Reducing cetacean interactions with bottom set-nets and purse seining using acoustic deterrent devices in southern Iberia

Marçalo, Ana; Carvalho, Flávia; Frade, Magda; Bentes, Luís; Monteiro, Pedro; Pontes, João; Alexandre, Sofia; Oliveira, Frederico; Kingston, Allen; Erzini, Karim; Gonçalves, Jorge M.S.

Date of deposit 14/02/2025

Document version Author’s Accepted Manuscript

Citation for published version Marçalo, A., Carvalho, F., Frade, M., Bentes, L., Monteiro, P., Pontes, J., Alexandre, S., Oliveira, F., Kingston, A., Erzini, K., & Gonçalves, J. M. S. (2025). Reducing cetacean interactions with bottom set-nets and purse seining using acoustic deterrent devices in southern Iberia. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *35*(2), Article e70061.

Link to published version https://doi.org/10.1002/aqc.70061

Reducing cetacean interactions with bottom set-nets and purse seining using acoustic deterrent devices in southern Iberia

Ana Marçalo[1*], Flávia Carvalho[1], Magda Frade[1], Luís Bentes[1], Pedro Monteiro[1], João Pontes[1], Sofia Alexandre[1], Frederico Oliveira[1], Allen Kingston[2], Karim Erzini[1], Jorge MS Gonçalves[1]

[1]Centre of Marine Sciences (CCMAR), Universidade do Algarve, Campus de Gambelas, FCT Ed. 7, 8005-139 Faro, Portugal

[2] Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, St Andrews, UK

Correspondence:

* Ana Marçalo, Centre of Marine Sciences (CCMAR), Universidade do Algarve, Campus de Gambelas, FCT Ed. 7, 8005-139 Faro, Portugal. Email: amarcalo@ualg.pt

Abstract

In southern Iberia (NE Atlantic), cetacean bycatch is reported in several fisheries, while depredation by bottlenose dolphin *(Tursiops truncatus)* is commonly observed in bottom-set net fisheries. This study tested the effectiveness of acoustic deterrent devices in discouraging small cetaceans from approaching bottom set-nets and purse seine, to reduce interactions. The acoustic deterrent devices used in the study were dolphin deterrent devices and dolphin interactive devices for the bottom set-net fishery to reduce dolphin bycatch and depredation, and dolphin deterrent devices in the purse seine fishery to reduce common dolphin (*Delphinus delphis*) bycatch. Data collection was carried out by at-sea observers and trained fishing vessel crew observers. Hauls with and without acoustic deterrent devices were compared and analyzed to investigate differences in catch per unit effort, factors affecting the interaction, probability of interaction and habituation (in bottom set-nets only). In bottom set-nets, the depredation rate was significantly lower and reduced by about 50 % in hauls using acoustic deterrent devices. Habituation of the bottlenose dolphins to the devices was observed but was gradual. In the purse seine fishery, common dolphin bycatch was reduced by 100 % when using the acoustic deterrent devices. Overall, the results are promising, but the different interaction reduction efficiencies observed between gear types, indicate that the potential application of acoustic deterrent devices should be considered on a métier-by-métier basis. Other mitigation measures should be developed, especially for static gears, in collaboration with the fishing sector in an inclusive management approach to reduce direct interactions between fisheries and cetaceans.

KEYWORDS

acoustic deterrent devices, bottom set-nets, bycatch, cetaceans, depredation, habituation, mitigation, purse seine, Southern Iberia

1 | INTRODUCTION

Direct and indirect interactions between fishing gears and cetaceans occur when fishing grounds overlap with the cetaceans' preferred feeding habitats. Direct interactions occur when cetaceans come into contact with fishing gear, potentially resulting in bycatch often leading to serious injury or even mortality (Northridge & Hofman, 1999; Read 2008; Jog et al., 2022). These interactions represent a conservation concern as they pose a threat to certain cetacean populations, particularly if bycatch surpasses the population's capacity to maintain their abundance levels (Read 2008). Another form of direct interaction is depredation, where cetaceans interfere with fishing activities by preying on the fish caught resulting in economic loss for fishers due to damaged gear and/or reduced catch (Brotons, Grau & Rendell, 2008; Bearzi & Reeves 2022). Indirect interactions result from fishery-induced changes to ecosystem dynamics, such as resource competition, which can lead to prey depletion (Kaschner & Pauly, 2005; Alexandre et al., 2022) and impact cetacean behaviour and distribution (Aguilar, 2000).

Cetacean bycatch occurs when individuals are accidental entangled, trapped, or hooked in fishing gear. Bycatch events have been reported in various gear types (FAO, 2021; ICES, 2022), with drivers of incidental capture being mostly related to gear operational aspects (e.g. gear type, fishing practices, location, fishing effort and crew awareness) and target species, which may also be the main prey for certain megafauna species (Kaschner & Pauly, 2005; Plagányi & Butterworth, 2009). In Europe, cetacean bycatch is most commonly associated with purse seining, bottom set-nets (gillnets and trammel nets) and pelagic trawls (Marçalo et al., 2015; Dias et al., 2022; ICES, 2022). Meanwhile, depredation is associated with artisanal static net fisheries (Bearzi, 2002; Cox et al. 2004; Read, 2008; Brotons, Grau & Rendell, 2008; Gönener & Özdemir, 2012; Rechimont et al., 2018; Revuelta et al., 2018), with reports indicating that some fishers respond by taking retaliatory measures against cetaceans (Gazo, Gonzalvo & Aguilar, 2008; Read, 2008; Wells & Scott, 2009; Revuelta et al., 2018).

In Portuguese mainland waters, bycatch predominantly occurs in gillnets and trammel nets, with the common dolphin (*Delphinus delphis*), the most abundant cetacean species, being most affected (Silva & Sequeira 2003; Gilles et al. 2023; Marçalo et al. 2024). Studies have identified areas of significant habitat overlap between cetaceans and the Portuguese purse seine fishing fleet, particularly when targeting sardine (*Sardina pilchardus*), a primary prey of common dolphins, leading to frequent interactions and incidental bycatch (Wise et al., 2018; Marçalo et al., 2015; Dias et al., 2022). Additionally, research has documented cetacean-fishery interactions across various fisheries and estimated bycatch rates (Goetz et al., 2014; Alexandre et al., 2022). Bottlenose dolphins (*Tursiops truncatus*) are also known to frequently interact with coastal commercial fisheries, often due to depredation events in bottom-set nets, particularly gillnets and trammel nets targeting species such as hake (*Merluccius merluccius*) or red mullet (*Mullus surmuletus*) (Alexandre et al., 2022; Marçalo et al., 2024). These issues are especially pronounced in southern Portugal, which, due to its proximity to the Mediterranean, faces similar challenges to those reported in Mediterranean fisheries, where such interactions are a common source of conflict (Bearzi, 2002; Cox et al., 2004; Brotons, Grau & Rendell, 2008; Read, 2008; Gönener & Özdemir, 2012).

To address such interactions, two types of acoustic deterrent devices (ADDs), that should be chosen according to the cetacean species that has been interacting with the gear, have been developed by companies: low-intensity devices that emit low frequencies (<150-160 dB), mostly used to reduce bycatch of small cetaceans; and louder devices emitting higher frequencies (>132-185 dB) to reduce cetacean bycatch and discourage depredation, with studies indicating no significant impact on target fish catch rates (Dawson et al., 2013; Hamilton & Baker, 2019). Over time, ADDs have evolved in peak frequency, signal length, and source level, incorporating random periodicity and varied intensity of frequency to address responding the growing challenges of reducing cetacean interactions in specific fisheries of concern, such as gillnet fisheries (Waples et al., 2013; Dawson et al., 2013, Puente et al. 23).

Studies have shown significant success in using ADDs in various regions to reduced bycatch of harbour porpoises (*Phocoena phocoena)* in the United States and Europe (Kraus et al., 1997; Trippel et al., 1999; Palka et al., 2008; Carlström, Berggren & Tregenza, 2009; Gönener & Bilgin, 2009; Larsen, Krog & Ritzau, 2013; van Beest et al., 2017), franciscana *(Pontoporia blainvillei)* in Argentina (Bordino et al., 2002), beaked whales in the United States (Carretta, Barlow & Enriquez, 2008) and small cetaceans (e.g. common dolphin) in California (Barlow & Cameron, 2003) and Peru (Alfaro-Shigueto et al., 2010). However, some trials have reported limited efficacy of ADDs with certain studies showing no deterrent effect (Stephenson & Wells, 2008; Berrow et al. 2009; López & Marinõ, 2011; Santana-Garcon et al., 2018). Research on bottlenose dolphins, in particular, have shown varied results, ranging from significant reductions in direct interactions (Gazo, Gonzalvo & Aguilar, 2008; Waples et al., 2013; Ceciarini et al., 2023), to cases where ADDs had no deterrent effect (Cox et al., 2004; McPherson et al., 2004; Erbe et al., 2016) and even reports of bycatch in nets equipped with active devices (Ana Marçalo pers. Comm.; Northridge, Vernicos & Raitsos-Exarchopolous, 2003; Read & Waples, 2010). This inconsistency in effectiveness suggests that the utility of ADDs is likely influenced by specific factors such as area, species, and gear type (Hamilton & Baker, 2019). In addition to effectiveness concerns, the use of ADDs raises welfare issues, as these devices may lead to habitat exclusion causing cetaceans to avoid essential areas. To mitigate these risks, European regulations now impose limits on ADD sound intensity and frequency to help reduce potential physiological impacts on cetaceans while still effectively deterring bycatch (Dawson et al., 2013; Hamilton & Baker, 2019). The potential welfare implications highlights the importance of implementing carefully tailored and context-specific approaches when using ADDs as a sustainable mitigation tool.

