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Reducing invertebrate by-catch in a coastal fishery using a raised monofilament trammel net

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ABSTRACT

Trammel nets are one of the least selective fishing gears and are known to catch a variety of species, many of which are discarded, including important invertebrates that are considered habitat-forming species. Although there are few studies focusing on this type of by-catch, these habitat-forming species include corals and sponges that are vulnerable to disturbances from fishing activities using bottom contact gear. Experimental fishing was conducted off the port of Portimão (southern Portugal) from November 2021 to April 2022 using standard and modified trammel nets rigged to be lifted off the bottom with the objective of reducing invertebrate by-catch and impacts on the bottom habitat. The modified lifted net caught 36% less by-catch of invertebrates in numbers than the standard net, with no significant decrease of biomass and value of target species. The results obtained with the two net types are discussed, as well as the necessity for good video recording equipment that can improve sampling accuracy, and the usefulness of interviewing the fishers on net performance after experimental fishing was conducted.

1. Introduction

Commercial fishing activities contribute to the degradation of seabed habitats due to the by-catch of invertebrates that serve as habitat-forming structures and ecosystem engineers. Organisms including corals, sponges, and kelp promote species' recruitment, diversity, foraging areas and reproductive grounds, but they are vulnerable to crushing, severing, or getting buried as a consequence of different types of fishing activity (Sainsbury et al., 1997; Bell, 2008; Fuller et al., 2008). While trawling has been the main focus when addressing ecosystem effects of fishing, static gears are also of concern (Veiga et al., 2016). Although invertebrate by-catch, including crustaceans, echinoderms, and gastropods, has been documented in set nets, including trammel nets, habitat-forming invertebrates have not been explicitly focused on (e.g., Gonçalves et al., 2007; Gonçalves et al., 2008; Metin et al., 2009; Martínez-Baños and Maynou, 2018; Sartor et al., 2018; Szynaka et al., 2018).

Trammel nets and gillnets are extensively used by European fishing vessels, in particular by local and coastal fleets in Southern Europe. In Portugal, they are used by the majority of the vessels of the local and coastal multi-gear fleet (around 5500 vessels and 23 000 GT), in many different fisheries along the entire coast, to catch a great variety of commercially valuable species (Directorate-General for Natural Resources, Safety and Maritime Services - DGRM, 2022). Impacts of trammel nets on benthic species and their habitats can be high; Gonçalves et al. (2007, 2008) reported values up to 50% in numbers of unwanted by-catch, discarded at sea, in trammel nets operating off the Portuguese coast, due to their low selective properties, making these nets one of the main fishing gears negatively impacting coastal benthic communities. The use of gillnets was found to result in some of the highest by-catch rates of habitat-forming structures, with up to 85% of gillnet deployments in the south of Portugal catching corals, and 45% of the corals consisting of entire colonies (Dias et al., 2020). Similar studies in Thermaikos Gulf, Mediterranean Sea, resulted in the occurrence of the Mediterranean-endemic scleractinian coral *Cladocora caespitosa* in 61% of the gillnet hauls, resulting in colony detachment (Ganias et al., 2023a), while in another study, Catanese et al. (2018) found that discards from trammel nets in the Mediterranean contained many

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habitat-forming structures including seagrass, kelp, sponges, and hard corals, as well as a calcareous alga (*Lithothamnion* spp.).

By-catch and discarding are a shared problem worldwide; in the EU, a discard ban (landing obligation) is in force since 2019, along with the recommendation to develop and use more selective and less impactful, innovative fishing gear as a mitigation measure (European Commission, 2013; ICES, 2020). Trammel nets, consisting of three net panels, two outer large mesh size and a single inner small mesh size panel, are less species and size-selective than gillnets (Fabi et al., 2002; Erzini et al., 2006; Karakulak and Erk, 2008). In addition to the catch mechanisms of gillnets (wedged, gilled or entangled), trammel nets mainly catch fish and invertebrates by pocketing or trammeling (Fabi et al., 2002; Erzini et al., 2006).

In trammel nets, the use of a guarding panel, sometimes referred to as "greca", corresponding to a single large mesh panel net placed between the net panels and the leadline, has been tested as a tool for by-catch reduction, when targeting various species including the caramote prawn, *Penaeus kerathurus* (Metin et al., 2009), red mullets, *Mullus* spp. (Aydin et al., 2013), the spiny lobster, *Palinurus elephas* (Catanese et al., 2018), and the cuttlefish, *Sepia officinalis* (Madia et al., 2023). These experiments have resulted in between 17% and 63% reduction in discard rates of by-catch species, along with non-significant decreases in commercial catch. However, in other studies where this type of panel was tested, a decrease in commercial catch of target species, including the cuttlefish (Sardo et al., 2023; Szynaka et al., 2018), the green tiger prawn *Penaeus semisulcatus* (Gökçe et al., 2016), and the caramote prawn *P. kerathurus* (Sartor et al., 2018) was recorded with the use of modified nets, preventing their acceptance by fishers. Only one study reported a significant decrease in discards, mainly invertebrates, and a significant increase in the catch rates of the target species, cuttlefish (Martínez-Baños and Maynou, 2018).

