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Seasonal variation in seabird abundance and bycatch at artisanal bottom-set net fisheries in the southern Iberian Atlantic coast

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ABSTRACT

Bycatch is a major cause of seabird mortality, yet most studies focus on industrial fisheries, with limited knowledge on artisanal fisheries. This study investigates the seasonal abundance of seabirds off the southern-eastern coast of mainland Portugal, their attendance at artisanal bottom-set net fisheries, and observed bycatch, using onboard observations and fishermen interviews. From March 2020 to November 2022, 24,643 seabirds were observed attending fishing vessels in 183 daily fishing trips (98.4 % of 186 trips), spanning 20 species across 7 families, with 25 seabirds recorded as bycatch. Lesser black-backed and Yellow-legged gulls (*Larus fuscus* and *Larus michahellis*) were the most abundant species, followed by Audouin's gulls (*Ichthyaetus audouinii*), Great shearwaters (*Ardenna gravis*), and Northern gannets (*Morus bassanus*). During summer, the abundance of Yellow-legged and Audouin's gulls (local breeders) and Lesser black-backed gulls (non-breeding species) increased with fishery catch per unit effort. Great shearwaters were more affected by gear type, exhibiting higher attendance and bycatch in trammel nets during autumn. 65 % of Great shearwater bycatch occurred during a single fishing event, probably from fishermen cleaning nets and discarding fish and viscera during net setting. Fishermen interviews identified Northern gannets and Great cormorants (*Phalacrocorax carbo*) as the most frequently bycaught species, particularly in winter when onboard observations were limited. These findings underscore the impact of artisanal fisheries on seabird populations and highlight the importance of combining onboard data with fishermen interviews to improve bycatch estimates and inform conservation efforts. Our study also suggests that fishermen behaviour during fishery operations significantly influence seabird bycatch.

1. INTRODUCTION

Seabirds and fisheries have coexisted for centuries. Fishermen have traditionally used seabird aggregations to locate fish schools, while seabirds benefited from the food supply generated by fisheries (Le Bot et al., 2018). These interactions make seabirds vulnerable to bycatch, although the risk often varies among species, regions and gear types (Oliveira et al., 2022). Considering that bycatch has been identified as one of the major threats to seabirds globally (Dias et al., 2019), a comprehensive understanding of the extent and magnitude of bycatch, along with the factors influencing fishery attendance, is crucial for designing effective mitigation measures in space and time to reduce this threat (Lewison et al., 2014).

Studies assessing the risk of seabird bycatch have primarily focused on pelagic industrial fisheries (Anderson et al., 2011; Phillips et al., 2024), while impacts from small-scale artisanal fisheries remain relatively underexplored (Pott and Wiedenfeld, 2017; Votier et al., 2023). This lack of information is concerning, as artisanal fisheries represent

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the majority of the world's fishing fleets (Rousseau et al., 2019). Moreover, fishing effort (Alfaro-Shigueto et al., 2010) and bycatch rates (Dias et al., 2019) in small-scale fisheries have been shown to be similar to those in industrial fisheries, indicating that artisanal fisheries may pose a greater, but often unreported, threat to some seabird populations (Suazo et al., 2013). Bycatch risk in coastal areas can be further exacerbated in upwelling regions, as artisanal fisheries mainly operate in nearshore regions featuring high productivity, and therefore are likely to overlap in the same areas as marine megafauna (Peckham et al., 2007), including seabirds (García-Barón et al., 2023).

Onboard observer programs, whether from scientific cruises or fishing vessels, are the primary and the most accurate source of information for estimating seabird bycatch, and for identifying the main drivers of seabird-fishery interactions and bycatch rates (Le Bot et al., 2018). Although onboard observer data provide accurate information, bycatch estimates in artisanal fisheries are often difficult to obtain because data collection requires trained observers and systematic monitoring programs, which can be costly, time-consuming, logistically demanding, and affected by weather and sea conditions (Moore et al., 2021). Fishermen interviews can help overcome some of these challenges (Salas et al., 2007): they are a time- and cost-effective method that covers broad spatial and temporal scales and multiple fishing fleets, while promoting fishermen cooperation in data collection (Alexandre et al., 2022; Johnson and van Densen, 2007). Although limitations of fishermen interviews are acknowledged (e.g. frequent under-reporting, poor data reliability, and inconsistent methodologies; Silver and Campbell, 2005), they have been widely used to obtain minimum bycatch estimates of marine megafauna across several artisanal fishing fleets (Kusuma Mustika et al., 2021; Oliveira et al., 2015; Suazo et al., 2013).

Fixed nets (gill and trammel nets) fisheries are responsible for some of the highest seabird bycatch rates worldwide, primarily affecting diving species such as auks, cormorants, and gannets (Žydelis et al., 2013). Recent estimates suggest that 95,000 seabirds are bycaught annually in European waters, with the highest bycatch rates occurring in the Baltic Sea and Northeast Atlantic Ocean (Ramírez et al., 2024). In mainland Portugal, entanglement in fixed net fisheries was identified as a major cause for the extinction of the southernmost population of Common guillemots (*Uria aalge*) at Berlenga Island (Munilla et al., 2007), and one of the gears with the highest bycatch rates for Balearic shearwaters (*Puffinus mauretanicus*) and Northern gannets (*Morus bassanus*) (Araújo et al., 2022a; Oliveira et al., 2015). Although mitigation measures to reduce seabird bycatch in gillnets have been tested (Løkkeborg, 2011), much of this research is ongoing, and there are still relatively few successful solutions (Almeida et al., 2023). Understanding the drivers of seabird attendance at fishing vessels and fishermen behaviour is therefore crucial for designing effective mitigation measures to reduce bycatch in this sector.

This study combined onboard observations and fishermen interviews (2020–2022) in the southern-eastern coast of mainland Portugal to: (1) quantify the most abundant seabirds attending artisanal bottom-set net fisheries; (2) explore the drivers of seabird attendance at fishing vessels; and (3) estimate bycatch mortality. Northern gannets and gulls (Yellow-legged *Larus michahellis*, Lesser black-backed *Larus fuscus* and Audouin's gulls *Ichthyaetus audouinii*) were expected to be the most abundant species attending fishing vessels, due to their high occurrence in the study area (Meirinho et al., 2014) and scavenging behaviour (Arcos et al., 2001; Votier et al., 2013). Local breeders (Yellow-legged and Audouin's gulls) were expected to attend fishing vessels in greater numbers during the breeding period (spring and summer), while non-breeding species (Lesser black-backed gulls and Northern gannets) were anticipated to increase their attendance at boats during autumn and winter (Matos et al., 2018; Meirinho et al., 2014). Seabird attendance at fishing vessels was also expected to be influenced by fishing variables, as these were known to enhance prey availability and accessibility around boats (Calado et al., 2021a; Matos et al., 2018). Lastly, seabird bycatch rates were likely to be higher for diving seabirds (e.g. Northern gannets) compared to surface feeders (Alexandre et al., 2022; Almeida et al., 2023; Oliveira et al., 2015).