Given the high levels of documented cetacean-fishery interactions along the Portuguese mainland coast, this study focused on bottom set-nets and purse seines—the two gears with the most significant records of direct conflict with cetaceans (Marçalo et al., 2015, 2024; Alexandre et al., 2022; Dias et al., 2022; ICES, 2022). Over a three-year period, pilot mitigation trials were conducted as part of two projects along the south coast of Portugal (NE Atlantic, FAO Division 27.9.a.) to evaluate the effectiveness of loud acoustic deterrent devices (ADDs) in reducing cetacean interactions with bottom set-nets (gillnet and trammel net) and purse seine fisheries. This study aimed at determining whether ADDs could reduce cetacean bycatch and depredation by bottlenose dolphins in bottom set-nets and bycatch of common dolphins in purse seines. In addition, we assessed the potential for habituation – the gradual reduction in cetacean response to the acoustic signals over time - which may lessen the deterrent effect of the devices. We also investigated whether the use of ADDs could lead to habitat exclusion, where cetaceans might avoid areas where devices are deployed, potentially altering their natural behavior or habitat use. Finally, we examined the potential impact of the use of ADDs on the commercial catch per unit effort (CPUE) in both fisheries, providing insights into the broader implications of ADDs as a sustainable mitigation tool.

2 | MATERIALS AND METHODS

2.1 | Study area

The study area included the waters off southern mainland Portugal (Figure 1), also known as the Algarve. The study area comprises a small area in the south-west coast (~50 km extension), from Odeceixe (37◦26’ N - 8◦47’ W) to Cape São Vicente (37◦1′ N - 8◦59′ W), and the Southern coast (~170 km extension), from Cape São Vicente to Vila Real de Santo António (37º11’ N - 7º25’ W). This coastal region has a very narrow continental shelf (5–20 km wide) influenced locally by upwelling events that occur mostly in the south-western area.

2.2 | Fleet characterization and target gears for trials

The Portuguese fishing fleet is composed of around 3100 licensed vessels, with around 80 % classified as "local" vessels, a designation for those under 9 meters in length (DGRM, 2022). These local vessels predominantly operate as multi-gear vessels, using a variety of fishing methods including gillnets and trammel nets, longlines, pots and traps and less frequently purse seines. Vessels with ≥9 meters in length are categorized as "coastal" vessels. The coastal fleet is more diverse, including multi-gear vessels as well as large purse seiners, bottom trawlers and offshore vessels that operate in international waters, such as longliners. Both local and coastal multi-gear vessels target a range of pelagic and demersal species, while purse seiners specifically target small schooling pelagic fish, including sardine (*Sardina pilchardus*), horse mackerels (*Trachurus* spp.), Atlantic chub mackerel (*Scomber colias*) and European anchovy (*Engraulis encrasicolus*). Around 30 % of the national fleet is based in the Algarve (INE, 2023). For the mitigation trials, selection of vessels operating bottom-set nets and purse seines was randomised within a subset of fishers with whom trust bonds exist (Table 1) and the number of ADDs available. The chosen vessels made daily fishing trips.

2.3 | Data collection and monitoring

Data on cetacean bycatch and depredation were collected using two methods: (1) At-Sea Observers (SO) and (2) Vessel crew Observers (VO). SOs were trained biologists who went on board to collect data, VOs were crew members, normally skippers, that were trained by the SOs to collect data. For VO, paper logbooks were designed specifically for the trials and were filled in voluntarily by the skippers of the vessels participating in the trials. For both methods, data collected included: fishing gear configurations (including gear dimensions and mesh size), environmental conditions (Beaufort wind and Douglas sea state scales), vessel activities (timing of fishing operations - net shooting, hauling, and soaking times), location at the beginning of the haul, fish caught (weight in kg per species), cetacean presence and cetacean species identification in the vicinity of the boat during fishing operations and type of interaction (bycatch with or without mortality and/or depredation).

We monitored fishing hauls with (experimental) and without (control) the use of acoustic deterrent devices (ADDs). Although the decision to deploy ADDs was at the discretion of the fishers during the testing period, they tended to use the devices more frequently in métiers or when targeting species with higher interaction rates, such as hake and red mullet in bottom-set nets (Marçalo et al., 2024) or sardine in purse seines (Marçalo et al., 2015; Dias et al., 2022). Recognizing this potential for bias, we implemented regular oversight to balance the data collection process. Scientific Observers (SOs) conducted weekly onboard visits to guide and monitor Voluntary Observers (VOs), verifying that control hauls and experimental hauls using ADDs were conducted consistently across different times and areas. While we acknowledge that full control over fisher choices in an operational setting is challenging, this strategy allowed us to achieve a balanced and representative dataset for analysis. An increased SO effort during the initial testing year (2019) was intentional, aimed at selecting and training vessel crew members to ensure effective data collection.

Depredation by bottlenose dolphins was assessed based on visible signs of damage to both fish and gear, whether or not the animals were observed near the vessels. Distinctive indicators include: 1) partially consumed catches, often with the head intact and identifiable bottlenose teeth marks; and 2) cases where the entire prey is consumed, leaving noticeable tears or holes in the nets, as bottlenose dolphins typically tear through the net to feed on entangled prey (Revuelta et al., 2018; Marçalo et al., 2024).

2.4 | Equipment – Acoustic devices

The ADDs used in this study were "Dolphin Deterrent Devices" (DDD; model DDD 03), and "Dolphin interactive Devices" (DiD), produced and distributed by STM Products (Italy). The DDD 03 is an electronic device with a microprocessor of 16 bits that controls the emission circuit for randomized signals. These ADDs activate when submerged in water, where the sounds start being emitted with sequences of random frequencies that vary from 5 to 500 kHz and a potency of emission not higher than 165 dB (1µPa@1m). The random frequencies should decrease habituation. The DiD model is an upgrade of the DDD with an internal function that only activates the acoustic emissions when any cetaceans (species not specified by the manufacturer) are in the vicinity, and not when it falls into the water (https://www.stm-products.com/en/products/fishing-technology). For bottom set-nets (gillnets and trammel nets), both the DDD 03N and the DiD models were used, whereas for purse seine nets only the DDD 03H model was used. Their application followed the recommendations of the manufacturer with some adaptations as explained in section 2.5. These models were chosen and used taking into account the statement of the manufacturer affirming that they are certified as not being physiologically harmful to cetaceans or fish.

2.5 | Experimental design

2.5.1 | Bottom set-nets

Bottom-set net trials were conducted along the Algarve coast, off Quarteira, Olhão, Culatra Island, Portimão and Monte Gordo, from June 2019 to June 2022 (Table 1). The ADDs were applied to the bottom set-nets with the aim to reduce bycatch and depredation by bottlenose dolphins (Alexandre et al., 2022; Marçalo et al., 2024). According to information from fishers from previous studies, depredation resulting in loss of catch and gear damage is most frequent in fisheries targeting hake, red mullets, occasionally soles (*Solea* spp.), and cuttlefish (*Sepia officinalis;* Alexandre et al., 2022), so we focused the bottom set-net trials on vessels targeting those species (Table 1).

The spacing of ADDs on the bottom set-nets followed a consistent design across all trials conducted (Supplementary Figure 1A), to make sure the performance of the acoustic devices remained unaffected. The DDD 03N model was attached to the nets at intervals of 400 meters, while the DiD model was attached every 800 meters, which was the maximum distance recommended by the manufacturer. SO monitoring effort was used to ensure battery autonomy and performance (battery duration was, on average, 48 hours soaking time), checking for battery life span with a voltmeter and training fishers in this process. When charging was needed, the devices were collected, charged, and delivered back to fishers. From 2021 onwards, battery chargers were delivered to fishers together with a battery life protocol based on the previously tested average battery charge duration.

2.5.2 | Purse seine nets

The purse seine trials were conducted along the Algarve coast, off Olhão, Portimão, and Sagres, in 2021 and 2022, during the peak sardine (*Sardina pilchardus*) fishing season (mid-spring to early autumn). This period corresponds to increased fishing effort and a heightened risk of common dolphin (*Delphinus delphis*) bycatch (Marçalo et al., 2015; Dias et al., 2022). Information on the number of vessels participating in the trial is presented in Table 1. The manufacturer suggested the use of 3 ADDs per purse seine net, one of them attached to the seiner, which required hanging ropes that could lead to unwanted entanglements in the vessel propeller and detrimental implications during the setting of the net. After a preliminary consultation with skippers, it was decided to use just one ADD for practical reasons. This protocol was maintained up to the end of the trials, as one ADD showed good results and covered the range of the diameter of the net. After the initial trips when the SOs checked for battery life span and delivered a battery charging protocol to the fishers, each unique vessel was equipped with one ADD and one charger. The ADD was connected at the end of a 10 meters rope, taken by the fisher in the skiff and put in the water in the beginning of net shooting. Since the ADD remained in the water only during the shooting and encircling, the soak time of the device was no longer than 4-5 minutes (Please check diagram on DDD application in a purse seiner in supplementary Figure 1B).

2.6 | Analysis

In this study, due to the high incidence of hauls with zero interactions, we employed a two-stage model, commonly known as the "hurdle model", applied in previous studies, particularly following the approach of Puente et al. (2023). Separate models were developed for bottom set-nets and purse seine. For bottom set-nets, we only tested for depredation due to the rarity of bycatch events. We used Generalized Additive Models for Location, Scale, and Shape (GAMLSS) with a two-stage “Zero Adjusted Poisson” (ZAP) distribution and logit link function to analyse the presence and absence of interaction in both fisheries. This approach using the gamlss.dist R package allowed us to: (1) Model the probability of the occurrence of direct interactions (bycatch) in purse seine nets, and depredation in bottom set-nets with a logistic Generalized Linear Model (GLM); (2) For the hauls where direct interactions did occur, estimate the intensity or count of interaction events (such as the number of depredation events or individuals caught) using a zero-truncated Poisson GLM. The probability of having an interaction event (bycatch in purse seine nets, and depredation in bottom set-nets) was analysed using a binomial test considering the presence-absence of cetacean interaction for experimental hauls (with ADDs) and control hauls (without ADDs), obtaining 95% confidence intervals.

To assess the factors influencing cetacean depredation in bottom-set nets, we analysed several explanatory variables in control hauls, including latitude, longitude, depth, year, season, month, soaking time, total CPUE, CPUE of striped red mullet, CPUE of hake, and observer type (SO or VO). Starting with a model that included all explanatory variables, we used backwards selection to identify the best model (i.e. each time the least important non-significant variable was dropped, and the model was re-run). The best model was the one that presented the lowest Akaike Information Criterion value [AIC, (Akaike, 1974)].