The present study was carried out in order to evaluate the potential of a new, modified raised trammel net designed to reduce by-catch in the cuttlefish (*Sepia officinalis*) trammel net *métier* in southern Portugal. This is one of the ten *métiers* identified by Szynaka et al. (2021) using analysis of landing profiles and validated through the integration of scientific results with Local Ecological Knowledge (LEK), during interviews with fishers (Szynaka et al., 2022). In this fishery, cuttlefish are targeted with 100–120 mm inner panel mesh size trammel nets, in winter and spring, at depths up to 100 m. The main objective of the present study is to compare standard and modified nets in terms of their catch composition (commercial, by-catch and discards), economic yield and the number of invertebrates captured, which translate into associated ecosystem impacts.

2. Materials and methods

2.1. Net design

Two types of net were rigged: a standard trammel net (SN), commonly used in this fishery, and a modified net (AN), raised from the seabed by means of a net panel that is placed between the net and the leadline, made of a thin line mounted in a diagonal pattern, that the fishers called "spider" (*aranha*, in Portuguese; Fig. 1). In the experimental sets a total of 15 net panels, each 45 m in length were used per net type, with three standard and three modified nets alternating five times, giving a total of ten sections (e.g., Standard section one: nets SN1…SN3; Modified section one: nets AN1…AN3, Standard section two: nets SN4…SN6, etc.). Between each section a two-meter gap was used to reduce bias due to fish guidance effect, (Holst et al., 1998) for a total of approximately 1.5 kilometers of net.

The inner and outer panels of both the standard and the modified nets were made of polyamide (PA) monofilament. The inner mesh panel had a 120 mm stretched mesh size (measured knot to knot) of 0.35 mm diameter monofilament, and was 50 meshes high and 1000 meshes long. The two large mesh (680 mm stretched mesh) outer panels were made of 0.60 mm diameter monofilament and were 4.5 meshes high and 200 meshes long. The only difference in the modified net, when compared to the standard net, is the existence of a section that raises the net 20 cm off the bottom, made of 6 mm polyethylene cable inserted between the net panels and the leadline (Fig. 1). The vertical slack (height of the inner panel divided by the height of the outer panel) for all nets was 1.96, while the hanging ratio for all the nets, calculated as the length of the floatline divided by the length of the inner panel, was 0.41.

2.2. Experimental fishing

Experimental fishing took place off the coast of Algarve (southern Portugal), onboard a commercial fishing vessel, with an overall length of 14.24 m, belonging to the coastal multi-gear fleet registered in the port of Portimão (37.1362° N, 8.5377° W) (Fig. 2). A total of 16 experimental fishing trials were conducted from November 2021 to April 2022, during the cuttlefish fishing season, near rocky bottoms, at depths around 50 m on different types of substrates (ranging from mud with gravel and sand components to mixed sediments with pebbles, gravels, and sand and mud in more even proportions). The nets were usually set in the morning and hauled in the afternoon, with a few exceptions. For all the hauls, the soak time was less than 24 hours and there was no significant difference in catch rates ($p > 0.05$) due to soak time. Fishing occurred according to the normal commercial practices employed by the fishers during the sole and cuttlefish season. Two HD resolution cameras (GoPro Hero 7 and 6) were set up on board to record any overlooked individuals in the net, specifically the invertebrate discards, to allow the validation of the by-catch abundance. This was done as the hauling speed is increased when the nets are free of any commercial individuals, and this increase makes it difficult to properly record all individuals caught. The videos were analyzed using VLC (VideoLAN Client v. 3.0.1) to slowdown and observe any individual from the classes indicated, counting each severed piece of sponges as individuals, and in which net type the individual was caught in. A total of 10 videos were analyzed out of the 16 trips due to poor footage quality or technical issues with the GoPros.

The net was hauled with a hydraulic hauler; upon arrival on board,

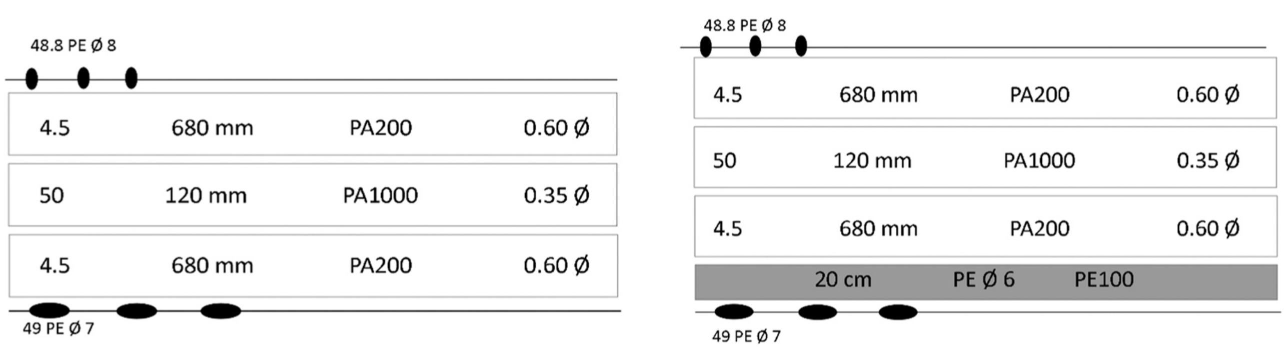

Fig. 1. Technical drawings of the two net types, the standard (left) and the modified net (right).