2. Materials and methods

2.1. Characterisation of seabird species in the study area

This study was conducted in the southern-eastern coast of mainland Portugal. More specifically, the study area covered a small coast of approximately 80 km, between Albufeira (37° 05′ N; 8° 14′ W) and Vila Real de Santo António (37° 11′ N; 7° 25′ W), also known as the Algarve leeward region (Fig. 1). The area holds important seabird breeding populations, including the largest known population of Audouin's gull (5,393 breeding pairs; Pereira et al., 2022a), as well as of Yellow-legged gull (641 breeding pairs; Pereira et al., 2022a), and of Little tern (*Sternula albifrons*, 442 breeding pairs; Pereira et al., 2022b). Non-breeding species also use this region, including the Balearic shearwater (Pereira et al., 2018), listed as critically endangered by the IUCN Red List (Birdlife International, 2018), and the European storm-petrel (*Hydrobates pelagicus*) (De la Cruz et al., 2023). The Algarve region is characterised by relatively intense fishing activity, with more than 90 % of the fishing fleet mostly comprising artisanal and small polyvalent fishing vessels (<12 m) (Instituto Nacional de Estatística, 2023). The fishing harbour of Olhão is one of the most important harbours in the region, and in 2022 accounted for more than 50 % (3910 tonnes) of the fish landed by polyvalent fisheries in the Algarve (Instituto Nacional de Estatística, 2023).

To estimate seabird abundance in the study area, at-sea counts were conducted over 49 days onboard a recreational boat (sailing catamaran), from January 2020 to January 2022. These surveys covered the coastline from Albufeira to Vila Real de Santo António, extending up to 20 nautical miles offshore (Fig. 1a). Monthly at-sea surveys were carried out once per month over two or three consecutive days along the same predefined transect (Fig. 1a), following the European Seabirds At Sea (ESAS) methodology (Camphuysen and Garthe, 2004; Tasker et al., 1984). The transect was surveyed continuously from sunrise to sunset for each day of observation. All seabirds observed were counted, identified to species level whenever possible, and recorded up to 300 m to one side of the vessel, by at least three trained observers. Identifications to family level were made when accurate identification to species was not possible. Their behaviour (e.g. birds exhibiting directional flights and birds sitting on the water surface) was also recorded. Seabirds sitting in the water surface were grouped within predefined distance bands (0–20 m, 20–50 m, 50–100 m, 100–200 m, 200–300 m). Seabirds in flight were counted using a snap-shot method (Tasker et al., 1984), and then aggregated into 5 min sampling units.

2.2. Characteristics of the sampled fleet and attendance of seabirds to fishing vessels

To estimate seabird abundance around fishing vessels, onboard observations were conducted on five different vessels operating bottom-set nets from Quarteira and Olhão fishing harbours (Fig. 1b). These observations were carried out over a total of 186 daily fishing trips, from March 2020 to November 2022, by one or two trained observers. The sampled fleet consisted of artisanal boats ranging from 7 to 15 m in length, with crews of 2–6 members. In 2022, bottom-set net fisheries (<15 m in length) accounted for more than 90 % of the Algarve's fishing licenses, with 601 registered fishing vessels (Instituto Nacional de Estatística, 2023). These vessels operated gillnets (mesh sizes: 60 mm, 80 mm and 220 mm) and trammel nets (mesh size: 120 mm inner and 640 mm outer panels). Nets were typically set in the morning and hauled at dawn the following day, with each fishing trip lasting less than 24 h (8.1 ± 0.1 h fished per trip). Fishermen operating bottom-set nets in the southern-eastern coast of mainland Portugal mainly target demersal

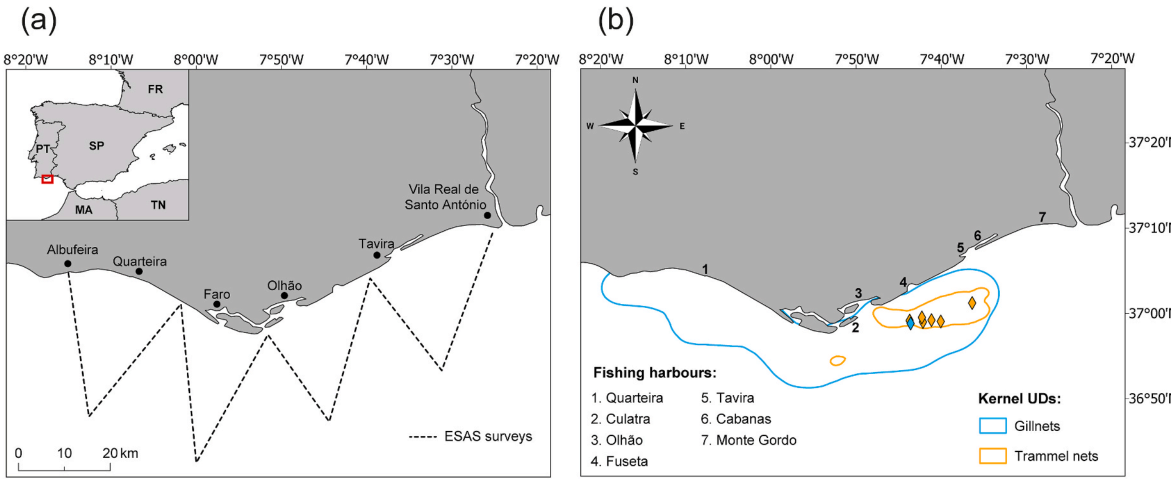

Fig. 1. Map showing (a) the European Seabirds at Sea (ESAS) transects (dashed black line) conducted from January 2020 to January 2022, to study the overall abundance of seabirds over the study area (red square). The main cities from the leeward region of Algarve are also highlighted on the map; and (b) fishing harbours used to study seabird attendance and bycatch at artisanal bottom-set net fishing vessels through onboard observations (from March 2020 to November 2022 in harbours 1 and 3) and fishermen interviews (from February 2020 to July 2022 in harbours 1–7). 95 % kernel Utilization Distributions (UDs) in (a) were computed using the '*adehabitatHR*' R package (Calenge, 2006), and represent the overall fishing effort of gillnets (blue) and trammel nets (orange); and seabird bycatch events (symbols). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

fish, focusing on high-value commercial species such as European hake (*Merluccius merluccius*), monkfish (*Lophius piscatorius*), or red mullet (*Mullus surmuletus*) (Alexandre et al., 2022).

