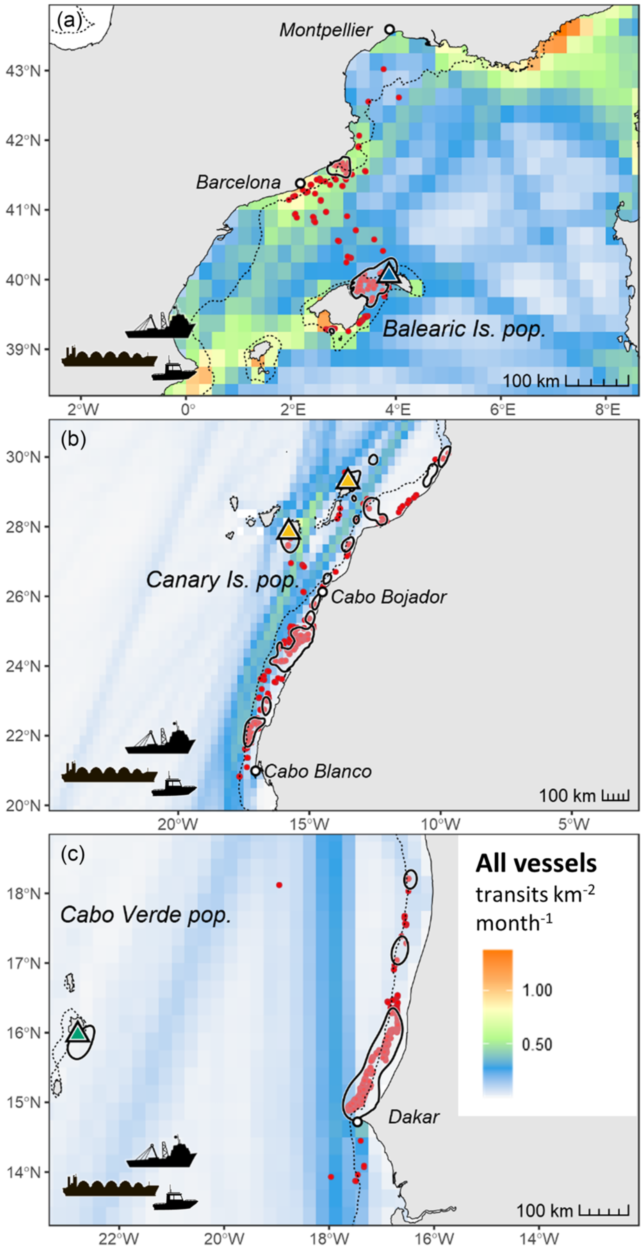

FIGURE 2 Radar-equipped shearwater detections of vessels and shearwater core habitat: core areas (solid black line, 50% kernel contour of GPS fixes) and radar-equipped shearwater detections of vessels (red dots) of (a) Balearic Islands shearwater population, (b) Canary Island shearwater population, and (c) Cabo Verde shearwater population from 2018 to 2020 (triangles, breeding colony locations; black dashed line, isobath at 200 m; cell colors, marine traffic density [mean value of the number of transits per unit area from all types of vessels log(x+1) transformed from June and July of 2019 and 2020]; empty cells, mean = 0).

mitigation measure to reduce bycatch rates (Cortés et al., 2018). We also found that shearwaters from Balearic Islands population interacted with industrial fishing vessels mainly during weekdays, when the trawler fleet operates. This workweek effect has been shown in the Mediterranean and is thought to promote a peak of seabird bycatch in longlines during the weekend, when this fleet operates (Soriano-Redondo et al., 2016). However, we did not find such an effect in shearwaters foraging in the CCLME, perhaps because national and international fleets operating in this area do not follow the European workweek and weekend schedule, as shown for Chinese vessels (Kroodsma et al., 2018; Li et al., 2021). This basic spatiotemporal information confirms the potential of bird-borne radar detectors to determine where and when seabirds interact with what type of vessels from what countries, which can help one infer their vulnerability to vessel activity and the derived political responsibilities (Beal, Dias, et al., 2021; Weimerskirch et al., 2020).

