



Mitigation measures to reduce seabird's interactions with bottom-set nets in southern Iberia

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ABSTRACT

Bycatch poses a significant threat to seabird populations globally. On the southern coast of mainland Portugal, mitigation measures were tested to reduce seabird interactions with fishing vessels. Between 2021 and 2023, this study evaluated the effectiveness of a visual deterrent (a 'scarybird' device), an acoustic deterrent (megaphone broadcasts), alongside modification in fisher's behaviour discard management—avoiding discards during fishing operations to minimize seabird interactions. Observers monitored 166 fishing events, comparing control and experimental treatments. Discard management was the most effective deterrent, significantly reducing seabird abundance, particularly gulls (*Larus* spp.) and northern gannets (*Morus bassanus*). Model predictions indicated a 37 % and a 47 % reduction in the abundance of gulls and northern gannets, respectively, around commercial fishing vessels when discard management was used. This practice effectively kept a substantial proportion of birds away from the vessel during operations, thereby reducing their vulnerability to bycatch. The megaphone showed limited efficacy, with higher seabird abundance in treatment groups compared to controls. The scarybird device was largely ineffective in deterring gulls unless combined with discard management but showed potential in reducing interactions with northern gannets. Importantly, all mitigation measures did not negatively impact Landings Per Unit Effort (LPUE), which facilitated their acceptance among fishers. Our findings suggest that simple modifications in the fisher's behaviour, such as retaining fish discards and viscera onboard, could serve as a promising bycatch mitigation measure, potentially eliminating the need for additional less effective mitigation devices that fishers may be reluctant to adopt.

1. Introduction

Fisheries impact marine life, including seabirds, both indirectly and directly. Indirect effects arise from altering food chain dynamics, such as overfishing or increasing food availability through discards (Jennings and Kaiser, 1998; Valeiras, 2003; Tyson et al., 2015; Oliveira et al., 2022). Generally, seabirds feed in productive oceanic regions, which overlap with areas targeted by commercial fisheries (Yorio et al., 2010). This spatiotemporal and trophic overlap can trigger interactions between seabirds and fishing activities, including attraction to discards for feeding or active engagement with fishing gear (e.g. diving near gear), leading to mixed outcomes (Montevecchi, 2002). On the positive side, fishers may benefit by using seabird aggregations to detect fish schools, while seabirds exploit discards from fishing operations as an easy and

predictable food source (Tasker et al., 2000). Discards, defined as the portion of the catch not retained on board during fishing operations and returned to the sea (Kelleher, 2005; Oliveira et al., 2022), provide a readily accessible food source for seabirds, reducing their foraging effort and potentially enhancing breeding success and survival rates, thereby promoting population growth (Oliveira et al., 2022). However, interactions can also have negative consequences for both seabirds and fisheries. Seabirds may steal bait, damage fishing gear, or reduce catch quantity, negatively impacting fishing operations (Oliveira et al., 2015; Votier et al., 2004). More concerning, these interactions can also lead to unintentional capture, or bycatch, which is one of the primary threats to seabird populations, particularly given their low reproductive rates and delayed maturity (Dias et al., 2019; Oliveira et al., 2021). Fisheries bycatch, defined as the accidental capture of non-target species (Read

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et al., 2006), is considered to be one of the main threats to several seabird populations, especially due to seabirds low reproductive rates and delayed maturity. Seabird bycatch is a worldwide problem witnessed in both commercial and recreational fisheries, especially in longlines and set-nets, where hundreds of thousands of seabirds are estimated to be killed annually (Anderson et al., 2011; Oliveira et al., 2015, 2021; Calado et al., 2021; Araújo et al., 2022; Votier et al., 2023). In European waters, the estimated annual seabird bycatch numbers are as high as 95,229 for gillnets, 80,211 for longlines, 1168 for pots and traps, 541 for trawls, and 204 for purse seines (Ramírez et al., 2024). Thus, while interactions with fishing operations can offer food benefits to seabirds, these same interactions also elevate the risk of bycatch, a pressing concern for their conservation.

Several operational (fishers' behavioural changes during fishing operation) and technical measures (modifications to the fishing gear or use of specific mitigation devices) have been tested worldwide over the years to mitigate the accidental capture of seabirds (Furness et al., 2007; Williams et al., 2012; Pierre et al., 2014) with varying success dependent on the fisheries, seabird species, and the area of operation. Commercial gillnetters, often neglected in seabird bycatch research pose a severe threat to various protected, endangered, and threatened seabird populations (Zydalis et al., 2013). For bottom-set nets (that also include gillnets), effective technical solutions for mitigating seabird bycatch are limited, with most tested solutions proving to be impractical for onboard implementation due to their time-consuming nature, making fishers apprehensive in adopting them (Melvin et al., 1999; Trippel et al., 2003; Mangel et al., 2018; Oliveira et al., 2021; Almeida et al., 2023). In line with these findings, and based on observations from onboard monitoring in the Algarve (Pereira et al., 2025), seabird bycatch risk appears to be highest during net deployment and hauling operations rather than during soak time. This highlights the need for mitigation strategies tailored to these critical fishing phases, while also reinforcing the importance of considering local operational specificities when designing and implementing effective mitigation measures.

In a study conducted off the Portuguese mainland coast, Oliveira et al. (2021) tested the efficacy of a visual deterrent called scarybird device to deter several seabird species from interacting with commercial fishing vessels operating demersal longlines, bottom gill nets, and purse seine. Furthermore, a recent work by Almeida et al. (2023) on commercial bottom-set gillnetters targeting demersal species in central Portuguese waters showed the scarybird device being effective in reducing the numbers of seabirds including gulls (*Larus* spp), great skuas (*Stercorarius skua*), Balearic shearwaters (*Puffinus mauritanicus*), and northern gannets (*Morus bassanus*) around fishing vessels during gear deployment and hauling. Additionally, managing discards is crucial for mitigation of seabird bycatch, with ACAP (2019) identifying a discard ban as the most effective solution.