Seabirds attending fishing vessels were counted every 15 min during net setting in the morning (0.75 ± 0.02 h) and during hauling at sunrise (3.8 ± 0.08 h), and were identified to the species level whenever possible. Their behaviour was also recorded during these fishing operations. Identifications to family level were made when accurate identification to species was not possible. Age class (adults *vs*. immatures) was registered whenever possible based on observations of plumage characteristics (Svensson et al., 2023). Due to difficulties on accurate identification among immatures of Lesser black-backed and Yellow-legged gulls in large mixed flocks, both species and all age classes were merged into a single group for further analysis (Almeida et al., 2023; De la Cruz et al., 2022). Seabird counts were not carried out during night-time due to poor visibility. Detailed descriptions of the fishing practices (e.g. operational characteristics, fishing grounds, target species) were registered for each fishing trip. Specifically, for each fishing event observers registered the time of day, the location (latitude and longitude), the fishing process (setting or hauling), the amount of time spent in each fishing process (in hours), the gear type used (gillnets or trammel nets), net characteristics (net length and mesh size), and the fishery catch (total number of fish caught, number of fish retained and number of fish discarded).

2.3. Seabird bycatch

Between March 2020 to November 2022, onboard observers recorded the number of bycaught seabirds, exclusively during hauling operations, and identified them to species level and age class whenever possible. Additionally, interviews with boat skippers were carried out in person, by two or three trained observers, from February 2020 to July 2022. The interview survey was conducted quarterly, with boat skippers operating bottom-set nets in 7 fishing harbours of the leeward region of Algarve (Quarteira, Culatra, Olhão, Fuseta, Tavira, Cabanas and Monte Gordo; Fig. 1b). The sampled fleet comprises local (<9 m in length) and coastal (>9 m in length) fishing vessels. Detailed procedures for fishermen interviews are described in Supplementary Material 1.

2.4. Data analysis

Seabird abundance (number of individuals per trip) was calculated for each seabird species both in the study area (ESAS surveys) and at fishing vessels (onboard observations). To compare seabird abundances in the study area and at fishing vessels, we calculated richness (S', total species count), diversity (H', Shannon-Wiener index), and evenness (J', Pielou's index) based on seabird observations across all years and seasons.

To investigate the factors affecting the abundance of seabirds observed at fishing vessels, we fitted generalised linear mixed models using the '*glmmTMB*' R package (Brooks et al., 2017). Analyses were conducted considering the abundance of the most common species (>1 %) attending fishing vessels (i.e. Lesser black-backed and Yellow-legged gulls, Audouin's gull, Great shearwater and Northern gannet) as a response variable in each model (Supplementary Material Table S1). In these models, we considered only observations of seabirds exhibiting circular flights around fishing vessels, and seabirds sitting on the water surface up to 100 m from the boat, as proxies of fisheries attendance (Calado et al., 2021a). In all models we began by including season (spring, summer and autumn), year (2020, 2021 and 2022), gear type (gillnets and trammel nets), fishery catch per unit effort (CPUE), hauling hours, as well as the two-way interactions between season and fishery CPUE, year and fishery CPUE, and gear type and fishery CPUE as fixed effects. The least significant fixed-effect terms were removed sequentially via backward stepwise selection to obtain the models with the lowest value of Akaike's information criterion corrected for sample sizes (AICc). We tested fixed-effect terms for collinearity through the calculation of variance inflation factors (VIF) under the '*usdm*' R package (Naimi et al., 2011). In addition, we checked the models that performed best for normality and homogeneity by visual inspection of residual plots using '*DHARMa*' R package (Hartig, 2022). For each model we used a negative binomial distribution error to reduce overdispersion in count data. Trip identity was fitted as a random effect to control for the non-independence between trips within the same fishing vessel.

Seasons were described following the meteorological calendar as: winter (December to February), spring (March to May), summer (June to August), and autumn (September to November). Great shearwaters and Northern gannets (non-breeding species in Portugal) were rarely observed attending fishing vessels during spring and summer (Supplementary Material Table S1). Therefore, these seasons were not included in the analysis for these two species, and neither season was included as a predictor in the full models for these species. Autumn was also not included in the analysis for Audouin's gull due to the rare observations during this season (Supplementary Material Table S1). Winter was excluded from the analysis for all species, because the observation effort during this season was reduced or nearly absent compared to the other seasons, due to frequent poor weather conditions (Supplementary Material Table S1).

Fishery catch per unit effort (CPUE) was calculated as the total number of fish caught in each fishing trip, divided by the total length of the net (km) used in the same trip. Initially, we included the number of fish discarded in the full models, but we decided to exclude this variable from further analysis because it was highly correlated (bivariate Spearman correlation $|rs| > 0.7$), and collinear (VIF values ≥ 2.5; Johnston et al., 2018) with the total number of fish caught (Supplementary Material Tables S2 and S3). Moreover, when running univariate models with the number of fish discarded as a covariate, their AIC values were comparably higher than their colinear counterparts (Supplementary Material Table S4). Chi-squared (χ^2) tests were used to compare the number of adult and immature seabirds attending fishing vessels.

Bycatch rate from onboard observations was estimated as the number of bycaught seabirds divided by the number of observed fishing trips (birds/trip). Bycatch rate from fishermen interviews was estimated following (Oliveira et al., 2015), as the total number of seabirds reported to be bycaught per year, divided by the product of the number of interviews and the annual average number of trips per fishing vessel. To evaluate differences in bycatch risk, we used a Fisher's exact test to compare the number of bycaught individuals for each species in (1) onboard observations and (2) fishermen interviews. The expected values were calculated using the total number of birds attending fishing vessels (for onboard observations) and those estimated by ESAS surveys (for fishermen interviews), as these provide an independent estimate of species abundance in the area. A similar Fisher's exact test was used to assess the influence of gear type (gillnets and trammel nets) on the total number of seabirds bycaught for all species, based on both onboard observations and fishermen interviews.

All statistical analysis were carried out in R v. 4.1 (R Core Team, 2024). All data are presented as mean ± SE (standard error) unless otherwise stated. Differences were considered statistically significant at $p \leq 0.05$.

3. Results

3.1. Characterisation of seabird species in the study area

Based on the data collected to estimate abundance of seabirds at-sea, we detected 12,548 seabirds from at least 9 families and 30 species over the study area (richness: $S' = 30$; diversity: $H' = 2.2$; and evenness: $J' = 0.6$). Most common species observed at-sea were Lesser black-backed and Yellow-legged gulls (31.7 %, 76.4 ± 16.4 birds/trip), followed by Northern gannets (28.6 %, 69.1 ± 11.5 birds/trip), Cory's shearwaters (11.9 %, 28.8 ± 7.2 birds/trip), and Audouin's gulls (7.3 %, 17.6 ± 5.5 birds/trip; Supplementary Material Table S5).