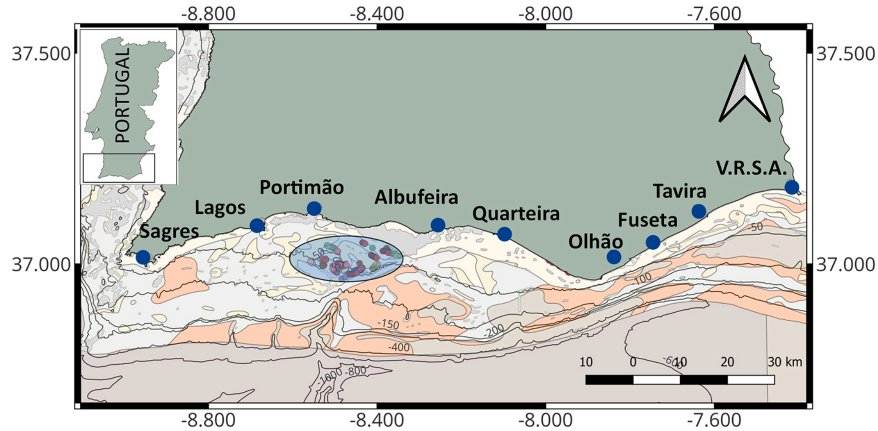

Fig. 2. Map of the Algarve coast with the ellipse representing the general location of the experimental fishing trips, including dots that represent the hauling locations.

each organism was removed manually, assigned the net type in which it was caught, and identified to the lowest possible taxonomic level. The size of individual fishes was measured as the total length, while for crustaceans, the carapace width, and for cuttlefish (*Sepia officinalis*), the mantle length, were measured. Each organism was registered as 'discard' (including by-catch of unwanted species and undersized, predated or scavenged commercial species) or 'commercial' according to the fishers sorting the catch.

2.3. Data analysis

Weight-length relationships were used to estimate biomass in grams of each individual fish (Gonçalves et al., 1997; Santos et al., 2002; Borges et al., 2003; Veiga et al., 2009; Rodríguez-García et al., 2023) from total length in cm (Froese and Pauly, 2022):

$$Biomass = a^{*}Length^{b}$$

The total catch (kg) of each species was converted into value in euros using the average price per kg obtained from the first auction sale (DGRM 2020). The weight of by-catch species individuals was recorded for all hauls in the two net types: SN (standard) and AN ("Aranha" – modified). Catch per unit effort (CPUE) was calculated as the numbers of individuals and the biomass per unit of net length ($CPUE_n$, $CPUE_{kg}$), along with the mean value (euros) per 1000 m of trammel net and the respective standard deviation.

$$CPUE = \left(\frac{i\ of\ individuals}{total\ length\ of\ net}\right)^{*}1000m$$

where the variable 'i' represents either the number (n) or the biomass (kg) of individuals.

Ratios of abundance, biomass, and value (for the commercial catch) of modified net to the standard net were calculated using the following equation:

$$Ratio(SN:AN) = \frac{Modified\ Net}{Standard\ Net}$$

Paired t-tests (Stats package R Core Team, 2022) were carried out after the Shapiro-Wilk test was performed on the log-transformed CPUE data ($p > 0.05$; null hypothesis that the data are normally distributed not rejected). The two-sample Kolmogorov-Smirnov test (Stats package R Core Team, 2022) was used to test for differences in size frequency distributions between the two net types, based on the length distributions of the species with over 100 individuals caught in total over the course of the 16 trips. Furthermore, nMDS (Nonmetric multidimensional scaling) was used for visualizing the similarity between net type (AN = experimental net and SN = standard net) as a function of response variables that were standardized using the CPUE (commercial species CPUE and discard species CPUE), with Season (Fall, Winter, Spring), and trip number (T1…T16) as factors, using the software PAST 4.03 (Hammer, 2020). A PERMANOVA test was performed to look at the interaction between net type and season, followed by a SIMPER analysis to identify the main contributing species and an ANOSIM to observe if the SIMPER results were significant.

2.4. Interviews

Following the trials, preliminary results with CPUEn and CPUEkg of the total commercial catch, the total discarded catch, and the cuttlefish and flatfish captured in the standard and modified nets, were presented to 16 skippers of vessels operating trammel nets, which represent approximately 23% of the total number of vessels using trammel nets in the Algarve. The fishers were asked to give their opinions on the performance of the nets (standard vs. modified net), and which one they believe would be more useful and would be more likely to use in the future. The fishers were asked about the cost per panel of a standard net to understand how prices of the current modified nets compare to what is typically paid for a trammel net panel.

3. Results

3.1. Commercial catch

A total of 418 commercially valuable individuals were caught over the course of 16 trips, with a total weight of 358 kg, and a first sale at auction value of €1870. The standardized values of commercial species caught in each net type are shown in Table 1. A total of 237 individuals (188 kg and €1003) were caught in the standard net (SN) and 181 individuals (170 kg and €866) in the modified "aranha" net (AN). The CPUE for the standard net was 17.41 kg per 1000 m of net (22 individuals per 1000 m of net, with a standard deviation of 12.46) and the VPUE (value per unit of effort) of € 92.91. For the modified net, the CPUE was 15.74 kg per 1000 m of net (17 individuals per 1000 m of net,

Table 1
Mean commercial catch per 1000 m of trammel net in numbers ($CPUE_n$) and biomass ($CPUE_{kg}$), and value (VPUE€) and associated standard deviations (sd) for the modified trammel net (AN) and the standard trammel net (SN). The main target species are in bold.