Here, we evaluated three mitigation measures aimed at reducing seabird bycatch in fishing vessels using bottom-set nets at periods of most risk (gear deployment and hauling; Pereira et al., 2025): the megaphone (acoustic deterrent), the scarybird device (visual deterrent), and modified fisher behaviour procedure (discard management). We also assessed the efficacy, practical applicability, and economic viability of each measure. The impact of these measures on seabird interactions with fishing boats was determined by comparing paired fishing events with and without the implementation of the mitigation strategies.

2. Material and methods

2.1. Study area

The study area was off the Leeward region of the Portuguese southern coast (Algarve) (Fig. 1), from Armação de Pêra (37° 06' N 8° 21' W) to Manta Rota (37° 09' N, 7° 31' W), up to 18.3 km from the coast (~9.9 NM). This coastal region has a very narrow continental shelf (5–20 km wide) influenced locally by upwelling events, mostly

occurring in the south-western area. The southern area is also influenced by the more saline and warm waters of the Mediterranean Sea (Cunha, 2001; Bettencourt et al., 2004).

2.2. Data collection

Control and experimental fishing events tested the effectiveness of the three mitigation methods: megaphone, scarybird, and discard management. Identical fishing vessels and crews were used for both ensuring consistent gear sinking times and the use of identical nets and fishing materials (Almeida et al., 2023). Additionally, day-to-day procedures were standardized to ensure comparability between control and experimental operations.

Trials were conducted aboard commercial vessels (6–14 m lengths overall -LOA) from the ports of Olhão and Quarteira (Fig. 1), employing bottom-set nets, that include gillnets (GNS; mesh sizes: 60 mm, 80 mm and 220 mm) and trammel nets (GTR; mesh size: 120 mm inner and 640 mm outer panels). A trained observer collected comprehensive data on the fishing operations including navigation, gear deployment, and hauling. Additionally, the observer recorded the GPS location of fishing activities and documented interactions between seabirds and the fishery. Bird counts and species identification were conducted every 15 min, from nautical sunrise onward. Each bird's distance from the vessel was categorized into bands (A = 0–20 m, B = 20–50 m, C = 50–100 m, D = 100–200 m, E = 200–300 m, F ≥ 300 m) using a range finder specific to each observer and vessel (accounting for the observer's arm length and height, as well as the observation height above sea level). Additionally, the behaviour of each bird was recorded, noting whether it was in direct flight (not stopping or deriving flying route towards the vessel), circling around the vessel (actively prospecting or attracted by the vessel), or sitting on the water (after interaction with the fishing vessel or gear). The methodology followed the European Seabirds At Sea (ESAS) approach (Camphuysen and Garthe, 2004), with additional distance band (0–20 m) for closer interactions.

Data were recorded on a tablet (Samsung Galaxy Tab A 8.0, 8", 2 GB ROM) using the CyberTracker application (Version: 3.530), specifically developed by the Portuguese Society for the Study of Birds (SPEA).

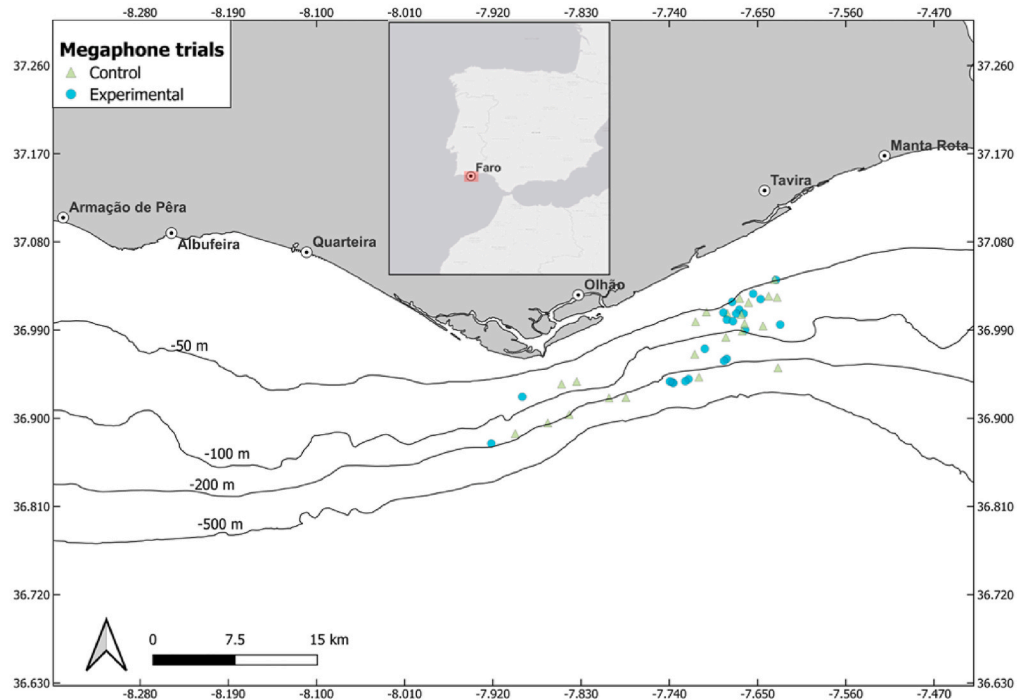
2.2.1. Acoustic device – megaphone

The megaphone device functioned as a distress caller, emitting pre-recorded calls of the European Herring Gull (*Larus argentatus*) at a frequency of 44,100 Hz and a volume of approximately 43 dB, chosen to be slightly louder than the vessel's engine noise. The device, was intended to deter birds by simulating natural distress levels, and we expected that other seabird species would also respond to these calls, as suggested in previous studies (Aubin, 1991; Gosler et al., 1995). The device was designed for the trials, featuring a 25W weatherproof horn speaker (AH25) with dimensions of 295 x 265 x 25 mm and weighing approximately 2 kg. It included a power module connected to the vessel's 12V and two external inputs (USB and microSD) for playing audio file. The system was manually activated by the vessel's skipper using a switch located near the throttle lever. To prevent habituation, the transmission speed was set to 51 kbps, with different time intervals between broadcasts, and the maximum vocalization duration of 3 min and 15 s. The device was installed at the highest point of the vessel and was activated during net setting (Fig. 2 A). Experimental trials using the megaphone and controls took place between April and October 2021 (Table 1) on two vessels operating out of the Olhão fishing port.