3.2. Attendance of seabirds to fishing vessels

Annually, the number of observed fishing trips was similar between years: 2020 (N = 59 trips), 2021 (N = 63 trips) and 2022 (N = 64 trips). Seasonally, the number of fishing trips was higher in the summer (N = 87 trips), followed by autumn (N = 60 trips), spring (N = 37 trips), and winter (N = 2 trips). Duration of fishing trips differed between years ($F_{2,181} = 4.18$, $p = 0.017$) but not between seasons (excluding winter; $F_{2,179} = 0.71$, $p = 0.492$). Duration of fishing trips was higher in 2020 ($t = 3.05$, $p = 0.003$).

The total number of fish caught during observed trips differed between years ($F_{2,181} = 6.82$, $p = 0.001$) and seasons (excluding winter; $F_{2,179} = 3.78$, $p = 0.025$). Total fishery catch was lower in 2020 ($t = 2.44$, $p = 0.016$), but higher during spring ($t = 2.20$, $p = 0.030$). European hake, Monkfish, Tickback sole (*Microchirus variegatus*), dogfish (*Scyliorhinus*) spp. and seabreams (*Pagellus* spp. and *Diplodus* spp.) were the most abundant demersal fish species found in fishery catches over four seasons (Supplementary Material Table S6). Mackerels (*Trachurus* spp. and *Scomber* spp.) were the most abundant pelagic fish species found in fishery catches, however the majority of *Scomber* spp. were discarded (Supplementary Material Table S6).

Seabirds were observed in 183 daily trips (98.4 % of 186 trips), totalling 24,643 individuals from at least 7 families and 20 species (richness: $S' = 20$; diversity: $H' = 1.4$; and evenness $J' = 0.5$). Lesser black-backed and Yellow-legged gulls were the most common species attending fishing vessels (71.4 %; 41.8 ± 4.3 birds/trip), followed by Audouin's gulls (2.7 %, 1.6 ± 0.2 birds/trip), Great shearwaters (1.3 %, 0.8 ± 0.3 birds/trip), and Northern gannets (1.1 %, 0.7 ± 0.2 birds/trip). All other species observed were comparatively less abundant (<1 %; Table 1). The observed and expected frequencies of seabirds attending fishing vessels varied among age classes for Audouin's gulls (96.8 % of adults, N = 633 birds; $\chi^2 = 555.5$, $p < 0.001$) and Northern gannets (77.1 % of adults, N = 266 birds; $\chi^2 = 78.0$, $p < 0.001$) but not for Lesser black-backed and Yellow-legged gulls (50.4 % of adults, N = 16,635; $\chi^2 = 0.9$, $p = 0.332$).

The best supported models (Table 2) showed that year, season, hauling hours, fishery CPUE, and the two-way interaction between fishery CPUE and season significantly influenced the abundance of gulls (Lesser black-backed and Yellow-legged gulls, and Audouin's gulls) and Northern gannets attending fishing vessels. Gear type only influenced the abundance of Great shearwaters (Table 2). The number of Lesser black-backed and Yellow-legged gulls observed attending fishing vessels was higher in 2021, during both autumn and spring, and positively associated with hauling hours and fishery CPUE during summer (Fig. 2). It should be noted that between June and July, the number of adult Lesser black-backed and Yellow-legged gulls attending fishing vessels was significantly higher than that of immatures (87.1 % of adults, N = 2,882 birds; $\chi^2 = 1589.0$, $p < 0.001$; Supplementary Material Table S1). In contrast, during August, immatures were more abundant than adults (43.6 % of adults, N = 3,092 birds; $\chi^2 = 51.2$, $p < 0.001$; Supplementary Material Table S1). Audouin's gulls were more abundant in spring, and positively associated with hauling hours and fishery CPUE during summer (Fig. 2). All the Audouin's gulls observed during summer were adults (Supplementary Material Table S1). The number of Great shearwaters was higher in both 2020 and 2021, and when boats were using trammel nets (Fig. 2). The number of Northern gannets was positively associated with fishery CPUE but negatively associated with hauling hours (Fig. 2).

3.3. Seabird bycatch

Bycatch was recorded on only 7 trips (3.8 %), with an overall bycatch rate of 0.131 ± 0.086 birds per trip. In total, 25 seabirds were caught, representing at least 3 identified species, but some gull individuals remained unidentified (Fig. 3a). Details on seabird bycatch are given in Supplementary Material Table S7. Great shearwater was the most bycaught species (N = 20; 80 %), followed by Northern gannet (N = 3; 12 %) and gulls (N = 2; 8 %). Of the total bycatch events, 96 % occurred in just three weeks (21 days) in October 2022. 65 % of all bycaught Great shearwaters were recorded in a single fishing event. Great shearwaters and Northern gannets were exclusively caught by trammel nets during autumn, while gulls were caught by both gillnets and trammel nets, during autumn and summer. All bycaught Northern gannets were immatures. Bycatch events occurred on average 7.9 ± 0.6 km distant from the coastline (Fig. 1b). The observed and expected numbers of seabirds bycaught in fishing vessels differed among species and gear types (Fisher's exact test: $p < 0.001$). Great shearwaters and Northern gannets

Table 1
Average ± standard error (SE), abundance (N) and IUCN status of seabirds recorded by observers attending artisanal bottom-set net fishing vessels over four seasons between March 2020 and November 2022 in the study area (Fig. 1b). Species are listed in descending order based on total abundance of seabirds per family.