ADD efficiency, a variable to predict habituation, was estimated for bottom set-nets by dividing the number of fishing operations where ADDs were used and where no depredation occurred by the total number of fishing operations where ADDs were used. Polynomial regressions were used to determine the rate of efficiency of the ADDs.

Catch per Unit Effort (CPUE) was calculated by dividing the total catch by fishing effort. For bottom set-nets fishing effort was considered as the soaking time; for purse seine, fishing effort was considered as the time from the beginning of the search to the end of the fishing activity, marked by the end of fish transfer to the vessel (Marçalo et al., 2015). To test the potential influence of ADDs on commercial catches, square-root transformed CPUEs were compared between hauls with and without ADDs in both fisheries. Although we used the non-parametric Mann-Whitney test due to failed normality tests, the square root transformation was applied to reduce variability and improve data interpretability, thereby minimizing potential skewness and outlier influence. A significance level of 0.05 was used in all tests.

All analyses were performed using the R software (R Core Team, 2016) and maps were created using QGIS (Version 3.10.0; QGIS Development Team, 2019).

3 | RESULTS

3.1 | Bottom set-nets

3.1.1 | Effort and cetacean observations during fishing operations

A total of 877 trips in bottom set-nets (gillnets and trammel nets) were monitored (each trip represented a fishing day with one haul). The total effort for each ADD model was 360 days/hauls (151 days/hauls control plus 209 days/hauls with device) for DiD and 517 days/hauls (185 days/hauls control plus 332 days/hauls with device) for DDD (Table 2). Monitoring effort (number of hauls with or without ADDs) showed greater seasonal discrepancies in 2019 and 2022, as both were incomplete years (trials began in late June in 2019 and finished in June 2022). Soaking times were extended during hauls using DiDs, particularly in trials targeting hake, leading to longer gear deployment in the water. In the bottom set-net fishery, cetaceans were observed during 18.4% of control hauls and 13.6% of hauls using DDDs. Conversely, in hauls with DiDs, cetaceans were sighted more frequently, with 50.3% of control hauls and 80.9% of hauls using DiDs reporting cetacean presence. All observations occurred during hauling operations, with cetaceans (all bottlenose dolphins) seen from near the vessel to a maximum distance of 50 meters. Of all trips monitored, SO effort was 22% in 2019 and about 8 - 9% from 2020 to 2022, with the remaining trips being monitored by vessel crew observers (VO).

3.1.2 | Probability of interaction

Interaction with bottom set-nets, either depredation or bycatch, occurred along the whole study area in both control (Figure 1A) and experimental (Figure 1B) hauls. It is worth noting that bycatch occurrences were relatively rare, with only four animals being captured during the trials (Table 2). Three of these animals were captured in control hauls, while one animal was captured in a haul with a DiD device. However, it should be noted that during the haul using the DiD where the bycatch occurred, an onboard SO confirmed that the device closest to the animal was not functional. Depredation was observed in 9.9% (CI 7.2 -13.6%) of the hauls using DDDs, compared to 20.5 % (CI 14.7-26.4%) in the control treatment. Similarly, during trials using DiDs, depredation occurred in

18.2% (CI 13.2-24.1%) of hauls, versus 36.6% (CI 29.0-44.8%) in the control treatment. These differences were assessed using binomial testing, considering the presence or absence of cetacean depredation across treatments. The results showed significantly lower depredation rates in hauls using ADDs compared to control hauls, with a 48% reduction in depredation probability for DDDs and 50% for DiDs. Further statistical analysis using the GAMLSS model showed that the number of hauls with depredation was significantly different between control and experimental treatments (GAMLSS, $p < 0.01$ for both types of ADDs). This indicates that the use of ADDs significantly reduced the occurrence of depredation in bottom set-nets by bottlenose dolphins (Table 3).

3.1.3 | Factors affecting the interaction

Table 4 summarizes the model results during control hauls. For DDD control hauls, bottlenose dolphin depredation showed a slight positive relationship with year, a stronger positive relationship with latitude and vessel, and a negative relationship with the CPUE of red mullet. The best-fitting model, selected based on the lowest AIC value, explained 12.2% of the observed deviance. For DiD control hauls, depredation was negatively associated with the CPUE of hake and positively associated with latitude, with the final model explaining 5.4% of the deviance.

3.1.4 | Acoustic device efficiency

Throughout the period of the trials, the effectiveness of both ADDs in reducing depredation in bottom set-nets showed a decreasing trend (Figure 2A). Initially, in 2019, both models achieved efficiencies above 90%. However, by 2022, the efficiency of the DiD had decreased to 77 %, while the DDD's efficiency decreased to 73 %. Regarding seasonal variation, the efficiency of ADDs showed distinct patterns (Figure 2B). The DiD model demonstrated higher efficiency during spring, while the DDD model was more effective during summer and autumn. Indeed, at the conclusion of the three-year trial, it is clear that both ADD models achieved an overall average efficiency above 70%. Despite the observed seasonal variations in their effectiveness, the combined data from the entire trial period demonstrates that both DiD and DDD models consistently achieved a considerable level of efficiency in reducing depredation in bottom set-nets.

3.1.5 | Catch per unit effort

When comparing the total CPUE between hauls with and without ADDs, for both DDD and DiD models (Figure 3a and 3b, respectively), a significant difference was observed in the trial involving DDDs (Mann-Whitney test; $P < 0.001$), where experimental hauls showed higher CPUE values. Meanwhile, no significant CPUE differences were found between control and experimental hauls using DiDs (Mann-Whitney test; $P = 0.096$). Furthermore, when comparing CPUE between net hauls with and without depredation occurrences (Figure 3c), regardless of the type of treatment (with or without ADD), CPUE was significantly lower in hauls experiencing depredation (Mann-Whitney test; $P < 0.001$).

3.2 | Purse seine

3.2.1 | Effort and cetacean observations during fishing operations

A total of 461 fishing days/trips (518 hauls) were monitored in the purse seine fishery. Control (Figure 1C) and experimental (Figure 1D) treatments were distributed across the same fishing areas. Table 2 shows the total effort for each treatment, where 268 hauls were controls, and 250 hauls used ADDs. All cetacean sighted were common dolphins, which were mainly observed post-net shooting and during hauling. These sightings were observed in 18% of control hauls and 14% of experimental hauls. It is important to note that common dolphins when sighted during the experimental treatments were only seen after fishing operations were finished, when the ADD had already been removed from the water. Bycatch was observed only in control hauls (6%; Figure 1C). Of the 38 bycaught animals, 29 were released alive (post release mortality rates are unknown) and 9 were already dead when observed by the fishers. SO effort was 8% in 2020 and 4% in 2021, the remaining trips were monitored by VOs (Supplementary Table 1).

Monitoring effort during the trials increased in the second year as more vessels actively participated, leading to a higher number of monitored trips and hauls. This increase can be attributed to the positive perception among fishers regarding the successful prevention of common dolphin bycatch events when using the DDDs. As a result, fishers became more motivated to use these devices during their fishing operations, leading to a significant increase in the adoption of this preventive measure. In the meantime, SO´s, when present, made efforts to reinforce the need for control hauls to equilibrate the treatments.

3.2.2 | Probability of interaction

The binomial analysis investigating the presence and absence of cetacean bycatch in the purse seine fishery confirmed that hauls with ADDs had a significantly lower bycatch rate. On average, direct interactions occurred in 0 % (CI 0 -1.5 %) of hauls using the ADDs, compared to 5.6 % (CI 3.2 – 9.1 %) of hauls in the control group. Further analysis using the GAMLSS model showed that the number of hauls with bycatch was significantly different between control and experimental treatments, with hauls equipped with ADDs showing a significantly lower occurrence of common dolphin bycatch in purse seine nets (GAMLSS, $p < 0.01$; Table 3). This outcome highlights the effectiveness of ADDs in reducing the likelihood of cetacean bycatch during purse seine operations.

3.2.3 | Catch per unit effort

Considering all purse seine net hauls monitored during the trial, the medians of the Catch Per Unit Effort (CPUE) of the main target species of this fishery (sardine), showed a significant difference (Mann-Whitney test, $P < 0.001$) between hauls with and without ADDs (Figure 3d). CPUE values were higher when using ADDs, indicating that the presence of ADDs positively influenced the catch rates of sardines. Focusing on the subset of hauls where cetaceans were observed during fishing operations, CPUE of sardines was significantly higher when using the ADDs compared to the control hauls (Mann-Whitney test; P = 0.017; Figure 3e).

4 | DISCUSSSION

The mitigation trials conducted with two distinct fishing gears (bottom set-nets and purse seine nets), have provided valuable insights into the efficacy of DDDs and DiDs as mitigation tools in Southern Atlantic Iberia. The use of ADDs within each specific fishery demonstrated a substantial reduction in negative interactions between cetaceans and the fishing gears. It is important to note that this study is the first to report on the use of DDDs in purse seine fishery. The extended temporal scope of this study (3 years) allowed for an analysis of the potential habituation of the animals to the devices and an assessment of animal presence near the vessels. These observations are crucial for understanding possible habitat exclusion, a concern associated with the use of ADDs (Omeyer et al., 2020). The potential displacement of cetaceans from their usual habitat demands for a comprehensive evaluation of the broader ecological implications of ADDs (Kolipakam et al., 2022).

Direct interactions between fisheries and cetaceans depend on several variables such as the cetacean species, fishing operation, area, and sea conditions (Dawson et al., 2013). Therefore, mitigation measures that are successful in some areas may not be appropriate for others, which makes mitigating these conflicts a continuous challenge. Acoustic measures have been used for decades, an array of different ADD models have been developed to deter different species of cetaceans from approaching fishing gears (Dawson et al., 2013; Coram et al., 2014). DDDs and DiDs have primarily been used in short-term trials in trawl and bottom set-net fisheries in the European Atlantic, Mediterranean waters, and Australia (Morizur et al., 2009; De Carlo et al., 2012; Santana-Garcon et al., 2018; Ceciarini et al., 2023; Puente et al., 2023), with mixed outcomes regarding reduction of cetacean bycatch and depredation.