		Modified Net (AN)						Standard Net (SN)					
Class	Species	$CPUE_n$	sd	$CPUE_{kg}$	sd	VPUE€	sd	$CPUE_n$	sd	$CPUE_{kg}$	sd	VPUE€	sd
Actinopterygii	*Balistes capriscus*	0.18	0.74	0.12	0.5	0.53	2.17	0.83	1.53	0.58	0.98	2.48	4.25
	Dentex canariensis	(-)	(-)	(-)	(-)	(-)	(-)	0.09	0.37	0.20	0.80	3.37	13.50
	Diplodus sargus	0.09	0.37	0.15	0.61	1.22	4.91	(-)	(-)	(-)	(-)	(-)	(-)
	Diplodus vulgaris	0.09	0.37	0.01	0.04	0.02	0.12	0.28	0.60	0.06	0.19	0.15	0.46
	Merluccius merluccius	0.37	0.66	0.14	0.38	0.30	0.81	0.28	1.11	0.04	0.01	0.17	0.06
	Microchirus azevia	**5.28**	**7.24**	**0.72**	**0.97**	**9.26**	**12.51**	**6.67**	**8.72**	**0.94**	**1.21**	**12.14**	**15.69**
	Mullus surmuletus	0.18	0.51	0.05	0.17	1.03	3.20	0.18	0.51	0.09	0.28	1.71	5.35
	Pagellus acarne	0.64	1.32	0.18	0.43	0.92	2.21	0.46	0.89	0.15	0.37	0.77	1.96
	Pagellus bogaraveo	(-)	(-)	(-)	(-)	(-)	(-)	0.64	2.23	0.18	0.69	3.09	11.79
	Pagellus erythrinus	0.83	1.21	0.31	0.52	2.54	4.28	0.83	1.62	0.63	1.44	5.06	11.59
	Pagrus auriga	0.09	0.37	0.21	0.84	2.8	10.76	0.18	0.51	0.21	0.66	2.85	8.88
	Pagrus pagrus	0.09	0.37	0.06	0.26	0.85	3.53	(-)	(-)	(-)	(-)	(-)	(-)
	Phycis phycis	(-)	(-)	(-)	(-)	(-)	(-)	0.37	1.15	0.09	0.32	0.25	0.84
	Sarda sarda	0.09	0.37	0.03	0.15	0.29	1.2	(-)	(-)	(-)	(-)	(-)	(-)
	Scophthalmus rhombus	0.09	0.37	0.07	0.29	0.92	3.82	(-)	(-)	(-)	(-)	(-)	(-)
	Solea senegalensis	0.18	0.74	0.11	0.48	1.52	6.18	0.37	1.15	0.21	0.7	2.81	9.18
	Solea solea	0.46	1.50	0.07	0.27	1.02	3.51	0.37	1.15	0.05	0.17	0.73	2.26
	Sparus aurata	0.09	0.37	0.07	0.27	0.72	2.93	0.37	1.15	0.22	0.69	2.33	7.23
	Trisopterus luscus	(-)	(-)	(-)	(-)	(-)	(-)	0.09	0.37	0.02	0.11	0.08	0.33
	Uranoscopus scaber	(-)	(-)	(-)	(-)	(-)	(-)	0.37	0.86	0.16	0.36	0.68	1.55
	Zeus faber	(-)	(-)	(-)	(-)	(-)	(-)	0.18	0.51	0.09	0.26	0.4	1.13
Cephalopoda	*Octopus vulgaris*	0.18	0.51	(-)	(-)	(-)	(-)	0.18	0.74	(-)	(-)	(-)	(-)
	Sepia officinalis	**4.72**	**3.12**	**7.85**	**6.55**	**39.21**	**32.70**	**5.09**	**3.97**	**6.9**	**5.46**	**34.46**	**27.26**
Elasmobranchii	*Dipturus oxyrinchus*	(-)	(-)	(-)	(-)	(-)	(-)	0.18	0.51	0.71	2.61	2.09	27.27
	Raja brachyura	0.55	1.19	0.98	1.91	2.87	5.60	0.83	1.43	1.17	1.81	3.44	5.32
	Raja clavata	0.55	0.92	1.54	2.87	4.5	8.32	0.46	1.18	1.21	3.10	3.55	9.09
	Raja montagui	0.55	0.92	0.67	1.12	1.98	3.29	0.64	1.08	0.66	1.41	1.95	4.11
	Raja undulata	0.18	0.51	0.7	2.01	2.07	5.90	0.09	0.37	0.32	1.31	0.95	3.84
	Rostroraja alba	0.18	0.74	0.5	2.03	1.48	5.93	0.27	0.81	1.46	4.54	4.26	13.26
	Torpedo marmorata	0.74	1.43	0.89	1.73	2.61	5.09	0.55	1.19	0.48	1.22	1.41	3.57
	Torpedo torpedo	0.09	0.37	0.12	0.5	0.36	1.47	(-)	(-)	(-)	(-)	(-)	(-)
Gastropoda	*Bolinus brandaris*	(-)	(-)	(-)	(-)	(-)	(-)	0.09	0.37	(-)	(-)	(-)	(-)
	Charonia lampas	0.09	0.37	(-)	(-)	(-)	(-)	0.64	0.93	(-)	(-)	(-)	(-)
Malacostraca	*Maja squinado*	0.09	0.37	0.06	0.26	0.24	0.99	0.27	0.81	0.44	1.54	1.69	5.80

with a standard deviation of 9.43) and a VPUE of €80.24. The ratios (SN: AN) for abundance, biomass, and value are 1:0.76, 1:0.90, and 1:0.86, respectively. According to the paired t-test carried out for the net type, regarding the $CPUE_n$, the standard net caught significantly more commercial individuals ($p < 0.05$). However, there were no significant differences between the two net types ($p > 0.05$) in $CPUE_{kg}$ and VPUE.