Species	IUCN status	Winter (N = 2 trips)	Spring (N = 36 trips)	Summer (N = 86 trips)	Autumn (N = 59 trips)	Total annual (N = 183 trips)
		Birds/trip (N)	Birds/trip (N)	Birds/trip (N)	Birds/trip (N)	Birds/trip (N)
Hydrobatidae						
European storm petrel (*Hydrobates pelagicus*)	Least concern	0	0.08 ± 0.06 (6)	0.03 ± 0.01 (5)	0.3 ± 0.1 (36)	0.11 ± 0.04 (47)
Unidentified storm-petrel	–	0	0	0.02 ± 0.01 (3)	0.1 ± 0.1 (15)	0.04 ± 0.03 (18)
Laridae						
Lesser black-backed (*Larus fuscus*) and Yellow-legged gulls (*Larus michahellis*)	Least concern	5.0 ± 3.1 (20)	43.3 ± 8.0 (3,374)	31.4 ± 5.2 (6,272)	57.0 ± 9.7 (7,920)	41.2 ± 5.4 (17,586)
Unidentified gull	–	0.3 ± 0.3 (1)	11.7 ± 5.9 (916)	3.7 ± 1.0 (739)	26.3 ± 10.0 (3,662)	12.6 ± 3.5 (5,318)
Audouin's gull (*Ichthyaetus audouinii*)	Vulnerable	0	4.8 ± 0.9 (371)	1.3 ± 0.3 (266)	0.1 ± 0.1 (20)	1.6 ± 0.2 (657)
Black-headed gull (*Chroicocephalus ridibundus*)	Least concern	0	0	0.03 ± 0.03 (6)	0.1 ± 0.1 (11)	0.04 ± 0.03 (17)
Mediterranean gull (*Ichthyaetus melanocephalus*)	Least concern	0	0	0	0.1 ± 0.1 (12)	0.03 ± 0.02 (12)
Sandwich tern (*Thalasseus sandvicensis*)	Least concern	0	0.1 ± 0.1 (6)	0.01 ± 0.01 (2)	0.01 ± 0.01 (2)	0.02 ± 0.02 (10)
Black tern (*Chlidonias niger*)	Least concern	0	0.01 ± 0.01 (1)	0.04 ± 0.04 (7)	0	0.02 ± 0.02 (8)
Common tern (*Sterna hirundo*)	Least concern	0	0.01 ± 0.01 (1)	0.01 ± 0.01 (1)	0.01 ± 0.01 (1)	0.01 ± 0.01 (3)
Oceanitidae						
Wilson's storm petrel (*Oceanites oceanicus*)	Least concern	0	0.2 ± 0.2 (14)	0	0	0.03 ± 0.03 (14)
Phalacrocoracidae						
European shag (*Gulosus aristotelis*)	Least concern	0	0	0.01 ± 0.01 (2)	0	0.01 ± 0.01 (2)
Procellariidae						
Great shearwater (*Ardenna gravis*)	Least concern	0.5 ± 0.5 (2)	0	0.1 ± 0.1 (27)	2.1 ± 0.9 (297)	0.8 ± 0.3 (326)
Cory's shearwater (*Calonectris borealis*)	Least concern	0	0	0.7 ± 0.2 (131)	0.4 ± 0.4 (62)	0.5 ± 0.1 (193)
Balearic shearwater (*Puffinus mauretanicus*)	Critically endangered	0	0.01 ± 0.01 (1)	0.1 ± 0.1 (26)	0.04 ± 0.02 (6)	0.08 ± 0.03 (33)
Sooty shearwater (*Ardenna grisea*)	Near threatened	0	0	0.01 ± 0.01 (1)	0	0.01 ± 0.01 (1)
Unidentified shearwater	–	0	0	0.01 ± 0.01 (2)	0.5 ± 0.5 (63)	0.2 ± 0.2 (65)
Sulidae						
Northern gannet (*Morus bassanus*)	Least concern	1.5 ± 1.5 (6)	0.5 ± 0.3 (42)	0.06 ± 0.02 (11)	1.6 ± 0.6 (223)	0.7 ± 0.2 (282)
Stercorariidae						
Great skua (*Catharacta skua*)	Least concern	0	0.1 ± 0.1 (7)	0.02 ± 0.01 (4)	0.3 ± 0.1 (40)	0.12 ± 0.04 (51)
Total	–	7.3 ± 3.9 (29)	60.8 ± 10.5 (4,739)	38.6 ± 5.6 (7,505)	89.0 ± 14.1 (12,370)	58.5 ± 5.8 (24,643)

Table 2
Description of the best supported generalised linear mixed models (i.e. models with the lowest Akaike's information criterion corrected for sample sizes - AICc values) and the models with full interactions. The models with the lowest Δ AICc values for each species are shown first. These models explain the abundance of the most common species (>1 %) attending artisanal bottom-set net fishing vessels, as a function of fishery catch per unit effort (CPUE), gear type (gillnets and trammel nets), hauling hours, season (spring, summer and autumn) and year (2020, 2021 and 2022). Number of estimated parameters (df) and Akaike weight (Wi) are also shown. All models include trip identity as a random effect.

Candidate models	df	AICc	Δ AICc	Wi
Lesser black-backed and Yellow-legged gulls ~ Fishery CPUE x Season + Year + Hauling hours	**12**	**1895.1**	**0**	**0.94**
Lesser black-backed and Yellow-legged gulls ~ Fishery CPUE x Season + Fishery CPUE x Year + Fishery CPUE x Gear type + Hauling hours	16	1900.5	5.4	0.06
Audouin's gull ~ Fishery CPUE x Season + Hauling hours	**10**	**517.1**	**0**	**0.82**
Audouin's gull ~ Fishery CPUE x Season + Fishery CPUE x Year + Fishery CPUE x Gear type + Hauling hours	14	520.1	3.0	0.18
Great shearwater ~ Year + Gear type	**7**	**153.0**	**0**	**0.98**
Great shearwater ~ Fishery CPUE x Year + Fishery CPUE x Gear type + Hauling hours	12	160.5	7.5	0.02
Northern gannet ~ Fishery CPUE + Hauling hours	**6**	**217.1**	**0**	**0.93**
Northern gannet ~ Fishery CPUE x Year + Fishery CPUE x Gear type + Hauling hours	10	222.4	5.3	0.07

were more frequently bycaught than expected based on their attendance at fishing vessels (Fig. 3a), whereas gulls showed the opposite effect (i.e. less frequently bycaught). In terms of gear types, trammel nets caught more birds based on the number of seabirds observed associating with the fishery, while gillnets showed the opposite effect (Fig. 3b).

From a total of 808 fishermen interviews (N = 726 interviews for local boats; N = 82 interviews for coastal boats), bycatch was reported at a rate of 0.005 ± 0.001 birds/trip, accounting for 82 seabirds from at least 5 identified species, but some auk, gull and shearwater individuals remained unidentified (Fig. 3a). Northern gannet was the most reported species to be bycaught (N = 36; 44 %), followed by Great cormorant (N = 32; 39 %), gulls (N = 7; 9 %), auks (N = 5; 6 %) and shearwaters (N = 2; 2 %). Bycatch rate was reported to be higher during winter (N = 58; 71 %) than in the other seasons: autumn (N = 15; 18 %), spring (N = 8; 10 %) and summer (N = 1; 1 %). The observed and expected numbers of seabirds reported to be bycaught in fishermen interview data differed among species (Fisher's exact test: $p < 0.001$; Fig. 3c), but not among gear types (Fisher's exact test: $p = 0.579$; Fig. 3d). Great cormorants were more frequently reported to be bycaught than expected based on their abundance over the study area, whereas gulls showed the opposite effect (Fig. 3c).