In the context of bottom set-nets, this three-year study revealed a notable decrease in depredation rates when using ADDs. The implementation of both DiDs and DDDs culminated in an approximate 50 % reduction in depredation rates across various métiers, showcasing the efficiency of these devices in mitigating cetacean depredation. Some inferences could be taken from bycatch as well, revealing higher bycatch in the control hauls. However, despite hundreds of monitored fishing operations, the low rates of bycatch occurrence and low variance in the GAMLSS models for the bottom set-net fishery for both ADD models tested, highlights the need for caution when replicating these mitigation trials in other areas or drawing definitive conclusions.

In Portuguese waters, bottlenose dolphins are typically a coastal cetacean species known to have a flexible and opportunistic feeding behaviour on highly valuable fish and cephalopod species (Giménez et al., 2017; Ana Marçalo pers. comm.). These are also the target species in several coastal bottom set-net fisheries (Bearzi, 2002; Rechimont et al., 2018; Marçalo et al., 2024), potentially leading to the increase of depredation and/or bycatch. In our study, fishers expressed concerns about the fact that depredation occurred mostly in métiers targeting hake and red mullet, the most valuable species. However, métiers that target other species (i.e. soles) often also catch hake and mullets. As a result, the effort towards these two fish species is high, overlapping with bottlenose dolphin feeding grounds and preferred coastal habitats.

The presence of bottlenose dolphins and their interaction with bottom set-net fisheries can significantly impact catches and damage fishing gear, ultimately reducing the profitability of these fisheries (Revuelta et al., 2018; Rechimont et al., 2018; Alexandre et al. 2022; Marçalo et al., 2024). In the Alboran Sea, bottlenose dolphins and non-native species have been shown to negatively affect trammel net fisheries, leading to reduced catches and increased gear damage (Baéz et al., 2023). Similarly, spatial and temporal partitioning by resident dolphin species in the Western Mediterranean Sea affects the distribution and availability of target fish species (Torreblanca et al., 2023). Recently, the only study to date on bottlenose dolphin depredation in the Algarve region (Marçalo et al., 2024) showed that the impact of depredation might have similar consequences in the south of Portugal, potentially affecting local fish populations and fishing practices. In our present study, the negative correlation observed between depredation events and CPUEs of target fish species, suggesting that lower catch volumes may provoke increased depredation activity, presents an intriguing contrast to findings from Rechimont et al. (2018), where depredation was positively correlated with CPUE, with dolphins preferentially targeting nets with higher catch volumes. This discrepancy highlights the complex interplay between prey availability, dolphin behavior, and environmental factors, underscoring the need for careful interpretation of depredation dynamics, which may vary across fisheries, species, and ecological contexts. As noted previously, CPUE is influenced by numerous factors beyond depredation, including resource availability, crew expertise, fishing area, and temporal oceanographic changes (Chávez-Martínez et al., 2022), all of which could modulate these interactions.

Mitigation experiments often lack adequate funding for extended periods, preventing robust conclusions regarding animal habituation to the devices or insights into animal welfare (e.g. indirect interactions such as habitat exclusion or unintended harmful effects of the sound produced by the acoustic devices that could be detrimental to the protected species; Cox, Read & Tregenza, 2001; Kolipakam et al., 2022). In this regard, our study provided the opportunity to collect data over an extended period, making the findings and conclusions on ADD performance and cetacean habituation more robust. For instance, the decline in efficiency during the bottom set-net trial period highlights the need for continuous monitoring and potential improvements to maintain the effectiveness of ADDs in mitigating depredation in this fishery. However, an average efficiency above 70% at the end of the three-year trial indicates that the implementation of ADDs can be a valuable and effective approach in mitigating depredation events during fishing operations over an extended period of time.

Underwater noise associated with these types of ADDs should be taken into consideration and recommendations should be considered for their use (Read, 2021). In static fisheries such as bottom set-nets, which can be several kilometres long, it is wise to restrict the continuous use of this type of alarms wherever possible, for example by using them on a seasonal and métier specific basis (based on higher interaction rates). Mitigation with ADDs should always be considered with caution and not as the only solution, since it may be financially challenging to be applied in small-scale fisheries, and the fact that the large-scale use of ADDs can contribute to noise pollution in the marine environment. Opting for the use of DiDs seems to be a good option as they emit the sound only when dolphins approach the fishing gear, thus limiting noise pollution or potentially slowing habituation of the animals to the devices. However, it is important to note that this interactivity is largely theoretical and should be confirmed through further studies. The current models of DiDs are based on detecting cetacean presence through sound, but advancements in technology, such as AI-based systems (e.g. automated detection of dolphin whistles using convolutional networks, Korkmaz et al., 2023; Scaradozzi et al., 2024), could improve the accuracy and efficiency of such devices. Future research should focus on developing more reliable and interactive pingers to ensure minimal acoustic pollution and greater efficacy in mitigating interactions. Moreover, special care should be taken when considering the use of high frequency ADDs in designated priority areas where sensitive neophobic (timid) species occur, such as the harbour porpoise which, in Iberian waters, holds a critical threatened status (Pierce et al. 2024). In this respect other mitigation options should be considered such as reducing fishing effort of gears with higher interaction risk in seasons of higher abundance of individuals in a particular area (Read, 2021) coupled with seasonal gear shifts (Virgili et al. 2024).

Despite recent advancements in studying cetacean abundance and distribution along the Portuguese coast (Cañadas et al., 2023; Gilles et al., 2023), our understanding remains somewhat limited. While recent studies have provided valuable insights, the historical lack of comprehensive research has hindered progress in developing ecosystem-based management strategies and delayed the implementation of measures across various regions.

Regarding the purse seine fishery, the study encompassed two consecutive years characterized by enhanced fishing activity when targeting sardines, which occurs mostly from late spring to early autumn and peaks in the summer months when the resource is more expensive. Furthermore, sardines are also one of the primary prey species of common dolphins in the area (Marçalo et al., 2018). Consequently, the periods of higher fishing effort coincide with the peak occurrences of common dolphin bycatch (Marçalo et al., 2015; Dias et al., 2022). Our trials indicated that incidental captures occurred exclusively in control hauls. The absence of bycatch events in hauls using ADDs is an important finding, highlighting the effectiveness of these devices in reducing common dolphin bycatch during purse seine fishing operations. Results showed that the use of ADDs not only reduced cetacean bycatch, but also had a positive impact on the catch rates of the target species (sardine). Higher catch rates may be directly related to the reduced presence of cetaceans near the vessels during net setting, as their presence tends to disperse or break up the fish schools (Marçalo et al., 2015). According to Marçalo et al. (2015) and Dias et al. (2022), bycatch of common dolphins occurs in 1-2% of the annual purse seine fishing effort, this corresponds to the bycatch of hundreds of animals per year along the Portuguese mainland coast. Our results showed the successful elimination of bycatch during purse seine fishing operations when using DDDs, with the added benefit that only one DDD needs to be deployed during net setting (encirclement), which usually lasts around five minutes.

Our study provides preliminary evidence that the use of ADDs in fishing operations does not seem to induce habitat exclusion of dolphins, which is a crucial consideration for ensuring sustainable fisheries management and minimizing disruptions to cetacean populations. The abundance of dolphin sightings during hauls with ADDs, whether during net hauling (in both fisheries) or fish transfer (in purse seining only), challenges the notion that these devices deter cetaceans from the vicinity of fishing vessels. Observations in both fisheries revealed that a significant number of dolphins remained near the vessels during operations involving ADDs. In purse seining, cetaceans, if present during net setting with a DDD, were observed to quickly return to the area once the device was removed from the water, suggesting that their natural behavior was not substantially disrupted by the use of ADDs. However, further research is needed to confirm these observations over longer timeframes and across different environmental contexts. Such insights are vital for ensuring that mitigation tools like ADDs are both effective in reducing bycatch and minimally invasive to cetacean habitats.

While acknowledging the limitations inherent to our regional pilot study, conducted with a relatively small subset of vessels that represent less than 5% of the national purse seine fleet and less than 1% of the national polyvalent fleet operating bottom set-nets, our findings provide a valuable regional example for the appropriate utilization of ADDs. The conclusions drawn, along with the associated limitations, are particularly relevant within the context of the regional scenario, offering insights that can contribute meaningfully to the broader discussion on cetacean interactions in fisheries management. As a further limitation, it is important to note that our analysis combined gillnet and trammel net data to enhance dataset robustness, with the only discrimination being based on the target species of the métier (either red mullets or hake, used as explanatory variables, as both fish species are the most depredated; Marçalo et al., 2024). While our approach allowed for a comprehensive examination within these specific métiers, it may introduce nuances and complexities that could be better understood through more detailed métier-specific analyses in future studies.

There is no simple way to mitigate conflicts between fisheries and cetaceans. Nevertheless, there seems to be some consensus that mitigation should be an inclusive process involving all stakeholders (scientists, fishers, governmental entities, and NGO´s) to discuss strategies. These strategies rely on changes of behaviour when managing the ocean, from increasing global awareness, using mitigation tools, and reducing fishing effort to increasing surveillance. Similarly, the adoption of good practices on board should be voluntary as governmental impositions are not necessarily well accepted. Mitigation measures to reduce direct interactions with cetaceans must be practical and not consume much time and/or affect the regular fishing operations so that fishers can easily adopt them.

In the course of both projects (iNOVPESCA and CetAMBICion), several workshops with stakeholders took place, where the results of the mitigation trials were presented and fishers' knowledge and experience added to the discussions. We consider that finding solutions to reduce direct interactions with marine megafauna have to take comprehensive inclusive steps involving the fishing community and take into account the social context, area, type of fishery and target species, on a case-by-case scenario. Moreover, our findings hold broader implications for the conservation of cetaceans, as the collaborative and inclusive approach to mitigation strategies, as well as the successful integration of ADDs into fishing practices, exemplify a promising model for minimizing direct interactions between fisheries and marine megafauna. By fostering a constructive dialogue among scientists, fishers, governmental entities, and NGOs, our study not only contributes with valuable insights to local fisheries but also advocates for a holistic, community-driven approach that can be adapted and scaled for broader conservation efforts.