2.2.2. Visual device – scarybird

The scarybird device, shaped like a bird of prey, utilized a retractable system that keeps it in constant motion with a slight breeze (2 km/h), simulating a predatory bird's flight hovering above the fishing area. Its dimensions, 155 x 56 cm, mimicked a medium-sized raptor (bird pf prey), comparable to a red kite. Mounted on a 6 m pole and a 0.65 m craft line it was positioned at the highest point on the fishing vessel,

A.



B.

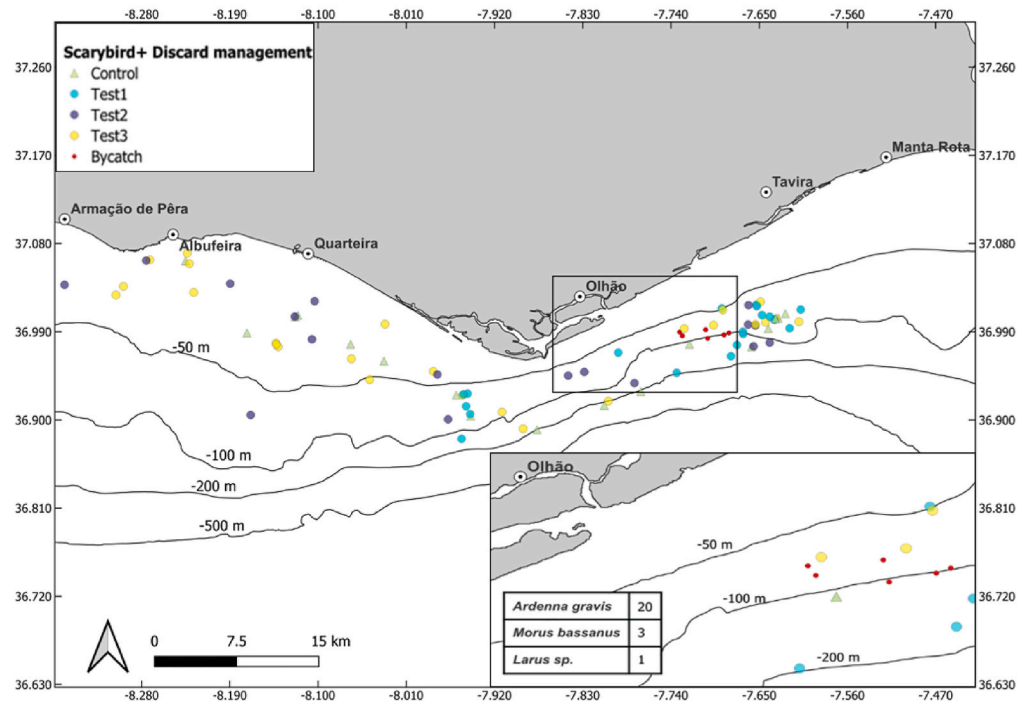


Fig. 1. A map of the study area per mitigation measure (offshore the south coast of Portugal, Algarve, Faro). A: The fishing events monitored for the megaphone trials; green triangles correspond to control fishing events and blue circles correspond to experimental fishing events. B: The fishing events monitored for the scarybird device and discard management trials, highlighting the area where bycatch occurred, along with the corresponding numbers for each species; green triangles correspond to Control fishing events, blue, purple, yellow and red circles correspond to Test 1, Test 2, Test 3 and bycatch events, respectively. Note (A and B): To ensure proper visualization and avoid cluttering, only a single point per fishing trip, specifically the location closest to the centroid among several GIS recordings, is displayed on the map. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



Fig. 2. (A) Megaphone implementation on a fishing vessel (top) and illustration of a fishing boat with the megaphone symbolizing the use of sound-based deterrents (below); (B) Scarybird implemented in a vessel (top) and illustration of a fishing boat with the scarybird representing visual deterrents (below); (C) Container strategically placed to the fishers, during net hauling and setting (top) and illustration representing the prohibition or management of offal discharge near fishing operations (below). Illustrations by Frederico Arruda. Photographs by Flávia Carvalho and Magda Frade.

Table 1

Summary information of the sampling trips and treatments. Season is described as Winter: January–March; Spring: April–June; Summer: July–September; Autumn: October–December. Soaking time (hours) and depth (meters) are presented as mean \pm standard error.

N vessels	Period	Code	Treatment	Season	N fishing events	Soaking time	Depth
2	Apr–Oct21	0	Control	Spring	11	68.06 \pm 3.91	107.8 \pm 4.76
				Summer	14		
4	Oct21–Jan23	1	Megaphone	Spring	11	57.11 \pm 3.30	108.4 \pm 4.08
				Summer	9		
		0	Control	Autumn	3	59.81 \pm 2.55	81.99 \pm 1.70
				Winter	3		
				Spring	10		
Test 1	Scarybird	Spring	2	75.79 \pm 2.01	95.88 \pm 1.37		
		Summer	5				
Test 2	Discard management	Autumn	24	44.52 \pm 2.01	66.23 \pm 1.39		
		Winter	2				
Test 3	Scarybird + discard management	Spring	3	29.78 \pm 2.04	64.12 \pm 1.33		
		Summer	15				
		Autumn	6				
				Spring	11		
				Summer	14		
				Autumn	8		

reaching up to 7 m above sea level. The device's placement was carefully considered so that it was set at a safe distance from vessel structures and the fishing equipment, ensuring it was close as possible to the deployed and retrieved area (Fig. 2 B). The device was installed and removed at the start and end of each fishing trip respectively, a process taking approximately up to 10 min by the observers. Trials were conducted from October 2021 to January 2023, starting with two vessels from Olhão fishing port and expanding to Quarteira fishing port in April 2022 (Table 1).