4. Discussion

4.1. Attendance of seabirds to fishing vessels

We investigated seabird abundance, attendance, and bycatch at artisanal bottom-set net fisheries along the southern-eastern coast of mainland Portugal. Our results indicate that seabird communities

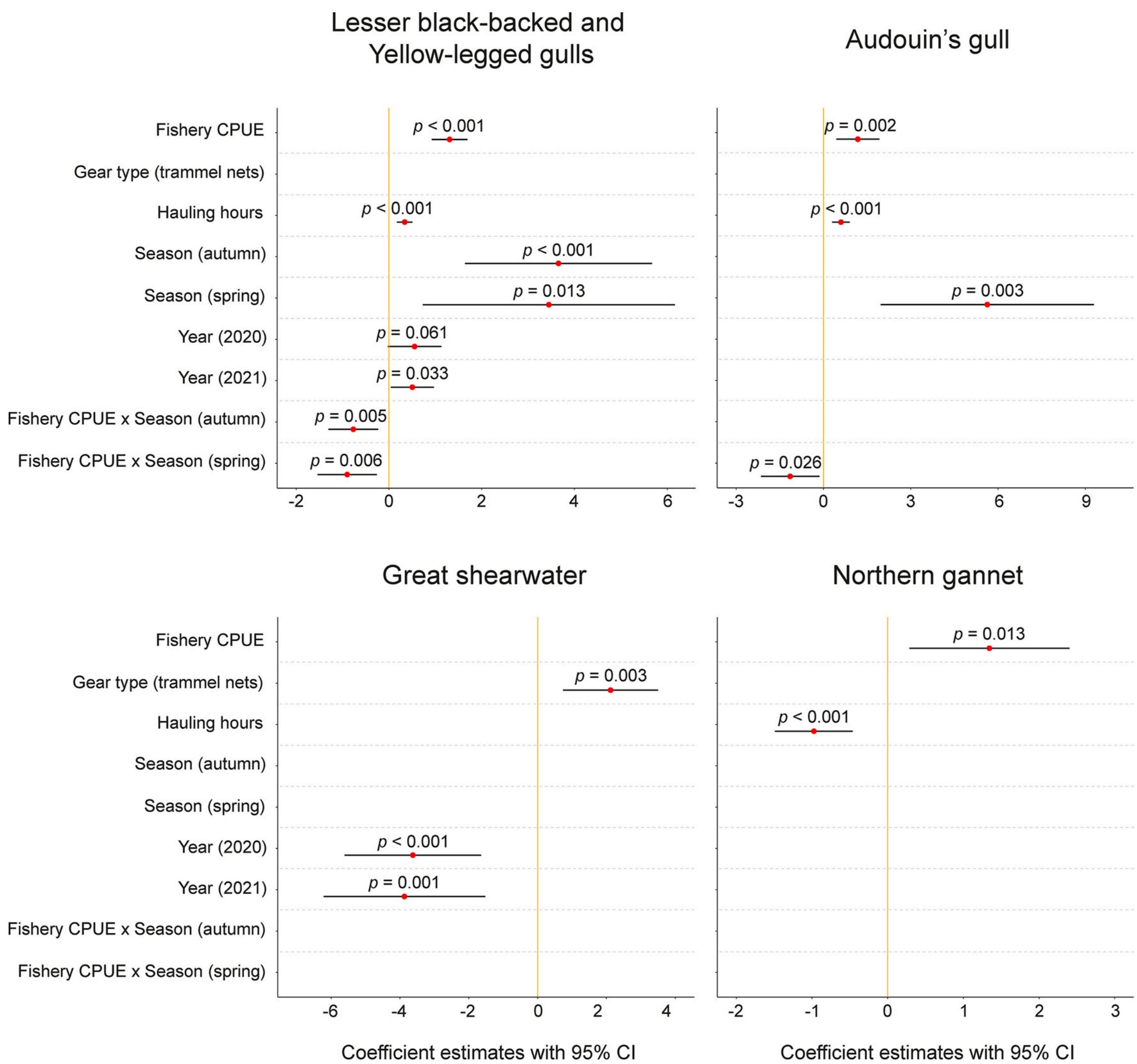

Fig. 2. Forest plot of estimates (95 % confidence intervals) and *p*-values from the best-supported generalised linear mixed models (models with the lowest Akaike's information criterion corrected for sample sizes - AICc values) explaining the abundance of the most common species (>1 %) recorded by observers attending artisanal bottom-set net fishing vessels, as a function of fishery catch per unit effort (CPUE), gear type (gillnets and trammel nets), hauling hours, season (spring, summer and autumn) and year (2020, 2021 and 2022). Coefficients of categorical factors (i.e. gear type, season and year) were calculated relative to their reference (whose coefficients are zero - orange line): gear type (gillnets), season (summer) and year (2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

attending fishing vessels in the study area are less diverse (i.e. lower richness and Shannon-Wiener index) and more unevenly distributed (i.e. lower Pielou's index) than those observed at-sea. The most common observed seabird species at-sea onboard recreational vessels were Yellow-legged and Lesser black-backed gulls, followed by Northern gannets, Cory's shearwaters, and Audouin's gulls. Excluding Cory's shearwaters, these species were also the most abundant seabirds observed attending fishing vessels. This suggests that only certain species in the area are attracted to fisheries. These results are consistent with our predictions and recent studies, showing that large gulls and Northern gannets frequently feed in association with bottom-set net fisheries along the west coast of Portugal (Almeida et al., 2023). Moreover, our results for Cory's shearwaters support previous research indicating that this species show limited spatial overlap with fishing vessels in this region (Pereira et al., 2021). In contrast, Great shearwaters were rarely observed at-sea, but aside from gulls, they were the most abundant species observed attending fishing vessels.

We found abundance of gulls (Lesser black-backed, Yellow-legged and Audouin's gulls) and Northern gannets attending fishing vessels to be positively associated with fishery CPUE (and likely with fishery discards). This result supports our hypothesis that scavenging seabirds are likely attracted to artisanal bottom-set nets due to the greater availability of food during net hauling. This is further supported by the positive relationship between hauling duration with gull abundance, but not with gannet abundance. Although bottom-set net fisheries generally provide fewer feeding opportunities for seabirds during the fishing operation compared to purse-seines and trawlers, they still represent a reliable food source through significant offal and fishery discards (Depestele et al., 2016).

The predominance of adult Yellow-legged and Audouin's gulls observed attending fisheries in the early summer (June and July) suggests that adults may depend on these predictable food subsidies during the breeding period, presumably to feed their chicks and maintain their body condition. This hypothesis is supported by previous research showing that during early chick-rearing, gulls primarily feed their offspring with fish (de Faria et al., 2021; Méndez et al., 2020), often originating from fishing discards (Romero et al., 2019). Gulls mostly relying on discards for feeding have been reported to exhibit higher reproductive success (van Donk et al., 2017), likely due to their increased net energy intake and provision of highly caloric food items to