A total of 106 commercial-sized individuals of cuttlefish (above the minimum landing reference size MLRS or Minimum Conservation Reference Size MCRS, >10 cm mantle length) were caught, totaling 159.44 kg and sold for €795.66 (Regulation (EU), 2019/124). The

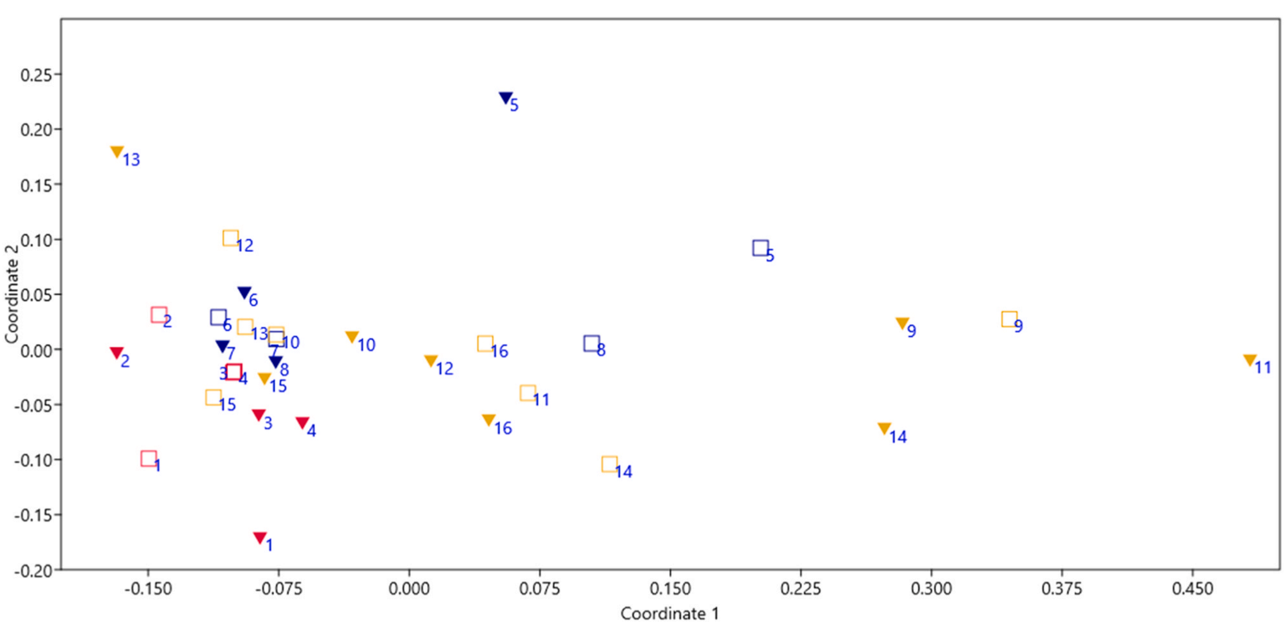

Fig. 3. A Nonmetric multidimensional scaling (nMDS) of the commercial CPUE (catch per unit effort) per gear type (open square – modified net, upside down triangle – standard) and season (crimson – fall, dark blue– winter, and goldenrod – spring) for the 16 trips.

standard net accounted for 52.6% of the number of individuals caught, and 46.8% of both the biomass and value; compared to the modified net which represented 47.4% of the number of individuals and 53.2% in biomass and value. The biomass and value ratio (SN:AN) was 1:1.13, with larger, higher valued individuals being caught in the modified net; the abundance ratio (SN:AN) was 1:0.92. A total of 129 commercial-sized individuals of the bastard sole (*Microchirus azevia*), with a size larger than its MLRS (18 cm), were caught, totaling 17.99 kg and sold for €185.30. The standard net accounted for 57.86% of the total individuals caught, 64.36% of both the biomass and value, compared to the modified net which represented 42.14% of the number of individuals and 35.64% in biomass and value. The biomass and value ratio (SN:AN) was 1:0.69 and the abundance ratio (SN:AN) was 1:0.79. Results of the paired t-test carried out on the combined CPUEs of cuttlefish and the bastard sole indicate no significant differences between the two net types ($p > 0.05$).

According to the nMDS of commercial CPUE, using season and net type as factors (Fig. 3), there is some similarity among the trips regardless of the net type or the season, with some exceptions like the standard net catch during trips 5, 9, 11 and 14 or the catch of the modified net during trips 5 and 9. When looking into the data, it appears that the CPUE of bastard soles is relatively high compared to many of the other trips with three to four other species being caught resulting in small CPUEs. This nMDS resulted in a stress value less than 0.1 (0.077), indicating a very good representation. The interaction between season and net type regarding the CPUEs for commercial species was not significant ($p > 0.05$) according to the two-way PERMANOVA. The overall average dissimilarity of commercial catch rates (CPUE) according to the SIMPER was 82.14 and the main species that contributed to this were the bastard sole, followed by cuttlefish and the common pandora (*Pagellus erythrinus*). However, the ANOSIM showed that the results of the SIMPER are not significant ($p > 0.05$) for both net type and season.