In all 3 species, the positive relationship between radar detections and fishing vessel activity was mainly driven by trawling activity. Shearwater distribution mostly overlapped with trawling activity, mostly concentrated in the continental shelves, which is also the dominant gear type of both the northwestern Mediterranean Sea and the CCLME (Leurs et al., 2021; Merino et al., 2019). Although bycatch rates in the trawling fleet do not seem to be relevant, its high overlap may suggest shearwaters feed on discards, and therefore any change to discard policies could have a strong impact on the feeding ecology of seabirds, due to the dependence of some species on this food resource (Bicknell et al., 2013). This has been shown for Scopoli's shearwaters in the Mediterranean Sea (Cortés et al., 2017, 2018; Reyes-González et al., 2021; Soriano-Redondo et al., 2016) and for Cory's shearwaters in the northeastern Atlantic coast (Calado et al., 2021), but this is the first time it has been shown for Cory's and Cape Verde shearwaters in the CCLME. Whether this close interaction can lead to bycatch is unknown in the case of the Cape Verde shearwater, but a matter of concern. The frequent interaction between fishing vessels and the 3 species suggests that mitigation measures should be implemented in all these areas. For the Balearic Islands population, the Spanish, Catalan, and Balearic governments are responsible for implementation of mitigation measures during the breeding season. Regarding mitigation measures in the CCLME, the 3 species feed in this area, either during the breeding season (Cory's and Cape Verde shearwaters) or during the nonbreeding season (Cory's and Scopoli's shearwaters). Although radar detectors can only be deployed during the breeding period so far, it is reasonable to infer that these species are also interacting with fisheries and at risk of bycatch in the CCLME out of the breeding season. The conservation of such wide-ranging seabird species crossing political boundaries outside and inside the CCLME requires a call for cooperation among West African countries, from Morocco to Guinea. However, it also extends political responsibilities to the European countries, where some of these shearwater species and populations are breeding, but also because many of the interactions took place with vessels with European flags.

Furthermore, a positive relationship between radar detections and nonfishing vessel activity was also found for the Balearic Islands. That was expected in the northwestern Mediterranean Sea, where there is a high density of merchant, passenger, and recreational vessels (Coll et al., 2012; March, Metcalfe, et al., 2021). Conversely, in West African waters, vessel traffic is mainly limited to merchant shipping and fisheries. However, it was difficult to tease apart the type of vessels