ACKNOWLEDGMENTS

The authors are grateful to all the fishers who promptly collaborated voluntarily in the trials. A special thank you to the observer Rúben Gregório for additional at-sea observer effort in the bottom set-net fishery. This work was supported by projects Mar2020- iNOVPESCA (DGRM/MM, MAR2020: MAR-01.03.01-FEAMP-0020), CetAMBICion (EU, DG-ENV/MSFD 2020) and LIFE Ilhas Barreira (LIFE18/NAT/PT/000927).. Additionally, this study was supported by the Portuguese Science and Technology Foundation (FCT) through projects UIDB/04326/2020, UIDP/04326/2020 and LA/P/0101/2020 to CCMAR. A special thank goes to two unknown reviewers whose comments contributed substantially to the improvement of the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ETHICS AND PERMIT APPROVAL STATEMENT

No approvals were required.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with this work.

ORCID

Ana Marçalo 0000-0002-0485-341X

Flávia Carvalho 0009-0001-2751-7689

Magda Frade 0000-0002-4006-5648

Luís Bentes 0000-0001-6884-2886

Pedro Monteiro 0000-0003-1446-8256

João Pontes 0000-0002-7223-5699

Sofia Alexandre 0000-0002-6647-2559

Frederico Oliveira 0000-0002-4318 -604X

Allen Kingston 0009-0003-8210-2413

Karim Erzini 0000-0002-1411-0126

Jorge MS Gonçalves 0000-0001-7704-8190

REFERENCES

Aguilar, A. (2000). Population biology, conservation threats, and status of Mediterranean striped dolphins (*Stenella coeruleoalba*). *Journal of Cetacean Research and Management,* 2, 17–26.

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Trans Autom Control*, 19, 716–723. http://dx.doi.org/10.1109/TAC.1974.1100705.

Alexandre S., Marçalo A., Marques, T.A., Pires, A., Rangel, M., Ressurreição, A. et al. (2022). Interactions between air-breathing marine megafauna and artisanal fisheries in Southern Iberian Atlantic waters: Results from an interview survey to fishers. *Fisheries Research*, 254, 106430. https://doi.org/10.1016/j.fishres.2022.106430.

Alfaro-Shigueto, J., Mangel, J.C., Pajuelo, M., Dutton, P.H., Seminoff, J.A. & Godley, B.J. (2010). Where small can have a large impact: Structure and characterization of small-scale fisheries in Peru. *Fisheries Research*, 106(1), 8–17. https://doi.org/10.1016/j.fishres.2010.06.004.

Baéz, J.C., Camiñas, J.A., Aguilera, R., Castro-Gutiérrez, J., & Real, R. (2023). When non-target wildlife species and alien species both affect negatively to an artisanal fishery: the case of trammel net in the Alboran Sea. *Review in Fish Biology and Fisheries*, 33 (4), 785-799. https://doi.org/10.1007/s11160-023-09759-6.

Barlow, J., & Cameron, G.A. (2003). Field experiments show that acoustic pingers reduce marine mammal bycatch in the California drift gillnet fishery. *Marine Mammal Science*, 19, 265–83. https://doi.org/10.1111/j.1748-7692.2003.tb01108.x.

Bearzi, G. (2002). Interactions between cetaceans and fisheries: Mediterranean Sea, in Notarbartolo di Sciara, G. (ed.) *Cetaceans in the Mediterranean and Black Seas: State of Knowledge and conservation strategies*. Monaco: ACCOBAMS, pp.78–97.

Bearzi, G. & Reeves, R.R. (2022). Marine mammals foraging around fishing gear or preying upon fishing catch and bait: it may not be "depredation". *ICES Journal of Marine Science*, 79(8), 2178–2183. https://doi.org/10.1093/icesjms/fsac173.

Berrow, S., O'Brien, J., O'Connor, I. & McGrath, D, (2009). Abundance estimate and acoustic monitoring of harbour porpoises (*phocoena phocoena* (l.)) in the Blasket Islands' Candidate Special Area of Conservation. *Biology & Environment Proceedings of the Royal Irish Academy*, 109B, 35–46. doi:10.3318/BIOE.2009.109.1.35.

Bordino, P., Kraus, S., Albareda, D., Fazio, A., Palmerio, A., Mendez, M. et al. (2002). Reducing incidental mortality of franciscana dolphin *Pontoporia blainvillei* with acoustic warning devices attached to fishing nets. *Marine Mammal Science*, 18(4), 833–842. https://doi.org/10.1111/j.1748-7692.2002.tb01076.x.

Brotons, J.M., Grau, A. & Rendell, L. (2008). Estimating the impact of interactions between bottlenose dolphins and artisanal fisheries around the Balearic Islands. *Marine Mammal Science*, 24, 112–127. https://doi.org/10.1111/j.1748-7692.2007.00164.x.

Buscaino, G., Ceraulo, M., Alonge, G., Pace, D.S., Grammauta, R., Maccarrone, V. et al. (2021). Artisanal fishing, dolphins, and interactive pinger: A study from a passive acoustic perspective. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 31(8), 2241–2256. https://doi.org/10.1002/aqc.3588.

Cañadas, A., Pierantonio, N., Araújo, H., David, L., Di Meglio, N., Dorémus G., Gonzalvo, J. et al. (2023). Distribution patterns of marine megafauna density in the Mediterranean Sea assessed through the ACCOBAMS Survey Initiative (ASI). *Frontiers of Marine Science*, 10, 1270917. doi:10.3389/fmars.2023.1270917.

Carlström, J., Berggren, P. & Tregenza, N.J.C. (2009). Spatial and temporal impact of pingers on porpoises. *Canadian Journal of Fisheries and Aquatic Sciences*, 66(1), 72–82. https://doi.org/10.1139/F08-186.

Carretta, J.V., Barlow, J. & Enriquez, L. (2008). Acoustic pingers eliminate beaked whale bycatch in a gill net fishery. *Marine Mammal Science*, 24(4), 956–961. https://doi.org/10.1111/j.1748-7692.2008.00218.x.

Ceciarini, I., Franchi, E., Capanni, F., Consales, G., Minoia, L., Ancora, S., DAgostino, A. et al (2023). Assessment of interactive acoustic deterrent devices set on trammel nets to reduce dolphin–fishery interactions in the Northern Tyrrhenian Sea. *Scientific Reports*, 13, 20680. https://doi.org/10.1038/s41598-023-46836-z.

Chávez-Martínez, K., Morteo, E., Hernández-Candelario, I., Herzka, S.Z., Delfín- Alfonso, C.A. (2022). Opportunistic gillnet depredation by common bottlenose dolphins in the southwestern Gulf of Mexico: Testing the relationship with ecological, trophic, and nutritional characteristics of their prey. *Frontiers of Marine Science* 9, 1–17. https://doi.org/10.3389/fmars.2022.870012.

Coram, A., Gordon, J., Thompson, D. & Northridge, S. (2014). Evaluating and assessing the relative effectiveness of non-lethal measures, including Acoustic Deterrent Devices, on marine mammals. Scottish Government.

Cox, T. M., Read, A.J. & Tregenza, N. (2001). Will harbour porpoises (*Phocoena phocoena*) habituate to pingers? *Journal of Cetacean Research Management*, 3 (1), 81-86.

Cox, T.M., Read, A.J., Swanner, D., Urian, K. & Waples, D. (2004). Behavioral responses of bottlenose dolphins, *Tursiops truncatus,* to gillnets and acoustic alarms. *Biological Conservation*, 115(2), 203–212. https://doi.org/10.1016/S0006-3207(03)00108-3.

Dawson, M.D., Northridge, S., Waples, D. & Read, A. (2013). To ping or not to ping: the use of active acoustic devices in mitigating interactions between small cetaceans and gillnet fisheries. *Endangered Species Research*, 19, 201 –221. https://doi.org/10.3354/esr00464.

De Carlo, F., Virgili, M., Lucchetti, A., Fortuna, C.M. & Sala, A. (2012). Interactions between bottlenose dolphin and midwater pair trawls: effect of pingers on dolphin behaviour. *Biologia Marina Mediterranea*, 19(1), 206–207.

DGRM, 2022. DATAPESCAS nº135 – janeiro a dezembro de 2022.

Dias, I., Marçalo, A., Feijó, D., Domingos, I. & Silva, A. (2022). Interactions between the common dolphin, *Delphinus delphis*, and the Portuguese purse seine fishery over 15 years (2003-2018). *Aquatic Conservation: Marine and Freshwater Ecosystems* (2022). https://doi.org/10.1002/aqc.3828.

Erbe, C., Wintner, S., Dudley, S.F.J. & Plön, S. (2016). Revisiting acoustic deterrence devices: Long-term bycatch data from South Africa's bather protection nets. *Proceedings of Meetings on Acoustics*, 27(1), 010025. https://doi.org/10.1121/2.0000306.

FAO, 2021. *Fishing operations. Guidelines to prevent and reduce bycatch of marine mammals in capture fisheries.* FAO Technical Guidelines for Responsible Fisheries No.1, Suppl. 4. Rome.

Gazo, M., Gonzalvo, J. & Aguilar, A. (2008). Pingers as deterrents of bottlenose dolphins interacting with trammel nets. *Fisheries Research*, 92, 70–75. https://doi.org/10.1016/j.fishres.2007.12.016.

Giménez, J., Marçalo, A., Ramírez, F., Verborgh, P., Gauffier, P., Esteban, R., Nicolau, L. et al. (2017). Diet of bottlenose dolphins (*Tursiops truncatus*) from the Gulf of Cadiz: Insights from stomach content and stable isotope analyses. *PLoS ONE*, 12(9). https://doi.org/10.1371/journal.pone.0184673.