3.2. Discarded catch

A total of 1447 individuals were discarded in 16 trips, with an abundance ratio (SN:AN) of 1:0.92 and biomass ratio (SN:AN) of 1:0.76. Regarding the targeted species, both cuttlefish and bastard soles were discarded due to being under the MLRS, and in some cases due to damage due to scavenging or predation. The primary reason for discarding was the lack of commercial value of the species, with the majority of by-catch belonging to the classes Anthozoa, Demospongiae and Gymnolaemata, and therefore no weight was assigned to the individuals. The individuals of species with commercial value, were primarily discarded due to damage, caused by predation/scavenging. The standardized values of the discarded species caught in each net type are shown in Table 2. The commercial individuals that were discarded were from the taxonomic classes Actinopterygii, Cephalopoda, Elasmobranchii, and Malacostraca totaling 81.53 kg. The standard net represented 52.1% and 53.4% of the abundance and biomass of discards, respectively. Regarding specifically the class Elasmobranchii, there is no difference in catch rates between the net types. The main discarded species included *Axinella polypoides*, *c.f. Desmacidon fruticosum*, *Parazoanthus axinellae*, and *Scomber scombrus*. Concerning the discards, significant differences between the two net types ($p < 0.05$) were found when a paired t-test was carried out on the CPUE in number from the onboard observations. However, there were no significant differences between the two net types in terms of CPUE biomass ($p > 0.05$).

According to the nMDS of commercial CPUE, using season and net type as factors (Fig. 4), there is some similarity among the trips regardless of the net type or the season, with the exception of trip 2 in both net types. Looking into the data, there was a relatively high CPUE of the by-catch species *Scomber scombrus*. This nMDS shows a stress value of 0.113, indicating an acceptable representation (Clarke and Warwick, 1994). The interaction between season and net type regarding the CPUEs for discards was not significant ($p > 0.05$) according to the two-way PERMANOVA. The overall average dissimilarity of discard catch rates (CPUE) according to the SIMPER analysis was 85.62 and the main species that contribute to this were *Parazoanthus axinellae*, *Scomber scombrus*, and *Axinella damicornis*. However, the ANOSIM results showed that the results are not significant ($p > 0.05$) for both net type and season.

3.3. Video analysis

According to the analysis of videos for 10 trips, a total of 1260 individuals from the classes Anthozoa, Demospongie, Gymnolaemata were discarded. Approximately 61.0% of the total number of these individuals was caught in the standard net. Discards included some species such as *Dendrophylia ramea* (considered a rare species and IUCN lack of data) and *Paramuricea cf. grayi* (vulnerable) which are protected under Portuguese Law (Decreto-Lei n.º 38/2021). The paired t-test showed a significant difference between the two net types, with higher catches in the standard net ($p < 0.05$).

3.4. Length distributions

The length frequency distributions of the four most abundant species caught are shown in Fig. 5. The bastard sole had the widest length range, from 12.0 cm to 37.0 cm represented in the standard net (SN) and a reduced length distribution in the modified trammel net (AN) with individuals ranging from 18.9 and 31.0 cm. The mantle length frequency distributions of cuttlefish ranged from 17.5 cm to 41.0 cm for both net types. The longfin gurnard (*Chelidonichthys obscurus*) displayed a length frequency distribution from 18.0 to 28.0 cm in the standard trammel net, while in the modified net individuals were caught ranging between 20.0 and 26.0 cm. The Atlantic mackerel had the smallest length range of the three species, from 21.2 cm to 28.0 cm in the modified net and a narrower distribution in the standard net with individuals between 21.5 and 27.1 cm. The results of the K-S Test showed that none of these length distributions were significantly different between net type.

3.5. Fishers' perceptions

A total of 16 interviews were conducted in five ports in Southern Portugal with fishers of both coastal and artisanal vessels (with an overall length, LOA, above and under 9 m, respectively) who use trammel nets (Table 3). Two vessels in Sagres used trammel nets to catch other species (*Lophius* spp. and *Zeus faber*) with the remainder of the vessels targeting cuttlefish during some part of the year. The inner mesh size used to target cuttlefish and sole varied between 66 mm (used inside the Ria Formosa, a coastal lagoon) and 120 mm stretched mesh (used off the coast), with prices per panel of 45 m ranging between €15 to €26 (just the panel without the buoys, leadlines, etc.) and €60 to €120 (with the leadline, buoys and weights). Their opinion on the performance of the modified nets were noted, with half of the fishers not being convinced or stating that they already attempted a similar design, and it did not function. By comparison, the other half of the interviewed fishers were interested or stated that they would use the modification if it provided good results.

4. Discussion

4.1. Do the raised nets work?

By-catch reduction is often focused on megafauna such as seabirds, marine mammals, and sea turtles caught in fishing gear and often resulting in their death (Lewison et al., 2004; Alexandre et al., 2022). Studies regarding by-catch reduction of invertebrates are not as common, even though invertebrates such as corals and sponges provide architectural complexity and shelter for many species (e.g., Moore et al., 2009; Grabowski et al., 2014; Brownell et al., 2019). They are often

Table 2
Mean discards per 1000 m of trammel net, according to the onboard observations, in numbers ($CPUE_n$) and biomass ($CPUE_{kg}$) and associated standard deviations (sd) for the modified trammel net (AN) and the standard trammel net (SN). Species with a (V) vulnerable, (NT) near threatened, CR (critically endangered) in Europe were classified according to the IUCN (International Union for Conservation of Nature). The main discarded species are in bold.