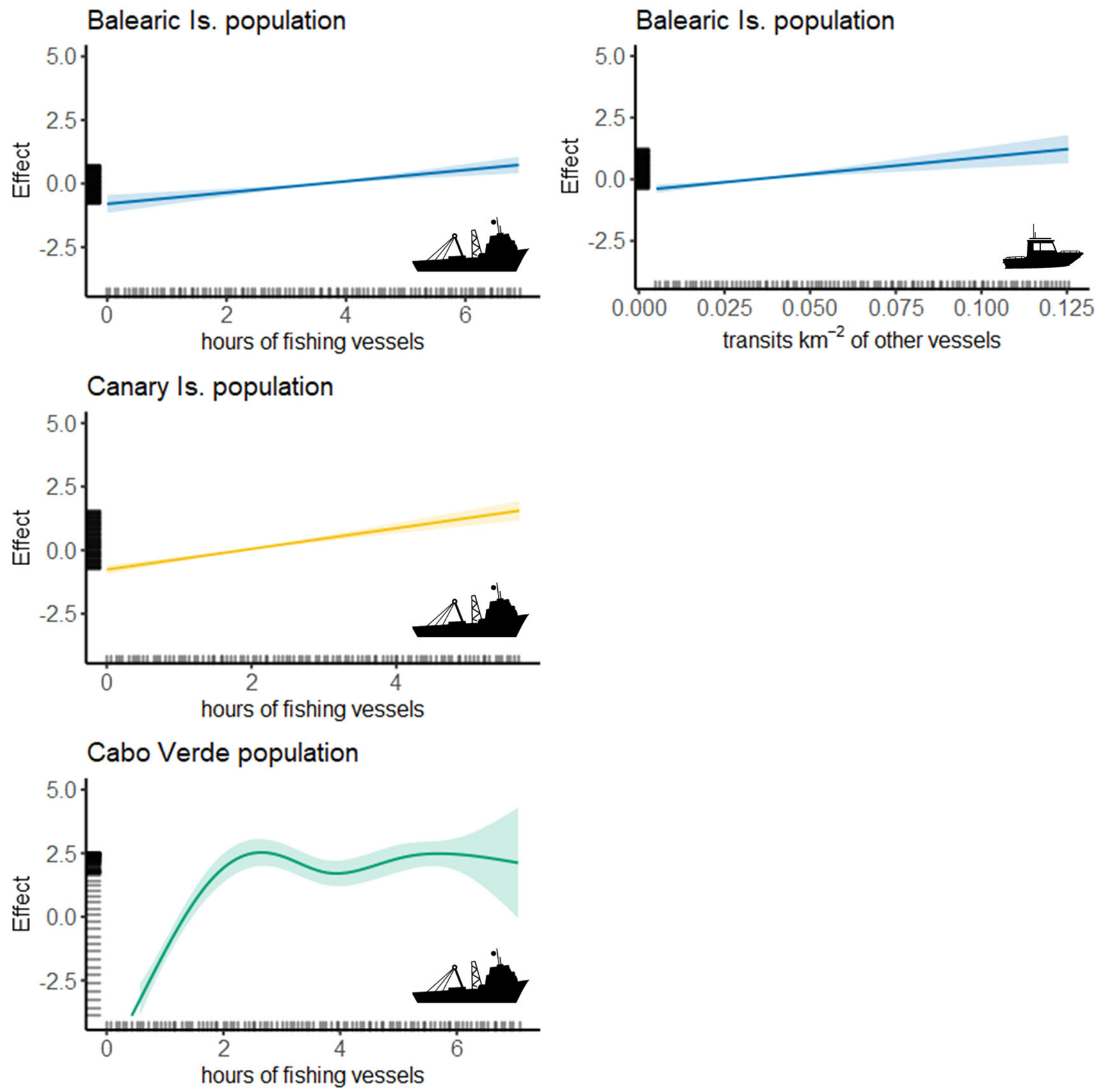

FIGURE 3 Partial effects of vessel activity (fishing and other vessels [icons]) on radar-equipped shearwater detections of vessels from the best generalized additive mixed models of the Balearic Island (blue), Canary Island (yellow), and Cabo Verde populations (green) (shading, 95% confidence intervals; hash marks on x-axes, occurrence of each covariate; vessel illustrations, fishing and other type of vessels indicated on the x-axes; values on x-axes are $\log[x + 1]$ transformed).

interacting with seabirds in areas where both fishing grounds and shipping routes occurred simultaneously. Nevertheless, in areas where merchant shipping is unusual but fishing activity is intense, such as in some relatively coastal areas of Mauritania and Senegal waters, radar detections are likely to indicate vessels switching off AIS transponders. Indeed, IUU trawling activity has been reported in and around that area (Sarr et al., 2023). Although IUU fishing does not necessarily result in seabird bycatch, its hidden operations constitute a major threat to marine biodiversity and undermine sustainable fishing management. Furthermore, fishing activity irregularities in the Canary Current threaten not only Cory's and Cape Verde shearwaters, but also the entire seabird community foraging in the CCLME during the breeding and nonbreeding periods (Grecian et al., 2016).