Gilles, A., Authier, M., Ramirez-Martinez, N.C., Araújo, H., Blanchard, A., Carlström, J., Eira, C. et al. (2023). *Estimates of cetacean abundance in European Atlantic waters in summer 2022 from the SCANS IV aerial and shipboard surveys*. Final report published 29 September 2023. 64 pp. https://tinyurl.com/3ynt6swa.

Goetz, S., Read, F.L., Ferreira, M., Portela, J., Santos, M., Vingada, J., et al., (2014). Cetacean occurrence, habitat preferences and potential for cetacean-fishery interactions in Iberian Atlantic waters: results from cooperative research involving local stakeholders. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 25(1), 138–154. https://doi.org/10.1002/aqc.2481.

Gönener, S.& Bilgin, S. (2009). The effect of pingers on harbour porpoise, *Phocoena phocoena* bycatch and fishing effort in the turbot gill net fishery in the Turkish Black Sea coast. *Turkish Journal of Fisheries and Aquatic Sciences*, 9(2), 151–157. doi:10.4194/trjfas.2009.0205.

Gönener, S. & Özdemir, S. (2012). Investigation of the Interaction Between Bottom Gillnet Fishery (Sinop, Black Sea) and Bottlenose Dolphins (*Tursiops truncatus*) in Terms of Economy. *Turkish Journal of Fisheries and Aquatic Sciences*, 12(1), 111–122.

Hamilton, S. & Baker, G.B. (2019). Technical mitigation to reduce marine mammal bycatch and entanglement in commercial fishing gear: lessons learnt and future directions. *Reviews in Fish Biology and Fisheries*, 29, 223–247. https://doi.org/10.1007/s11160-019-09550-6.

ICES (2022). *Working Group on Bycatch of Protected Species (WGBYC).* ICES Scientific Reports, 4(91), 265 pp. https://doi.org/10.17895/ices.pub.21602322.

INE (2023). Estatísticas da Pesca 2023. ISSN 0377-225-X.

Jog, K., Sutaria, D., Diedrich, A., Grech, A. & Marsh, H. (2022). Marine Mammal Interactions With Fisheries: Review of Research and Management Trends Across Commercial and Small-Scale Fisheries. *Frontiers in Marine Science*, 9:758013. https://doi.org/10.3389/fmars.2022.758013.

Kaschner, K. & Pauly, D. (2005). Competition between marine mammals and fisheries: Food for thought. In: Salem, D.J. & Rowan, A.N. (Eds.) *The state of the animals III: 2005*. Washington, DC: Humane Society Press, pp.95-117.

Kolipakam, V., Jacob, M., Gayathri, A. et al. (2022). *Pingers are effective in reducing net entanglement of river dolphins*. Scientific Reports 12, 9382. https://doi.org/10.1038/s41598-022-12670-y.

Korkmaz, B., N., Diamant, R., Danino, G. &Testolin A. (2023). Automated detection of dolphin whistles with convolutional networks and transfer learning. *Frontiers of Artificial Intelligence*, 6:1099022. Doi: 10.3389/frai.2023.1099022

Kraus, S.D., Read, A., Anderson, E., Baldwin, K., Solow, A., Spradlin, T. et al. (1997). Acoustic alarms reduce porpoise mortality. *Nature*, 388. https://doi.org/10.1038/41451.

Larsen, F., Krog, C. & Ritzau, E.O. (2013). Determining optimal pinger spacing for harbour porpoise bycatch mitigation. *Endangered Species Research*, 20, 147–152. https://doi.org/10.3354/esr00494.

López, B.D. & Mariño, F. (2011). A trial of acoustic harassment device efficacy on free-ranging bottlenose dolphins in Sardinia, Italy. *Marine and Freshwater Behaviour and Physiology*, 44(4), 197–208. https://doi.org/10.1080/10236244.2011.618216.

Marçalo, A., Katara, I., Feijó, D., Araújo, H., Oliveira, I., Santos, J. et al. (2015). Quantification of interactions between the Portuguese sardine purse-seine fishery and cetaceans. *ICES Journal of Marine Science*, 72(8), 2438−2449. https://doi.org/10.1093/icesjms/fsv076.

Marçalo, A., Nicolau, L., Giménez, J., Ferreira, M., Santos, J., Araújo, H. et al. (2018). Feeding ecology of the common dolphin (*Delphinus delphis*) in Western Iberian waters: has the decline in sardine (*Sardina pilchardus*) affected dolphin diet? *Marine Biology*, 165(44). https://doi.org/10.1007/s00227-018-3285-3.

Marçalo, A., Samel, V., Carvalho, F., Frade, M., Erzini, K. & Gonçalves, J. M. S. (2024). Evaluating dolphin interactions with bottom-set net fisheries off Southern Iberian Atlantic waters. *Fisheries Research*, 278, 107100. https://doi.org/10.1016/j.fishres.2024.107100.

McPherson, G.R., Ballam, D., Stapley, J., Peverell, S., Cato, D.H., Gribble, N. et al. (2004). Acoustic alarms to reduce marine mammal bycatch from gillnets in Queensland waters: optimising the alarm type and spacing. *Proceedings of Acoustics*, 2, 1–6. https://api.semanticscholar.org/CorpusID:114341482.

Morizur, Y., Niliot, L., Buanic, M. & Pianalto, S. (2009). Expérimentations de répulsifs acoustiques commerciaux sur les filets fixes à baudroies en mer d'Iroise - Résultats obtenus au cours de l'année

2008-2009 avec le projet « PingIroise ». Le Conquet: Centre de Brest Sciences et Technologie Halieutiques, 17 pp.

Northridge, S. P., and Hofman, R. J. 1999. Marine mammal interactions with fisheries. In Conservation and Management of Marine Mammals, pp. 99 –119. Ed. by J. R. Twiss, and R. R. Reeves. Smithsonian Institution Press, Washington.

Northridge, S., Vernicos, D. & Raitsos-Exarchopolous, D. (2003). Net depredation by bottlenose dolphins in the Aegean: first attempts to quantify and to minimise the problem. Paper presented to the Scientific Committee of the International Whaling Commission, Berlin, May.

Omeyer, L.C.M., Doherty, P.D., Dolman, S., Enever, R., Reese, A., Tregenza, N., et al. (2020). Assessing the Effects of Banana Pingers as a Bycatch Mitigation Device for Harbour Porpoises (*Phocoena phocoena*). *Frontiers of Marine Science*, 7, 285. doi: 10.3389/fmars.2020.00285.

Palka, D.L., Rossman, M.C., VanAtten, A.S., & Orphanides, C.D. (2008). Effect of pingers on harbour porpoise *(Phocoena phocoena*) bycatch in the U.S. Northeast gillnet fishery. *Journal of Cetacean Research and Management*, 10(3), 217–26. https://doi.org/10.47536/jcrm.v10i3.638.

Pierce, G. J., Petitguyot, M. A. C., Gutierrez-Muñoz, P., Fariñas-Bermejo, A., Fernández-Fernández, D., Dolman, S. et al. (2024). An endangered population of harbour porpoise Phocoena phocoena hidden in plain sight: Biology, ecology and conservation of the Iberian porpoise. *Oceanography and Marine Biology: An Annual Review*, 62, 1-118. DOI: 10.1201/9781003477518-1

Puente, E., Citores, L., Cuende, E., Krug, I. & Basterretxea, M. (2023). Bycatch of short-beaked common dolphin *(Delphinus delphis*) in the pair bottom trawl fishery of the Bay of Biscay and its mitigation with an active acoustic deterrent device (pinger). *Fisheries Research*, 267. https://doi.org/10.1016/j.fishres.2023.106819.

QGIS Development Team, 2019. QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org.

R Core Team (2016). R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Read, A.J. (2008). The looming crisis: interactions between marine mammals and fisheries. *Journal of Mammalogy*, 89, 541–548. https://doi.org/10.1644/07-MAMM-S-315R1.1.

Read, A.J. & Waples, D. (2010). *A pilot study to test the efficacy of pingers as a deterrent to bottlenose dolphins in the Spanish mackerel gillnet fishery.* Bycatch reduction of marine mammals in Mid-Atlantic fisheries, Final report, Project 08-DMM-02. Beaufort, SC: Duke University.

Read, F.L. (2021). *Cost-benefit Analysis for Mitigation Measures in Fisheries with High Bycatch*. ASCOBANS Secretariat, Bonn, Germany. 52 pages. ASCOBANS Technical Series No. 2.

Rechimont, M.E., Lara-Domínguez, A.L., Morteo, E., Martínez-Serrano, I. & Equihua, M. (2018). Depredation by Coastal Bottlenose Dolphins (*Tursiops truncatus*) in the Southwestern Gulf of Mexico in Relation to Fishing Techniques. *Aquatic Mammals*, 43(5), 469–481. https://doi.org/10.1578/AM.44.5.2018.469.

Revuelta, O., Domenech, F., Fraija-Fernandez, N., Gozalbes, P., Novilla, O., Penades- Suay, J. et al. (2018). Interaction between bottlenose dolphins (*Tursiops truncatus*) and artisanal fisheries in the Valencia region (Spanish Mediterranean Sea). *Ocean and Coastal Management*, 165, 117–125. https://doi.org/10.1016/j.ocecoaman.2018.08.001.

Santana-Garcon, J., Wakefield, C.B., Dorman, S.R., Denham, A., Blight, S., Molony, B.W. et al. (2018). Risk versus reward: interactions, depredation rates, and bycatch mitigation of dolphins in demersal fish trawls. *Canadian Journal of Fisheries and Aquatic Sciences*, 75(12), 2233–2240. https://doi.org/10.1139/cjfas-2017-0203.

Scaradozzi, D., De Marco, R., Veli, D. L., Lucchetti, A., Screpanti, L. & Di Nardo, F. (2024). Convolutional Neural Networks for Enhanving Detection of Dolphin Whistles in a Dense Acoustic Environment. IEEEAccess. DOI: 10.1109/ACCESS.2024.3454815

Stephenson, P.C. & Wells, S. (2008*). Evaluation of the effectiveness of reducing dolphin catches with pingers and exclusion grids in the Pilbara trawl fishery.* Final report to Fisheries Research and Development Corporation on Project No. 2004/068. Fisheries Research Report No. 173. Western Australia: Department of Fisheries, 44p.