2.2.3. Good practices onboard – discard management

In addition to the tested acoustic (megaphone) and visual (scarybird) devices, on-board observers identified specific fisher behaviours to be the main cause for attracting birds to the vessel, specifically: 1) inadequate cleaning of nets (fish or fish remains kept in the net) before deployment, and 2) discarding fish, viscera or cleaning the vessel during operations. To address these issues, the team gradually suggested changes to fisher behaviour such as avoiding fish evisceration and discarding unwanted catch during fishing operations such as net hauling and setting (Fig. 2 C). Discards were retained in a secure container (e.g.

25 L bucket) and disposed overboard exclusively during vessel transiting between fishing grounds and the port. Furthermore, deck cleaning was also limited to navigating periods. Between May 2022 to January 2023 (Table 1), the experimental trials with discard management (Test 2) or scarybird with discard management (Test 3) were performed on four vessels.

2.3. Impact of the deterrent measures on fish catch

To assess if the deterrent measures had an impact on catches of fisheries, the landing per unit effort (LPUE), calculated as a kilogram of landings per kilometre of net ($\text{kg} \cdot \text{km}^{-1}$) were compared between experimental and control trips. Data collection was primarily carried out by on-board observers, except for the weight of the catches, which were obtained from the sales sheets provided by the skipper after the catch was weighed at the auction house using a standard weighing scale (accuracy = 0.1g).

2.4. Data analysis

The georeferenced locations of the fishing operations, for each trip, were mapped for both control and experimental events (Fig. 1) using the software QGIS Desktop (ver. 3.30.0). All the subsequent analyses were performed using the software R Studio (R Core Team, 2024).

The low number of fishing events with observed bycatch precluded any robust statistical analysis of mitigation efficacy. Alternatively, we used seabird abundance of in the vicinity of fishing vessels during net hauling or setting, as a proxy to evaluate the potential effect of each measure in reducing bycatch risk. These are critical moments for seabirds-gear interactions (Oliveira et al., 2022), which can lead to bycatch when birds become entangled in the gear. Bird counts of all the species observed from the vessel were conducted during these fishing phases, and fishing event occurrence (FO%) was calculated as the proportion of fishing events in which the species were observed. Due to difficulties in accurately distinguishing between immature yellow-legged gulls (*Larus michahellis*) and lesser black-backed gulls (*Larus fuscus*), all age groups and both species were combined into a single category, referred to as “gulls”, for the purpose of analyses. Generalized Linear and Mixed-effect Models (GLMs and GLMMs) with a Poisson or a negative binomial distribution and a log-link were employed to model the variation of seabird abundance around the fishing vessel during the processes of net setting and hauling using the R-package MASS (Venables and Ripley, 2002). The bird count of each species/group around the vessel was used as the response variable, while the fixed explanatory variables incorporated in the models were treatment type (Test and Control), distance (only the bands A, B, and C were included in the analysis to improve model accuracy), bird species (gulls and northern gannet), season (described as Winter: January–March; Spring: April–June; Summer: July–September; Autumn: October–December), behaviour (12: circular flight; 13: Resting on the water), the depth of fishing, and the fishing stage (hauling; setting). Vessel ID was not included as a random factor in the models, as several vessels switched between different gear types or operated multiple gear types during the study period, thereby violating the assumption of consistency required for random effects and rendering vessel ID unsuitable for inclusion. Only gulls were included in the model for megaphone trials (model 1) while both gulls (model 2) and gannets (model 3) were modelled to test the effect of scarybird and discard management practices, as the low occurrence and number of events involving other species precluded a statistically robust analysis (Table 2). To account for the variability between fishing events, the date of fishing was included as the random effect in the GLMMs (models 1 and 2). Lastly, the natural logarithm of net-length, used as a proxy for fishing effort, was added as an offset variable to account for the differences in fishing effort between treatments. Initially, descriptive plots were made to check for outliers, and the outliers once detected were discarded from the model data to

improve model performance. Consequently, 1 and 14 occurrences were identified as outliers and excluded from model 2 and 3, respectively (Table 3–A, Fig. S1). Two separate sets of models were created for the trials using the megaphone (described as Control: No megaphone used when fishing; Experimental: Megaphone used when fishing) and the scarybird device + discard management (described as Control: No scarybird + no discard management; Test 1: Only scarybird; Test 2: Only discard management; Test 3: Scarybird + discard management) trials, respectively. The best model was selected based on the AIC criteria as well as the principle of parsimony (Bozdogan, 1987). Model diagnostics included simulating residuals using the R-package DHARMA (Hartig, 2024). The alpha value was set at 0.05 and p-values less than 0.05 were deemed significant.

To assess the socio-economic impact of the deterrent measures, separate analyses were performed for the megaphone and the scarybird + discard management trials. Since the assumptions for parametric statistics (normality and homogeneity of variances between groups) were not satisfied, a Wilcoxon rank sum test was used to compare the LPUEs in the megaphone trials and a Kruskal - Wallis test for the scarybird + discard management trials.

3. Results

3.1. Characterization of fishing events

A total of 166 fishing events were monitored during this study with mean soak time and mean net lengths for each treatment presented in Table 1. For the megaphone trials, 48 fishing events were observed, focusing solely on net setting, with 25 control events and 23 experimental events.

For the scarybird and discard management trials, 28 fishing events were conducted under control conditions. In trials using only the scarybird device (Test 1), 31 fishing events were monitored. Trials implementing discard management alone (Test 2) included 26 fishing events. Finally, in trials combining discard management with the scarybird device (Test 3), 33 fishing events were observed.

3.2. Seabirds abundance and interactions with fishing vessels

Across the 48 fishing events monitored (control and treatment) for the megaphone trial and the 118 events monitored (control and treatments) for the scarybird and discard management trials, the results were consistent across different treatments (control, megaphone, discard management, scarybird, scarybird and discard management). For all trials, gulls (considering all gull species) were the most abundant species around the fishing vessel (mean abundance across all treatments of 72 individuals/fishing event), followed by northern gannets (mean abundance across all treatments of 4 individuals/fishing event), Cory's shearwater (*Calonectris borealis*), (mean abundance across all treatments of 1 individuals/fishing event) and storm petrels (*Hydrobates* spp. and *Hydrobates pelagicus*) (mean abundance across all treatments of 1 individuals/fishing event) (Table 2).