Although AIS is an excellent tool with which to examine seabird–vessel interactions and to improve seabird conservation, especially in inferring the general distribution of vessels in large regions (Orben et al., 2021), its limitations must also be acknowledged. Vessels tracked with AIS are usually larger than 24 m, but European fleets have adopted AIS for almost all vessels larger than 15 m (Taconet et al., 2019). Even though AIS is increasingly used on a voluntary basis in small fishing vessels (March, Metcalfe, et al., 2021), it entails an economic cost; thus, it is not guaranteed that AIS will cover vessels that are not required to carry it. Currently, AIS tracking mostly excludes small-scale fisheries; therefore, studies based on these data underestimate seabird–fishery interactions and the potential impact of bycatch in small-scale fisheries (Pott & Wiedenfeld, 2017). Radar detectors offer the possibility to increase to some extent the detection of seabird–fishery interactions with small-scale fisheries, although very small vessels are also unlikely to carry a marine radar device.

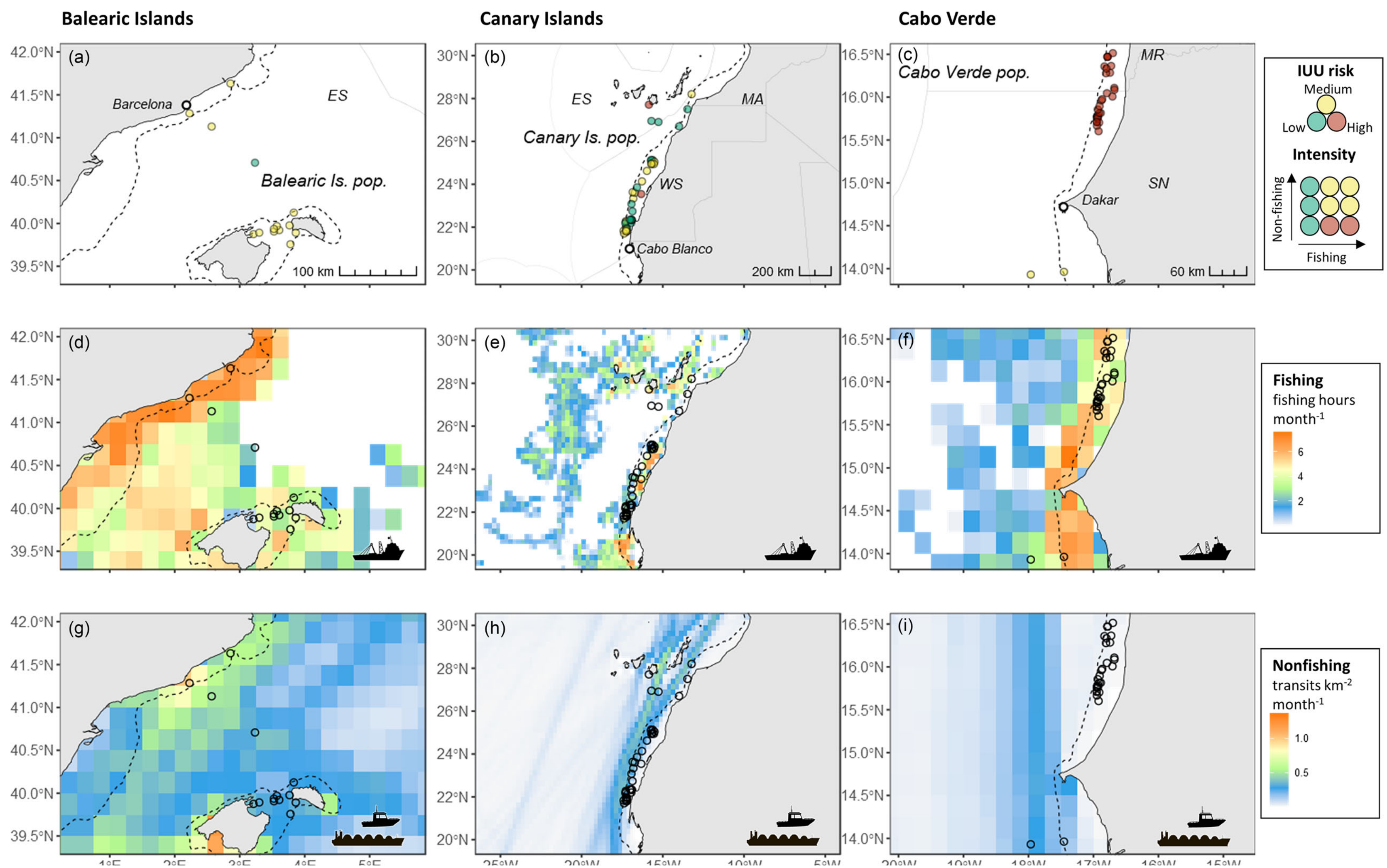

FIGURE 4 Radar-equipped shearwaters detections of vessels of Balearic Islands, Canary Islands, and Cabo Verde populations not matched with daily fishing activity: (a–c) location of first radar detection in a radar event (i.e., successive radar detections separated by 15-min intervals at most) (IUU, illegal, unreported, and unregulated fishing activity; red, radar event overlapped with a high-IUU-risk area; green, low fishing risk overlap; yellow, medium fishing risk overlap), (d–f) fishing effort (colors) (total fishing hours in June and July of 2019 and 2020 and log[$x + 1$] transformed) extracted from the Global Fishing Watch (GFW) data set, and (g–i) number of vessel transits per unit area (colors) (mean value in June and July of 2019 and 2020 and log[$x + 1$]-transformed value of nonfishing vessels, i.e., merchant and other vessel types [vessel icons]) (empty cells, 0). Circles in panels (d–i) are the radar events shown in panels (a–c).