		Modified Net (AN)				Standard Net (SN)			
Class	Species	$CPUE_n$	sd	$CPUE_{kg}$	sd	$CPUE_n$	sd	$CPUE_{kg}$	sd
Actinopterygii	*Boops boops*	0.37	0.66	0.02	0.07	0.18	0.74	(-)	(-)
	Chelidonichthys lastoviza	0.64	1.08	0.19	0.27	1.85	2.45	0.19	0.25
	Chelidonichthys lucerna	0.09	0.37	0.02	0.09	0.28	0.81	0.02	0.05
	Chelidonichthys obscurus	2.03	2.29	0.33	0.47	2.68	2.82	0.43	0.47
	Dicentrarchus labrax	0.09	0.37	0.13	0.52	(-)	(-)	(-)	(-)
	Diplodus vulgaris	0.09	0.37	(-)	(-)	0.09	0.37	(-)	(-)
	Fish n.id.	1.20	1.81	(-)	(-)	0.64	1.08	(-)	(-)
	Labrus mixtus	0.09	0.37	0.01	0.04	0.18	0.74	0.02	0.06
	Merluccius merluccius	(-)	(-)	(-)	(-)	0.09	0.37	0.01	0.05
	Microchirus azevia	1.75	4.47	0.17	0.49	2.03	5.21	0.17	0.52
	Mola mola	0.18	0.74	0.46	1.84	(-)	(-)	(-)	(-)
	Mullus surmuletus	0.18	0.51	(-)	(-)	(-)	(-)	(-)	(-)
	Pagellus acarne	0.46	1.29	0.06	0.20	0.18	0.74	(-)	(-)
	Pagellus bogaraveo (NT)	(-)	(-)	(-)	(-)	0.18	0.74	0.05	0.23
	Pagellus erythrinus	0.18	0.51	0.02	0.06	0.18	0.74	0.02	0.07
	Sardina pilchardus	0.18	0.51	0.01	0.03	(-)	(-)	(-)	(-)
	Scomber colias	0.74	1.87	0.06	0.12	0.83	2.65	0.03	0.11
	Scomber scombrus	**8.14**	**31.81**	0.75	2.95	**4.90**	**19.63**	0.44	1.80
	Scorpaena notata	0.18	0.51	0.01	0.03	0.55	1.06	0.06	0.11
	Serranus cabrilla	1.20	1.89	0.22	0.26	1.11	1.67	0.16	0.21
	Solea senegalensis	0.09	0.37	0.05	0.19	(-)	(-)	(-)	(-)
	Spicara maena	0.09	0.37	0.01	0.05	(-)	(-)	(-)	(-)
	Trachinus draco	1.01	2.00	0.04	0.07	0.74	1.53	0.05	0.12
	Trachurus trachurus	0.64	0.93	0.06	0.09	0.27	0.81	0.02	0.05
	Trisopterus luscus	0.09	0.37	0.02	0.08	0.37	1.15	0.04	0.11
	Zeus faber	(-)	(-)	(-)	(-)	0.09	0.37	0.03	0.10
Anthozoa	*Octocorallia n.id.*	(-)	(-)	(-)	(-)	0.09	0.37	(-)	(-)
	Dendrophyllia ramea	0.18	0.74	(-)	(-)	0.27	0.81	(-)	(-)
	Eunicella verrucosa (VU)	0.18	0.74	(-)	(-)	0.64	1.32	(-)	(-)
	Leptogorgia sarmentosa	2.96	5.27	(-)	(-)	3.79	5.24	(-)	(-)
	Paramuricea cf. *grayi*	1.85	4.28	(-)	(-)	2.40	5.77	(-)	(-)
	Parazoanthus axinellae	**13.79**	**19.14**	**(-)**	**(-)**	**11.75**	**20.93**	**(-)**	**(-)**
Ascidiacea	*Ascidiiae n.id.*	0.09	0.37	(-)	(-)	(-)	(-)	(-)	(-)
	Phallusia mammillata	0.09	0.37	(-)	(-)	(-)	(-)	(-)	(-)
	Synoicum blochmanni	0.09	0.37	(-)	(-)	0.18	0.51	(-)	(-)
Asteroidea	*Astropecten aranciacus*	0.09	0.37	(-)	(-)	0.55	1.06	(-)	(-)
	Ophidiaster ophidianus	0.18	0.74	(-)	(-)	0.18	0.51	(-)	(-)
Cephalopoda	*Octopus vulgaris*	(-)	(-)	(-)	(-)	0.18	0.51	(-)	(-)
	Sepia officinalis	0.27	0.60	0.15	0.63	0.46	1.18	0.85	2.69
Demospongiae	***Axinella polypoides***	**8.14**	**7.14**	**(-)**	**(-)**	**8.14**	**5.67**	**(-)**	**(-)**
	Cliona celata	0.37	0.66	(-)	(-)	1.66	3.15	(-)	(-)
	Demospongie	0.55	0.92	(-)	(-)	0.37	0.66	(-)	(-)
	Desmacidon fruticosum	**4.35**	**5.26**	**(-)**	**(-)**	**5.64**	**4.63**	**(-)**	**(-)**
	Porifera n.i.d.	0.18	0.74	(-)	(-)	0.09	0.37	(-)	(-)
Echinoidea	*Paracentrotus lividus*	(-)	(-)	(-)	(-)	0.09	0.37	(-)	(-)
Elasmobranchii	*Dipturus oxyrinchus (NT)*	(-)	(-)	(-)	(-)	0.18	0.74	0.05	0.18
	Myliobatis aquila (VU)	0.27	0.60	0.16	0.48	0.09	0.37	0.12	0.49
	Raja brachyura (NT)	0.27	1.15	0.19	0.77	0.18	0.51	0.27	0.86
	Raja microocellata (NT)	(-)	(-)	(-)	(-)	0.09	0.37	(-)	(-)
	Raja miraletus	0.09	0.37	0.02	0.10	(-)	(-)	(-)	(-)
	Raja montagui	0.37	1.15	0.23	0.80	0.27	0.81	0.21	0.69
	Raja undulata (NT)	0.09	0.37	0.22	0.91	0.09	0.37	0.25	1.00
	Rostroraja alba (CR)	(-)	(-)	(-)	(-)	0.09	0.37	0.23	0.92
	Torpedo marmorata	(-)	(-)	(-)	(-)	0.09	0.37	0.21	0.84
	Leucoraja naevus	(-)	(-)	(-)	(-)	0.09	0.37	(-)	(-)
Gastropoda	*Cymbium olla*	0.09	0.37	(-)	(-)	0.37	0.86	(-)	(-)
Gymnolaemata	*Adeonella calveti*	1.94	2.85	(-)	(-)	2.50	5.24	(-)	(-)
	Myriapora truncata	0.64	1.62	(-)	(-)	1.29	4.15	(-)	(-)
	Pentapora fascialis	0.46	1.18	(-)	(-)	0.64	1.32	(-)	(-)
Holothuroidea	*Holothuria arguinensis*	(-)	(-)	(-)	(-)	0.09	0.37	(-)	(-)
	Holothuria forskali	0.27	1.11	(-)	(-)	0.46	1.04	(-)	(-)
	Parastichopus regalis	0.09	0.37	(-)	(-)	0.46	1.04	(-)	(-)
Hydrozoa	*Hydrozoa n.id.*	0.09	0.37	(-)	(-)	0.18	0.74	(-)	(-)
Malacostraca	*Calappa granulata*	0.27	0.81	(-)	(-)	0.18	0.74	(-)	(-)
	Dardanus arrosor	0.74	1.62	(-)	(-)	1.66	1.78	(-)	(-)
	Homola barbata	(-)	(-)	(-)	(-)	0.09	0.37	(-)	(-)
	Maja squinado	(-)	(-)	(-)	(-)	0.09	0.37	0.03	0.14
n.id.	*Bryozoa n.i.d.*	0.27	1.11	(-)	(-)	0.27	1.11	(-)	(-)
Ophiuroidea	*Astrospartus mediterraneus*	3.42	3.66	(-)	(-)	5.55	7.74	(-)	(-)
Polychaeta	*Filograna implexa*	0.18	0.74	(-)	(-)	0.09	0.37	(-)	(-)
Scyphozoa	*Rhizostoma pulmo*	0.83	2.02	(-)	(-)	0.46	0.71	(-)	(-)
Thaliacea	*Pyrosoma atlanticum*	0.27	0.81	(-)	(-)	0.18	0.74	(-)	(-)