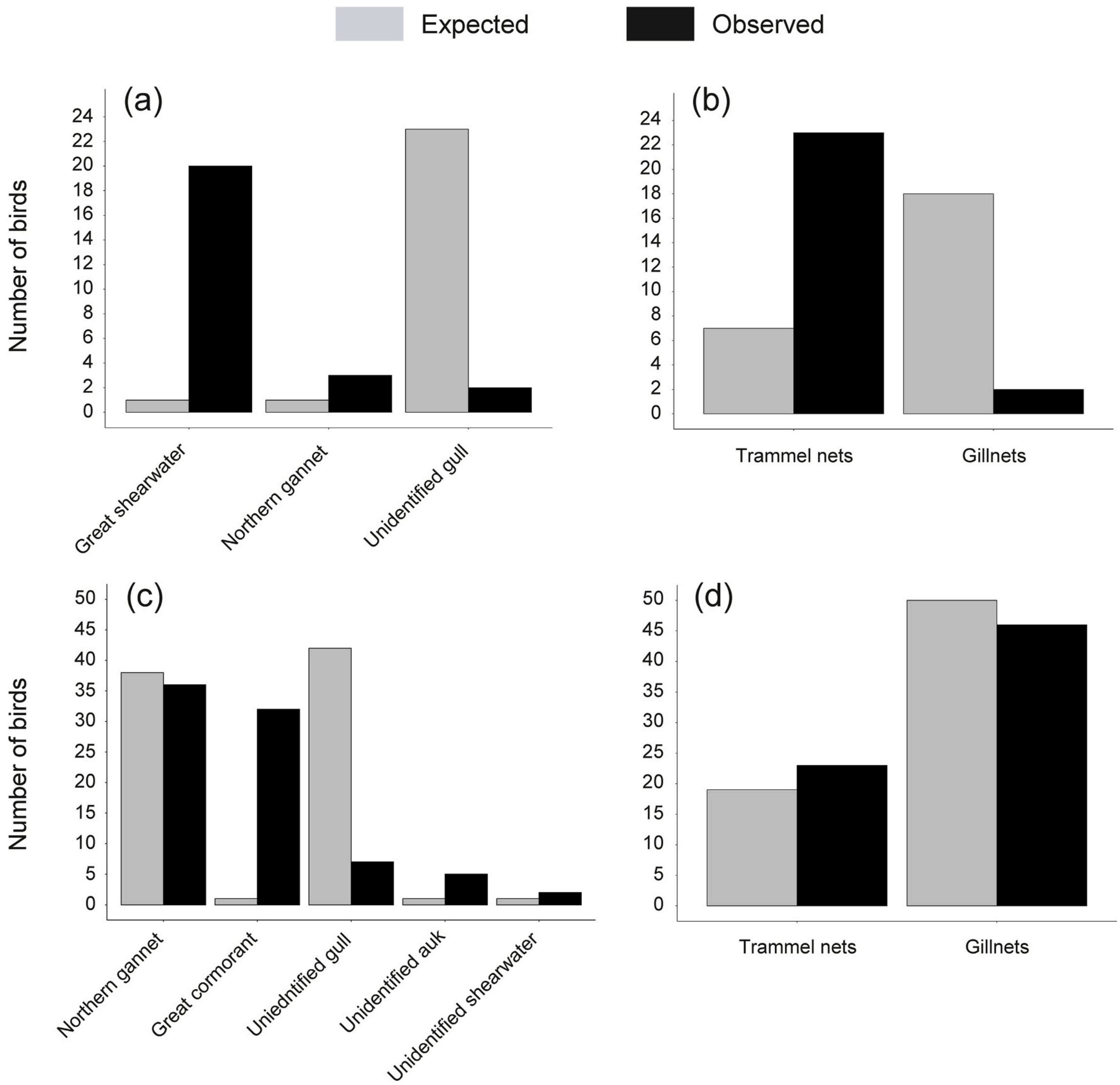

Fig. 3. Bycatch rate expected based on the number of seabirds attending fishing vessels (grey) *vs.* the number of bycaught seabirds recorded by observers at the same fishing vessels (black) for each species (a) and gear type (b); and bycatch rate expected based on the abundance of seabirds observed at-sea (grey) *vs.* the number of seabirds reported to be bycaught in fishermen interviews (black) for each species (c) and gear type (d).

their offspring (van Donk et al., 2019). In addition, fishing activity often intensifies during periods of favourable weather and sea conditions (Matos et al., 2018). During the summer months, fishing vessels undertook more frequent fishing trips (Henriques et al., 2024), and likely provided more predictable food sources to scavenging seabirds during the breeding period. Previous dietary studies (Calado et al., 2018, 2021b) have confirmed that adult Yellow-legged and Audouin's gulls in the study area feed on both pelagic (e.g., *Scomber* spp.) and demersal fish (e.g., *Diplodus* spp. and European hake) targeted by artisanal fisheries in the region during the breeding period (Supporting Material Table S6). These fish species can be caught naturally or through fishing operations, either as discards or facilitated prey (Matos et al., 2018). Together, our results suggest that predictable food subsidies provided by fisheries play a key role in the ecology of local breeding seabirds, with potentially strong implications for reproductive success, as well as for wintering Lesser black-backed gulls (mostly immatures), during late summer and autumn (August to November).

4.2. Seabird bycatch

Bycatch rates estimated from onboard surveys were relatively low throughout the 3-year study. Nevertheless, given that bottom set-nets comprise the majority of the Portuguese and Algarve fishing fleet, even a small number of bycaught seabirds could have a significant impact (Alexandre et al., 2022). Surprisingly, nearly all bycatch events (96 %) occurred within a three-week period (21 days) in October 2022. During this period, Great shearwaters were the most frequently bycaught species, followed by Northern gannets to a lesser extent, with all individuals found entangled in trammel nets. This corroborates the results of other studies in the area and in European waters, showing that the risk of bycatch in bottom-set net fisheries is higher for diving seabirds than for surface feeders as is the case with the species mentioned (Alexandre et al., 2022; Almeida et al., 2023; Ramírez et al., 2024). In addition, this finding reflects the higher abundance of the Great shearwaters around trammel nets during autumn. This aligns with their southward migration through the west Iberian Peninsula in late summer and early autumn (Araújo et al., 2022b), before returning to their breeding grounds in the south Atlantic (Cuthbert, 2005). In their breeding and pre-breeding grounds, Great shearwaters feed on fishery discards and capture prey, particularly anchovy and hake, with high bycatch mortality reported during hauling operations in Argentine demersal trawl fisheries (Paz et al., 2018, 2024). These findings support the observed increased abundance and bycatch of Great shearwaters at trammel nets in autumn, as this fleet primarily capture hake and small pelagic species, including *Scomber* spp., which are among the most frequently discarded fish species during this season (Supporting Material Table S6). Remarkably, more than half (65 %) of the Great shearwater bycatch was recorded during a single fishing event. Although large bycatch events are less frequent in artisanal fisheries, episodic events like the one reported here can still result in significant mortality. This episodic event can be explained by the synergistic effect of two main factors: (1) the irregular distribution of Great shearwaters in the region between different years (Araújo et al., 2022b); and (2) in the day prior to this bycatch event, onboard observers noted that fishermen were cleaning the net and discarding fish and viscera during net setting (F. Carvalho and M. Frade personal observation). These actions likely attracted a greater number of seabirds to the fishing area, increasing the risk of entanglement, and subsequent drowning in the nets (Frade, 2023). Similar findings have been reported by (Oliveira et al., 2015), who documented a significant bycatch of the critically endangered Balearic shearwater during a single purse-seine fishing event in Portuguese mainland waters.