Trippel, E.A., Strong, M.B., Terhune, J.M., & Conway, J.D. (1999). Mitigation of harbour porpoise (*Phocoena phocoena*) by-catch in the gillnet fishery in the lower Bay of Fundy. *Canadian Journal Fisheries and Aquatic Sciences*, 56, 113–23. https://doi.org/10.1139/f98-162.

Torreblanca, E., Real, R., camiñas, J. A., Macías, D., García-Barcelona, S., & Báez, J. C. (2023). Spatial and temporal partitioning of the Western Mediterranean Sea by resident dolphin species. *Mediterranean Marine Science*, 24(1), 34–49. https://doi.org/10.12681/mms.25543.

van Beest, F.M., Kindt-Larsen, L., Bastardie, F., Bartolino, V. & Nabe-Nielsen, J. (2017). Predicting the population-level impact of mitigating harbor porpoise bycatch with pingers and time-area fishing closures. *Ecosphere*, 8(4), e01785. https://doi.org/10.1002/ecs2.1785.

Virgili, A., Araújo, H., Astarloa, D. A., Dorémus, G., García-Barón, I., Eira, C., et al. (2024) Seasonal distribution of cetaceans in the European Atlantic and Mediterranean waters. *Frontiers of Marine Science*, 11:1319791. doi: 10.3389/fmars.2024.1319791

Waples, D.M., Thorne, L.H., Hodge, L.E.W., Burke, E.K., Urian, K.W. & Read, A.J. (2013). A field test of acoustic deterrent devices used to reduce interactions between bottlenose dolphins and a coastal gillnet fishery. *Biological Conservation*, 157, 165–171. https://doi.org/10.1016/j.biocon.2012.07.012.

Wells, R.S. & Scott, M.D. (2009). Common bottlenose dolphin: *Tursiops truncates*. In: Perrin, W.F., Würsig, B. & Thewissen, G.M. (Eds.) *Encyclopedia of Marine Mammals* (2ed). San Diego: Academic Press, pp. 249–255. https://doi.org/10.1016/B978-0-12-373553-9.00062-6.

Wise, L., Galego, C., Katara, I., Marçalo, A., Meirinho, A., Monteiro, S.S. et al. (2018). Portuguese purse seine fishery spatial and resource overlap with top predators. *Marine Ecology Progress Series*, 617–618, 183–198. https://doi.org/10.3354/meps12656.

TABLES

TABLE 1 Number of vessels in the trials by fishery, fishing port, vessel size, métier, device model, target species and mesh size. A. Project iNOVPESCA; B. Project CetAMBICion; GNS – Set gillnets; GTR – Trammel nets.

Fishery	**Ports**	**Vessel size**	**A. Nº vessels; Métier; Device model**	**B. Nº vessels; Métier; Device Model**	**Main target fish species**	**Mesh size (mm)**
Bottom set-nets	Olhão	> 9 m	1; GNS; DiD	2; GNS; DiD	Hake	80
	Culatra	< 9 m	1; GNS, GTR; DDD	2; GNS; DDD	Soles	50, 52, 55
	Quarteira	< 9 m	1; GNS; DDD	1; GNS; DDD	Red mullet	60
	Portimão	> 9m	-	1; GNS; DiD	Red mullet	75
	Monte Gordo	< 9 m	-	2; GNS; DiD	Soles	50, 52, 55
Purse seine	Olhão	> 9m	1; PS; DDD	4; PS; DDD	Pelagic fish (sardines, mackerels, anchovies)	16
	Portimão		2; PS; DDD	3; PS; DDD		
	Sagres		2; PS; DDD	2; PS; DDD		

TABLE 2 Monitoring effort in trials with two different models of acoustic device (i.e. experimental treatment) and without (i.e. control treatment) in bottom set-nets and purse seine. Number of trips; Number of hauls; Depth (mean and standard deviation); Number of hauls with cetacean interaction (bycatch and depredation) and with presence of cetaceans during fishing operations; Soak time (mean and standard deviation); TTR – *Tursiops truncatus*, DDE– *Delphinus delphis*. All bycaught animals were dead upon net retrieval.

Fishery	**ADD model**	**Control**	**Experimental**
Bottom-set nets	***DDD***		
	Hauls	185	332
	Depth (meters)	29.1 ± 33.6	31.6 ± 37.6
	Soak time (hours)	9.4 ± 10.1	6.0 ± 6.9
	Hauls with cetacean bycatch	1 (1 TTR)	0
	Hauls with cetaceans sighted during fishing operations	34 (18.4%)	45 (13.6%)
	Hauls with depredation	38 (20.5%)	33 (9.9%)
	DiD		
	Hauls	151	209
	Depth (meters)	65.1 ± 19.8	115.3 ± 65.2
	Soak time (hours)	15.2 ± 7.6	15.1 ± 7.6
	Hauls with cetacean bycatch	2 TTR	1 DDE *
	Hauls with cetaceans sighted during fishing operations	76 (50.3%)	169 (80.9%)
	Hauls with depredation	56 (37.1%)	38 (18.2%)
Purse seine	***DDD***		
	Trips	228	233
	Hauls	268	250
	Depth (m)	31.7 ± 11.9	32.2 ± 12.0
	Hauls with cetacean bycatch	15 DDE	0
	Cetaceans bycaught	38 DDE (9 dead)	0
	Hauls with cetacean sighted during fishing operations	47 (17.5%)	34 (13.6%)

*Acoustic device not functional

TABLE 3 Coefficients from GAMLSS Model for interaction with cetaceans, in the trial with and without acoustic devices. Here the intercept represents the rate of net interaction for the control (without alarm) condition. Significant terms are highlighted in bold.

Fishery	**Alarm Model**	**DDD**				**DiD**			
	Term	Estimate	SE	Z	p	Estimate	SE	Z	p
Bottom-set nets	*Intercept*	-0.71	0.10	-7.16	0.0000	-0.57	0.13	-4.46	0.0000
	Alarm-active	0.85	0.26	3.30	**0.0010**	0.95	0.25	3.89	**0.0001**
Purse seine	*Intercept*	-36.08	4430.97	-0.01	0.0060				
	Alarm-active	8.77	738.50	0.01	**0.0090**				

TABLE 4 Results of the final GAMLSS models for factors explaining the interaction of cetaceans with bottom set-nets with two types of acoustic devices (DDD and DiD). Akaike Information Criterion (AIC) and Simulation-based calibration (SBC) for best models are presented. Significant P-value (P <0.05) in bold.

Response variable (Model equation)	Explanatory variable	Estimate	SE	P-value	Explained Variance (%)	AIC	SBC
Bottom-set nets – DDD (Interaction_cetaceans ~ latdec + depth_m + soak + CPUE + cpue_stripedredmullet + year + factor(vessel))	latitude	25040	8346	**0.003**	12.2	161.0	193.1
	depth	4218	16.33	0.796			
	soak time	28.41	119.3	0.812			
	CPUE	-72.72	37.94	0.057			
	CPUE_striped mullet	-502.6	171.2	**0.004**			
	year	444.9	221.9	**0.046**			
	vessel	11350	32510	**0.008**			
Bottom -set nets – DiD (Interaction_cetaceans ~ latdec + CPUE + CPUE_hake + factor(observer_scheme))	latitude	18.54	8603	**0.036**	5.4	72.8	83.2
	CPUE	0.149	0.091	0.108			
	CPUE_hake	-0.274	0.133	**0.045**			
	Observer scheme	0.729	0.677	0.286			

FIGURE LEGENDS

FIGURE 1 – Map of the study area (Algarve, Mainland Portugal), showing the main fishing ports and the distribution area of fishing hauls. The map includes hauls from both bottom-set nets and purse seine trials, conducted with and without acoustic devices (ADDs). The hauls are categorized as follows: (A) bottom-set nets without acoustic devices (control), (B) bottom-set nets with acoustic devices (experimental), (C) purse seine without acoustic devices (control), and (D) purse seine with acoustic devices (experimental). Different bullet symbols in the legend represent the level of interaction in each haul for: no dolphins present; dolphins present but no interaction occurred; hauls with depredation (bottom-set nets only), and hauls with bycatch.

FIGURE 2 Polynomial regressions showing the acoustic device efficiency applied to bottom set-nets over the duration of this study by: A - year; B - season.

FIGURE 3 Square-root transformed catch per unit effort for the different treatments (control or acoustic device) for the two different acoustic device models in the trial with bottom set-nets (a - DDD; b – DiD; c - hauls with depredation and no depredation) and for the purse seine fishery (d - all hauls; e - only hauls with the presence of cetaceans during fishing operations). The median, first and third quartile, range of observed values and outliers are shown.