The potential to infer the impacts of fishing activity on seabirds is also limited by other factors. Unlike in the northwestern Mediterranean Sea (Cortés et al., 2018), in CCLME bycatch data are lacking (Pott & Wiedenfeld, 2017), making hypothetical the bycatch risk associated with each gear type. In addition, locations of shearwater–fishing interactions in CCLME might be biased by the limitations associated with the AIS-gridded products aggregated across multiple temporal periods. Aggregated data may fail to resolve concurrent seabird–vessel encounters. Analyses in which individual vessel tracks from raw AIS locations are used would help identify vessels with more certainty and provide details of seabird–fisheries interactions. However, relying solely on raw AIS locations has its limitations. It may fail in areas with high levels of IUU, where vessels intentionally disable their AIS. This is where gridded AIS data come in handy; it enabled us to pinpoint hidden fishing activity. Furthermore, other tags, such as bird-borne cameras, might be a potential tool to validate interactions and understand seabird behavior when attending a boat.

Overall, our results show that bird-borne radar detectors can reveal in detail the spatiotemporal dynamics of seabird–vessel interactions, even when vessel positions are unknown. The combination of this information with AIS data provided by GFW allowed us to break down the interactions by gear type and flag and identify some potential IUU fishing activities in some specific areas of the CCLME. This was validated by contrasting the result of this approach with raw AIS data, further showing the potential of using publicly available data provided by GFW. This information can be extremely useful to determining the exposure of seabirds to vessels and bycatch risk, which can be used to inform fisheries management. It may also be possible to identify the origin of a vessel with radar detections, which is crucial information to infer national responsibilities. Our results showed a high exposure of shearwaters to fishing vessels activity in the CCLME, increasing our concerns about the suspected seabird bycatch occurring in this area and highlighting the urgent need to assess the still unknown seabird bycatch rates in the Canary Current, as well as the need to develop international agreements to implement mitigation measures in this area.

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SUPPORTING INFORMATION

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