3.3. Bycatch

In total, there were 24 birds bycaught during fishing operations, all of them during the scarybird and discard management trials (Table 2). All the bycaught birds were captured during the process of net setting, resulting in 100 % mortality. Northern gannets (Test 1/only scarybird: n = 2 birds; Test 3/Scarybird + Discard management: n = 1 birds), Great shearwaters, *Puffinus gravis* (Control: n = 13 birds; Test 3/Scarybird + Discard management: n = 7 birds) and gulls (*Larus* sp.) (Test 1/only scarybird: n = 1) were the only three species bycaught. The bycatch rates differed considerably between the three trial types (Control; Test 1/only scarybird; and Test 3/Scarybird + Discard management) in which bycatch was observed (Control: 0.46 birds/event; Test 1/only

Table 2

Total number of birds of seabird species recorded in the study area (0–300 m distance band from the vessel) during the fishing events, including species-specific IUCN conservation status, percentage of fishing event occurrence (FO %) and number of bycaught individuals (BYC) across different mitigation tests.

Species	Megaphone						Scarybird and Discard management												Total	IUCN status
	Control			Megaphone			Control			Discards management			Scarybird			Scarybird + Discards management			Sum birds	
	FO %	Sum birds	BYC	FO %	Sum birds	BYC	FO %	Sum birds	BYC	FO %	Sum birds	BYC	FO %	Sum birds	BYC	FO %	Sum birds	BYC		
<i>Larus sp.</i> (Gulls)	96	481	–	100	882	–	100	2344	–	100	2085	–	94	4206	1	100	1900	–	11898	LC
<i>Morus bassanus</i> (Northern Gannets)	24	19	–	26	17	–	75	304	–	54	70	–	71	176	2	55	76	1	662	LC
<i>Calonectris borealis</i> (Cory's Shearwater)	28	19	–	17	39	–	32	29	–	38	32	–	26	20	–	45	85	–	224	LC
<i>Hydrobates spp.</i> (Petrels)	0	0	–	0	0	–	11	4	–	27	27	–	32	24	–	27	58	–	113	LC
<i>Hydrobates pelagicus</i> (European storm petrel)	0	0	–	9	17	–	7	4	–	27	57	–	26	23	–	15	16	–	117	LC
<i>Puffinus mauretanicus</i> (Balearic Shearwater)	8	2	–	22	12	–	4	2	–	23	23	–	6	3	–	18	14	–	56	CR
<i>Puffinus gravis</i> (Great Shearwater)	0	0	–	9	28	–	14	70	13	15	21	–	39	110	–	27	42	7	271	LC
<i>Puffinus sp.</i> (Shearwaters)	4	1	–	4	1	–	4	2	–	12	7	–	6	2	–	3	3	–	16	–
<i>Stercorarius skua</i> (Great skua)	4	1	–	4	1	–	11	6	–	8	2	–	23	11	–	6	2	–	23	LC
<i>Alca torda</i> (Razorbill)	0	0	–	0	0	–	0	0	–	8	2	–	0	0	–	0	0	–	2	LC
<i>Sterna hirundo</i> (Common tern)	0	0	–	0	0	–	0	0	–	4	2	–	0	0	–	0	0	–	2	LC
<i>Sternula albifrons</i> (Little tern)	0	0	–	0	0	–	0	0	–	4	1	–	0	0	–	0	0	–	1	LC
<i>Puffinus griseus</i> (Sooty shearwater)	0	0	–	0	0	–	7	2	–	0	0	–	3	1	–	3	1	–	4	NT
<i>Larus ridibundus</i> (Black-headed gull)	0	0	–	0	0	–	4	6	–	0	0	–	0	0	–	0	0	–	6	LC
<i>Oceanites oceanicus</i> (Wilson's storm petrel)	0	0	–	0	0	–	4	12	–	0	0	–	0	0	–	0	0	–	12	LC
<i>Gulosus aristotelis</i> (European shag)	0	0	–	0	0	–	0	0	–	0	0	–	0	0	–	3	2	–	2	LC
<i>Phalacrocorax carbo</i> (Great cormorant)	0	0	–	0	0	–	0	0	–	0	0	–	0	0	–	3	4	–	4	LC
<i>Puffinus puffinus</i> (Manx shearwater)	0	0	–	0	0	–	0	0	–	0	0	–	3	1	–	0	0	–	1	LC
<i>Sterna sp.</i> (Terns)	0	0	–	0	0	–	0	0	–	0	0	–	3	2	–	3	1	–	3	–
<i>Sterna sandvicensis</i> (Sandwich tern)	4	6	–	0	0	–	0	0	–	0	0	–	3	4	–	3	2	–	12	LC

Table 3

A. Model formulas of the most robust models (NB: Negative binomial distribution; μ , λ : Estimated number of birds; k: Dispersion parameter; β_0 : Intercept term; β_i : Fixed-effect estimates; b_{date} : Random intercept).