FIGURE 1

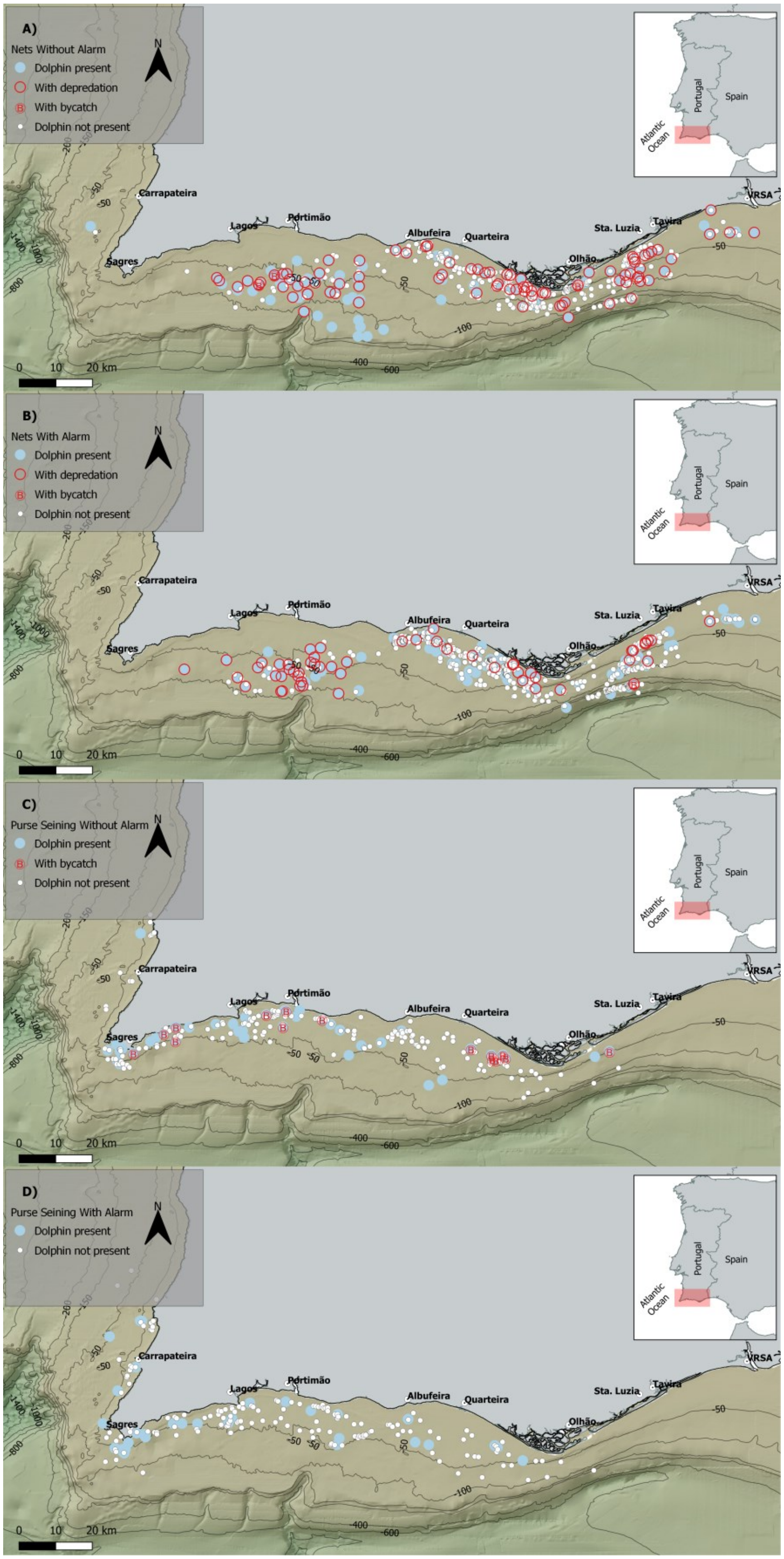

A)
Nets Without Alarm
Dolphin present
With depredation
With bycatch
Dolphin not present
B)
Nets With Alarm
Dolphin present
With depredation
With bycatch
Dolphin not present
C)
Purse Seining Without Alarm
Dolphin present
With bycatch
Dolphin not present
D)
Purse Seining With Alarm
Dolphin present
Dolphin not present
N
Portugal
Spain
Atlantic Ocean
Carrapateira
Sagres
Lagos
Portimão
Albufeira
Quarteira
Olhão
Sta. Luzia
Tavira
VRSA
-50
-100
-400
-600
-800
-1000
-1400
-200
-150
0
10
20 km

FIGURE 2

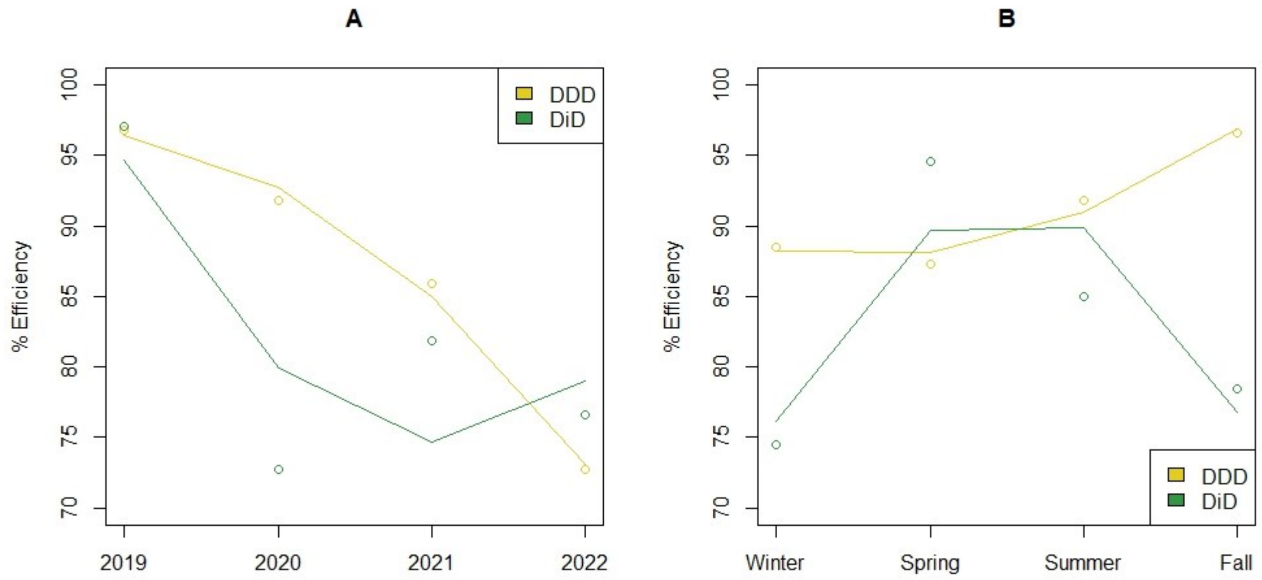
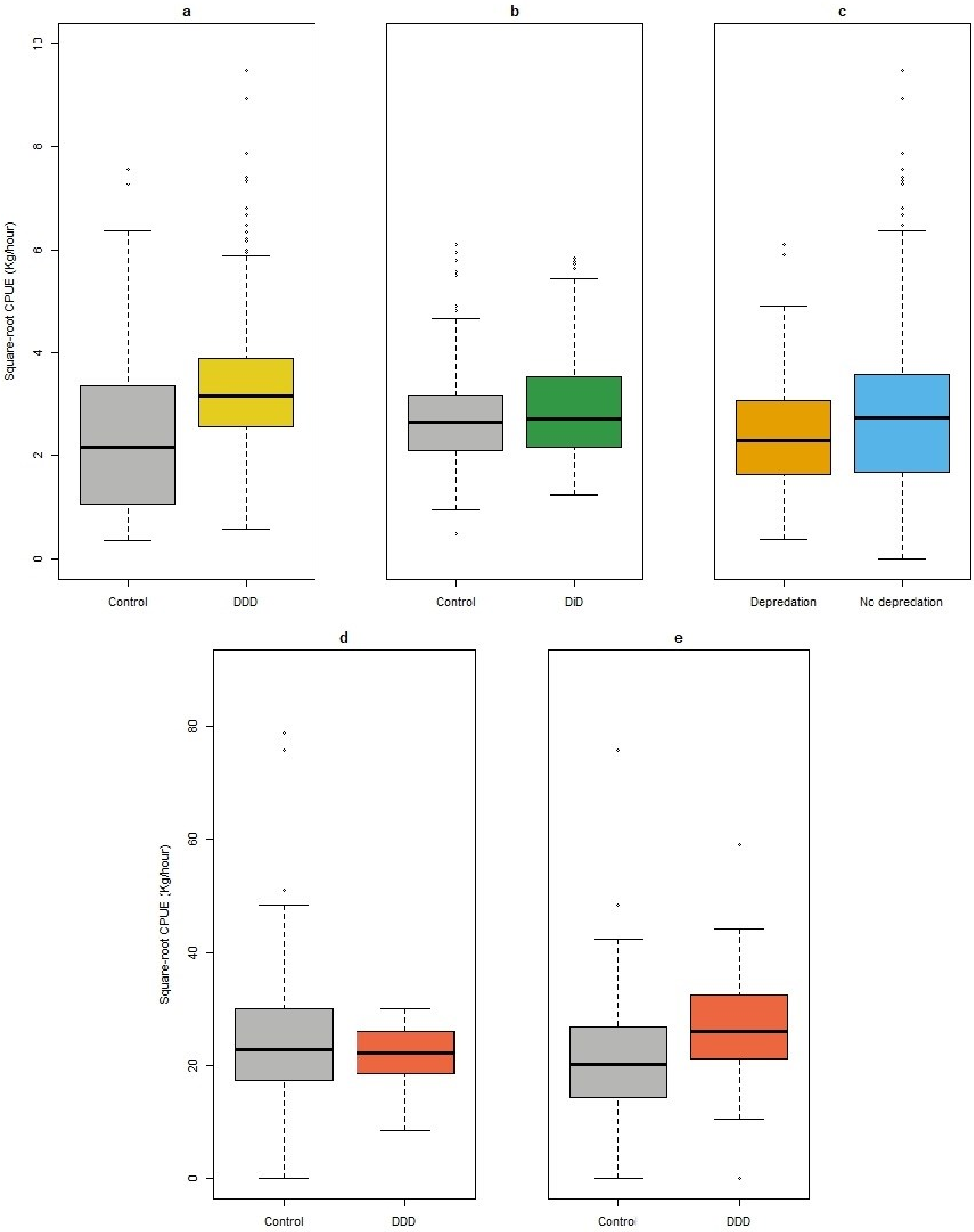

A
% Efficiency
70
75
80
85
90
95
100
2019
2020
2021
2022
🟨 DDD
🟩 DiD
B
% Efficiency
70
75
80
85
90
95
100
Winter
Spring
Summer
Fall
🟨 DDD
🟩 DiD

FIGURE 3


a
b
c
Square-root CPUE (Kg/hour)
0
2
4
6
8
10
Control
DDD
Control
DiD
Depredation
No depredation
d
e
Square-root CPUE (Kg/hour)
0
20
40
60
80
Control
DDD
Control
DDD