Results from fishermen interviews indicated even lower bycatch rates than those recorded through onboard observations, likely reflecting the underreporting commonly associated with interviews data (Silver and Campbell, 2005). Nevertheless, Northern gannets and Great cormorants were the most frequently reported species to be bycaught. Interestingly, Great cormorants were neither observed attending fishing vessels nor recorded as bycatch during onboard observations. Such discrepancy can be explained by three main factors: (1) Great cormorants are more abundant in the region during winter (Meirinho et al., 2014), but the onboard observation effort was significantly reduced or nearly absent during this season due to frequent poor weather conditions. This likely contributed to the low detectability of this species onboard fishing vessels; (2) over half (56 %) of the Great cormorants reported as bycatch were found in the easternmost fishing harbour of the study area, Monte Gordo (Frade, 2023), while onboard observations were conducted only from Quarteira and Olhão fishing harbours; and (3) Great cormorants are not often attracted to fishing vessels when they are operating, however the spatial overlap between bird feeding grounds and fishing areas in shallow coastal waters increases the risk of bycatch for this species when set-nets are soaked in the water (Christensen-Dalsgaard et al., 2019). The discrepancy between the limited winter observations and the high bycatch reported by fishermen in this season underscores the need for complementary methods to improve bycatch estimates. To address the limitations of observer programs and fishermen interviews, future studies should explore the use of complementary methods like electronic monitoring and self-reporting logbooks, which have been shown to effectively collect seabird bycatch data (Glemarec et al., 2020; Lago et al., 2023). Expanding observer coverage and using spatial modelling to identify high-risk periods and areas can further improve our understanding of seabird bycatch, particularly during underrepresented seasons like winter.

4.3. Wider implications

Discard bans are being implemented in European fisheries to promote sustainable practices (article 15, EU 1380/2013). Our results suggest that in regions with high discard rates, scavenging behaviour is likely to be widespread within seabird communities. Although the influence of fishery discards on seabird attendance at fishing vessels was not evaluated in this study, this variable was found to be positively correlated with the total number of fish caught (Supplementary Material Tables S2 and S3). A reduction in discarding rates could significantly affect seabird species that rely on these subsidies (Bicknell et al., 2013), especially during the breeding period, when adult seabirds depend on predictable and abundant food sources from fisheries to satisfy their energy demands and those of their growing chicks in early summer. Generalist species, such as Lesser black-backed and Yellow-legged gulls, may adapt to discard variations by shifting to alternative food resources, such as refuse dumps (Matos et al., 2018). However, such dietary shifts could result in nutritional trade-offs, as anthropogenic food sources generally have lower nutritional quality (Lopes et al., 2022), and can also be energetically costly to obtain (van Donk et al., 2019). In contrast, Audouin's gulls are a more specialised species that rely on fishery-related resources, including the fish targeted by the local fishing fleet (Calado et al., 2018, 2021b). These resources are likely made accessible to gulls through discards or facilitated prey during fishing operations (Matos et al., 2018). Under a discard ban scenario, individuals may have to increase foraging effort to search for less predictable and patchily distributed natural prey. This challenge could be further exacerbated by the sharp population growth of the largest known colony of the species, located at our study area, which increased from 900 to 5,393 breeding pairs between 2014 and 2022, respectively (Pereira et al., 2022a). Increased intra-specific competition, together with higher foraging costs, may ultimately prejudice species reproductive success, particularly under unfavourable environmental conditions (i.e. likely reduced food availability).

Although large bycatch events are relatively uncommon in artisanal fisheries (Oliveira et al., 2015), the factors driving seabird bycatch in this sector remains largely unexplored (Votier et al., 2023). Our study suggests that fishermen behaviour during the fishing operation may play a key role in influencing seabird bycatch at artisanal fishing vessels. Previous research has reported significant seabird bycatch when fishermen engage in activities such as sorting the catch, discarding unwanted fish, gutting commercial fish or even cleaning the vessel during the fishing operations with high bycatch risk (hauling and net setting) (Maree et al., 2014; Watkins et al., 2008). In contrast, implementing best practices onboard fishing vessels has been previously linked to significant reductions in seabird bycatch. For instance, these practices include net cleaning before setting, limiting the volume of discards during the fishing operations, and releasing discards in controlled batches (Almeida et al., 2023; Frade, 2023; Kuepfer et al., 2022; Pierre et al., 2010). This study highlights the significance of integrating both onboard observer data and interviews with fishermen, providing a comprehensive understanding of the factors driving seabird bycatch. Moreover, year-round studies are crucial to identify key areas, species, and seasons that contribute to higher bycatch rates, enabling more targeted mitigation strategies. A comprehensive assessment of seabird attendance and bycatch at fishing vessels, in relation to fishermen best practices, could provide valuable insights into discard management risks and help design effective mitigation measures to reduce this threat.

Efforts to enhance the conservation status of seabird species in the study area are currently ongoing. The Portuguese marine important bird area (IBA) inventory previously identified the need to extend the Ria Formosa IBA to include key marine feeding areas for Little terns. Recent tracking data, particularly for Audouin's gulls (Pereira et al., 2022c), demonstrated significant use of marine areas beyond the current special protected area (SPA) boundaries. The LIFE Ilhas Barreira project (https://www.lifeilhasbarreira.pt/en/) is addressing this by proposing an extension of the Ria Formosa SPA to encompass the main feeding habitats of Audouin's gulls. This process, currently under governmental evaluation, highlights the importance of integrating seabird conservation measures, such as habitat protection and bycatch mitigation, into broader marine spatial planning initiatives to protect seabird populations effectively.

CRediT authorship contribution statement

Jorge M. Pereira: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jaime A. Ramos:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis,

Conceptualization. **Ana Almeida:** Writing – review & editing, Validation, Methodology, Data curation. **Ana Marçalo:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Flávia Carvalho:** Writing – review & editing, Validation, Methodology, Data curation. **Isabel Fagundes:** Writing – review & editing, Validation, Methodology, Data curation. **Jorge MS. Gonçalves:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Magda Frade:** Writing – review & editing, Validation, Methodology, Data curation. **Nuno Oliveira:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Funding acquisition, Data curation. **Tânia Nascimento:** Writing – review & editing, Validation, Methodology, Data curation. **Vitor H. Paiva:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jorge M. Pereira reports financial support, equipment, drugs, or supplies, and travel were provided by LIFE EU programme. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2025.107660.

Data availability

The data underlying this article will be shared upon reasonable request to the corresponding author.

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