A.						
Model No.	Species	Treatment	Model formula			
1	Gulls (<i>Larus</i> sp.)	Megaphone	Number \sim NB(μ ,k) $\log(\mu) = \beta_0 + \beta_1 \cdot \text{Treatment} + \beta_2 \cdot \text{Distance} + \beta_3 \cdot (\text{Treatment} \times \text{Distance}) + \beta_4 \cdot \text{Mesh_Size} + \beta_5 \cdot \text{Season} + \log(\text{Effort}) + b_{date}$, $b_{date} \sim N(0, \sigma^2)$			
2	Gulls (<i>Larus</i> sp.)	Scarybird + Discard management	Number \sim NB(μ ,k) $\log(\mu) = \beta_0 + \beta_1 \cdot \text{Treatment} + \beta_2 \cdot \text{Distance} + \beta_3 \cdot \text{Fishingstage} + \beta_4 \cdot \text{Behaviour} + \beta_5 \cdot \text{Depth} + \log(\text{Effort}) + b_{date}$, $b_{date} \sim N(0, \sigma^2)$			
3	Northern Gannets (<i>Morus bassanus</i>)	Scarybird + Discard management	Number \sim Poisson(λ) $\log(\lambda) = \beta_0 + \beta_1 \cdot \text{Treatment} + \beta_2 \cdot \text{Mesh size} + \beta_3 \cdot \text{Depth} + \log(\text{Effort})$			
B.						
Model Number	1					
Predictors	Incidence Rate Ratios	CI	p			
(Intercept)	0	0.00–0.00	<0.001			
Treatment [1]	1.66	1.11–2.49	0.013			
Distance [B]	2.47	1.31–4.66	0.005			
Distance [C]	0.62	0.20–1.90	0.4			
Mesh Size [220 mm]	1.18	0.75–1.86	0.472			
Mesh Size [80 mm]	2.42	1.54–3.80	<0.001			
Season [Spring]	0.24	0.12–0.52	<0.001			
Season [Summer]	0.22	0.10–0.45	<0.001			
Treatment [1] \times Distance [B]	0.43	0.20–0.92	0.03			
Treatment [1] \times Distance [C]	2.04	0.58–7.16	0.264			
Random intercepts						
$\tau_{00 \text{ date}}$	0.18					
Observations	156					
C.						
Model Number	2		3			
Predictors	Incidence Rate Ratios	CI	p	Incidence Rate Ratios	CI	p
(Intercept)	0	0.00–0.00	<0.001	0	0.00–0.00	<0.001
Treatment Type [Test1]	0.85	0.59–1.21	0.361	0.58	0.37–0.91	0.018
Treatment Type [Test2]	0.63	0.43–0.92	0.017	0.53	0.28–0.97	0.045
Treatment Type [Test3]	0.65	0.46–0.91	0.013			
Distance [B]	1.11	0.99–1.25	0.066			
Distance [C]	1.22	1.04–1.43	0.017			
Mesh Size [220 mm]				1.11	0.71–1.74	0.635
Mesh Size [80 mm]				2.31	1.35–4.01	0.003
Fishing Stage [Setting]	1.42	1.19–1.71	<0.001			
Behaviour [13]	1.17	1.03–1.32	0.014			
Depth (m)	0.8	0.72–0.90	<0.001	1.37	1.14–1.64	0.001
Random Intercept						
$\tau_{00 \text{ date}}$	0.4					
Observations	1555			79		

B and C. The Incidence rate ratios, 95 % confidence intervals, and the p-values derived from the models that were fitted to predict the impact of B. Megaphone device and covariates on the abundance of gulls (Model 1); and C. Scarybird device, discard management and other covariates on the abundance of gulls (Model 2) and gannets (Model 3) around the vessel at the time of fishing ($\tau_{00 \text{ date}}$: Variance of the random intercepts, Observations: Sample size).

scarybird: 0.10 birds/event; Test 3/Scarybird + Discard management: 0.24 birds/event). Whilst there was an overall reduction of 33 % in the number of birds bycaught in the Test 3/Scarybird + Discard management trials, a small sample size (Control: n = 28 fishing events; Test 1/only scarybird: n = 31 fishing events; Test 3/Scarybird + Discard management: n = 33 fishing events) did not allow us to test the effectiveness of the bycatch mitigation measure for each species.

3.4. The deterrent effect of the mitigation measures

3.4.1. Megaphone

As shown in Fig. 3 - A, the average gull abundance was consistently higher in experimental trials compared to the control trials across all distance bands. This was also repeated in the case of northern gannet abundance except in distance band D, wherein the average gannet abundance in control trials exceeded that in the experimental trials (Fig. 3- B). Furthermore, modelling showed that the abundance of gulls

around the fishing vessel was predicted to be consistently higher in the experimental trips compared to the control trips ($p < 0.05$) (Table 3–B: Model 1, Fig. S2). The use of megaphone, however, significantly reduced the abundance of gulls at distance band B ($p < 0.01$). Furthermore, a significant increase in gull abundance was predicted in sets using the 80 mm mesh sized gillnet as compared to the 120 mm sized trammel nets ($p < 0.001$). Lastly, there was a notable increase in the abundance of birds during autumn as compared to spring and summer ($p < 0.001$). It is imperative to note, however, that these trials were not conducted during winter and hence, there is no data available for that season.

3.4.2. Scarybird and discard management

Although the average abundances were not uniform across distance bands and species, there was a general pattern of lower abundances in treatments Test 2 (Discard management without scarybird) and Test 3 (Scarybird + discard management), for which the discards were retained in a bucket (Fig. 3- C and D). The model prediction for gulls (Table 3–C:

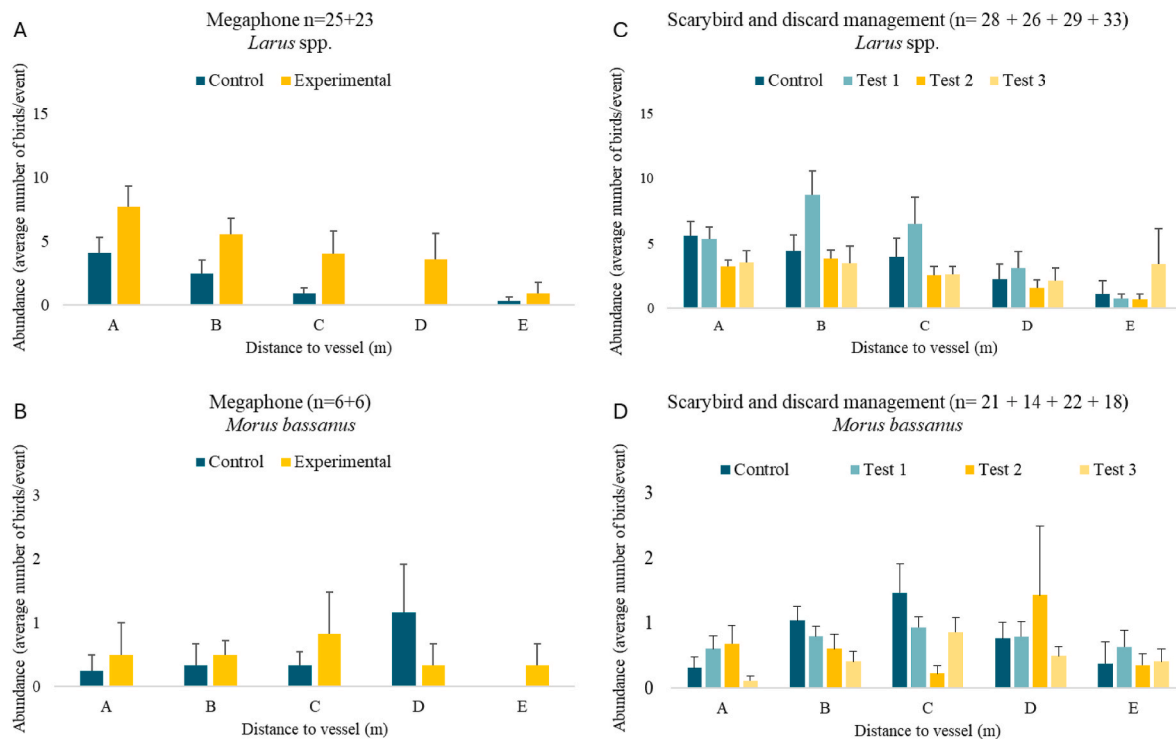


Fig. 3. Abundance of *Larus* spp. and *Morus bassanus* (average number of birds per fishing event and standard deviation) in different range bands from the fishing vessel, during the observations on board, testing the megaphone device (A and B) (Control - dark green bars, experimental - yellow bars) and the scarybird device with discard management (C and D) (Control - dark green, Test 1 – trials using the scarybird – light blue bars, Test 2 – experimental trials with discard management only – yellow bars, Test 3 – experimental trials with scarybird and discard management – light yellow bars). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Model 2, Fig. S3) confirmed our observations that the trials practicing discard management (Test 2 and Test 3) had a significantly lower abundance of seabirds ($p < 0.05$) around the vessel when compared to the control trials as well as those using the scarybird kite exclusively (Test 1). Whilst the abundance was predicted to be the highest in distance band C ($p < 0.05$), there was no interaction between the type of treatment and distance from the vessel, and hence, the interaction term was dropped from the final model as it caused an inflation of the AIC. In terms of the stage of fishing, the predicted abundance was considerably greater during the net setting stage ($p < 0.001$). Resting in the water was significantly predicted to be the most common behaviour ($p < 0.05$), with the abundance around the fishing vessel reducing significantly with an increasing fishing depth ($p < 0.001$).

Unlike gulls, a significant reduction in gannet abundance was predicted for both Test 1 and Test 2 treatments ($p < 0.05$) (Table 3–C: Model 3, Fig. S4). However, occurrences with Test 3 had to be removed from the analysis due to a small sample size ($n = 5$). Like model 1 for gulls, vessels using the 80 mm mesh sized gillnets had a higher abundance of gannets ($p < 0.01$) compared to the 120 mm mesh sized trammel. Unlike the model 2 for gulls though, the abundance of gannets around the vessel increased at higher fishing depths ($p < 0.001$).

3.5. Economic impacts of the mitigation measures

The use of the megaphone device had no impact on the LPUEs, and hence, on the total revenue during the fishing trials. The Wilcoxon rank sum test revealed no significant differences ($W = 207$, $p = 0.30$ in trials using a megaphone (20.57 ± 3.93 kg/km of net) and the control (20.48 ± 4.58 kg/km of net). In the different trials using the scarybird device and discard management, the LPUE values varied among the different tests: Control (10.25 ± 1.411 kg/km of net); Test 1 (18.01 ± 2.08 kg/km of net); Test 2 (13.60 ± 3.27 kg/km of net); Test 3 (16.78 ± 2.05 kg/km of net). However, the Kruskal- Wallis test showed no significant

differences between the LPUE values ($\chi^2 = 5.0$, $p = 0.17$).

4. Discussion

Our investigation underscores the complexity and challenges of implementing effective seabird mitigation measures around fishing vessels, particularly during critical operations such as hauling and setting of fishing gear. Two main categories of deterrents have been employed in fixed net fisheries— visual and acoustic measures underwater (Bull, 2007; Lucas and Berggren, 2023) or above the water surface (Vingada and Eira, 2018; Field et al., 2019; Almeida et al., 2023). We focused on above-water deterrents, specifically employing an acoustic device (megaphone), a visual device (scarybird), and fisher behavioural modifications (retaining fish discards or viscera onboard during net hauling and setting).

The megaphone exhibited suboptimal results across all gear types tested, with a higher number of observed seabirds in the treatment group using the device compared to controls (no megaphone). This contrasts with Diez (2017), where a similar acoustic deterrent device effectively deterred seabirds in 87 % of purse seine fishing events. The high abundance of gulls and northern gannets observed with the 80 mm mesh net, which also recorded the highest catch volume aligns with Calado et al. (2021), which showed that higher catch volume increased seabird interaction with fishing vessels, regardless of gear type. Furthermore, the considerable cost associated with implementing such equipment onboard renders it impractical for our artisanal fisheries.

Similarly, the scarybird yielded limited effectiveness in deterring gulls, with no significant differences in abundance around the fishing vessel unless combined with discard management. However, it effectively reduced the interactions with northern gannets. This partially contradicts findings by Almeida et al. (2023) in an area of the Portuguese western mainland coast where the scarybird demonstrated significant efficacy in deterring both gulls and northern gannets. The

divergent results underscore the context-specific nature of mitigation measures, influenced by geographical location, bird species, fishing practices and fisher behaviours. Consequently, it is essential to explore additional combined approaches as shown by Rouxel et al. (2021), with the Looming Eye Buoy, which reduced long-tailed ducks' (*Clangula hyemalis*) presence by 20–30 %. These trials, however, lacked real commercial fishing conditions.

Contrastingly, implementing good practices, specifically discard management onboard emerged as the most cost-effective and practical strategy (Magda Frade and Flávia Carvalho pers. Obs.). Gulls and northern gannets were the two most abundant species in the study, consistent with other studies on bottom-set nets in the coastal Portuguese Atlantic waters (Oliveira et al., 2015; Almeida et al., 2023). In our work, interactions were particularly prevalent when the gear was closer to the surface during fishing operations, especially during net setting, when gulls showed increased abundance. Moreover, interactions were particularly frequent at shallower depths, which could be attributed to their primarily coastal habitats and their behaviour as surface feeders (Schwemmer and Garthe, 2005; Catry et al., 2010). Contrarily, northern gannets are found foraging in highly productive waters associated with the continental shelf breaking zone (Hamer et al., 2000), which could explain the predicted increase of interacting gannets in deeper waters. Discard management consistently and significantly reduced the number of birds for both species across various distance bands, aligning with Kuepfer et al. (2022), who demonstrated that seabird abundance around trawl vessels significantly lower when discards were managed using batch (Discards temporarily stored before being batch discharged) or zero discard strategies compared to continuous discarding (Discards discharged on a continuous basis). These results align with broader evidence that species such as gannets and gulls are active consumers of fishery discards (Bicknell et al., 2013). Notably, gannets have been shown to actively respond to vessels engaged in discarding activities, while showing little or no response in areas where discarding is not permitted (Bodey et al., 2014; Clark et al., 2020). This highlights the critical role discard management plays in modulating seabird attraction to vessels and, consequently, the potential for bycatch through increased interactions during fishing operations.

In 2013, the EU's Landing Obligation (LO), aimed to reduce wasteful discarding by requiring all catches to be recorded and landed (European Commission: European Climate, Infrastructure and Environment Executive Agency, Heinrich, J., 2021). However, discarding persists suggesting reduced implementation (e.g. restricted to very few fisheries), weak enforcement, inadequate monitoring, and policy exemptions (Veiga et al., 2016; Borges, 2021). Strengthening monitoring and reassessing exemptions could improve the LO, though many practical challenges remain. A practical alternative is batch waste release, especially for trawlers (Bicknell et al., 2013; ACAP, 2019). We strongly recommend this approach in bottom-set nets, combined with better cleaning of the nets before setting, to reduce seabirds' interactions.

As highlighted by Suuronen (2022), fishers are often hesitant to adopt bycatch reduction technologies due to a lack of evidence demonstrating efficacy across diverse conditions. Therefore, our results suggest that, instead of relying on technical solutions like the megaphone or the scarybird, a simple behavioural modification among fishers could yield the most immediate and impactful results in mitigating seabird interactions. The fishing community, particularly artisanal fleets, is more likely to accept such measures if they are characterised by simplicity, ease of operation, minimal disruption to fishing activities, economic viability, and no adverse impact on catch volumes (Avery et al., 2017). Therefore, testing mitigation measures should encompass economic considerations and an evaluation of their acceptability within the fishing industry, as advocated by Good et al. (2020).

The implemented measures, including the scarybird and behaviour changes on board, were well received. Within this study, fishers easily accepted the scarybird as it required no cost or responsibility, while behaviour changes posed more of a challenge but were ultimately

accepted due to the observed reduction in bird attraction. Furthermore, none of the mitigation measures impacted fishery income, either in catch quantity or sales volume, consistent with expectations for above-water measures designed to deter birds rather than affect fishing gear (Rouxel et al., 2021). The value of catches was driven by market demand, not catch size. This outcome was crucial for the fishers' positive acceptance and highlights the potential of above-water measures that do not compromise target species catches.

Bycatch events were infrequent and sporadic throughout the study period. A notable increase of bycatch occurred in October 2022, when over 92 % of the total bycatch was recorded within a two-week span, coinciding with the implementation of good practices trials. Bycatch events primarily occurred during net setting, when fishers discarded fish remains into the water, potentially attracting seabirds and leading to entanglement (Magda Frade, pers. comm.). Additionally, inadequate net cleaning also contributed, as residual fish remains on nets attracted seabirds. However, due to study constraints, it was not feasible to consistently monitor or rigorously evaluate the impact of these practices on bycatch rates. Therefore, due to the limited bycatch data, it is premature to draw definitive conclusions about the effectiveness of the implemented mitigation measures. However, this bycatch observation corroborates with Bull (2007), which highlighted a lower bycatch rate with the retention of offal discards in several fisheries around the world.

Achieving long-term success in mitigating seabird bycatch will require not only ongoing monitoring and adherence to best practices but also a deeper understanding of fishers' perspectives and challenges. Strong partnerships with the fishing community are crucial for the adoption of mitigation measures, and these partnerships should be built on mutual trust, shared knowledge, and practical, context-specific solutions (Cox et al., 2007; Suuronen, 2022). In small-scale fisheries, discard management strategies can be relatively simple and manageable. However, in other fisheries with more extensive operations, where discard volumes of non-target/non-commercial species may be higher, discard retention and management on deck may become more complex. Therefore, effective discard management solutions should be adaptable to the scale of the fishery. These solutions must balance the need to minimize seabird attraction with the operational constraints of each type of fishery, ensuring that mitigation measures are both feasible and efficient across diverse fishing contexts.

CRediT authorship contribution statement

Magda Frade: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Flávia Carvalho:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Vighnesh Samel:** Writing – original draft, Visualization, Methodology, Formal analysis. **Nuno Oliveira:** Writing – review & editing, Methodology. **Ana Almeida:** Writing – review & editing, Methodology. **Joana Andrade:** Project administration, Conceptualization. **Jorge MS. Gonçalves:** Writing – review & editing, Supervision, Project administration. **Ana Marçalo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Data availability statement

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

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

Reports a relationship with that includes: Has patent pending to. 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 B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ocecoaman.2025.107767>.

Data availability

Data will be made available on request.

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