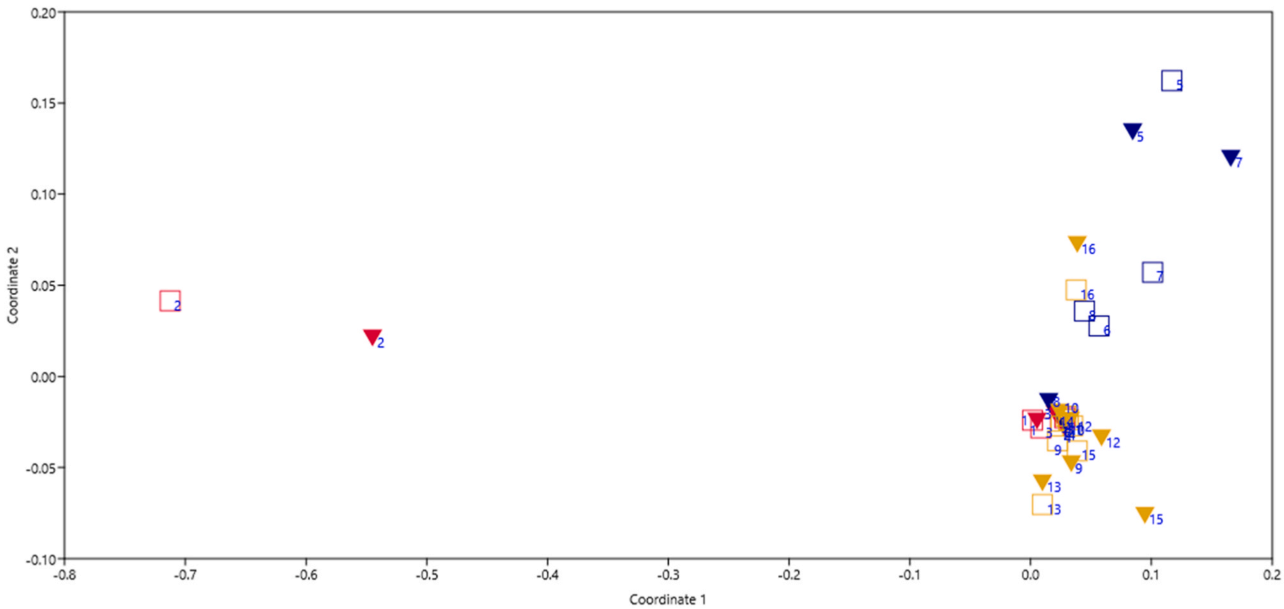

Fig. 4. A Nonmetric multidimensional scaling (nMDS) of the discarded CPUE (catch per unit effort) per gear type (open square – modified net, upside down triangle – standard) and season (crimson – fall, dark blue– winter, and goldenrod – spring) for 16 trips.

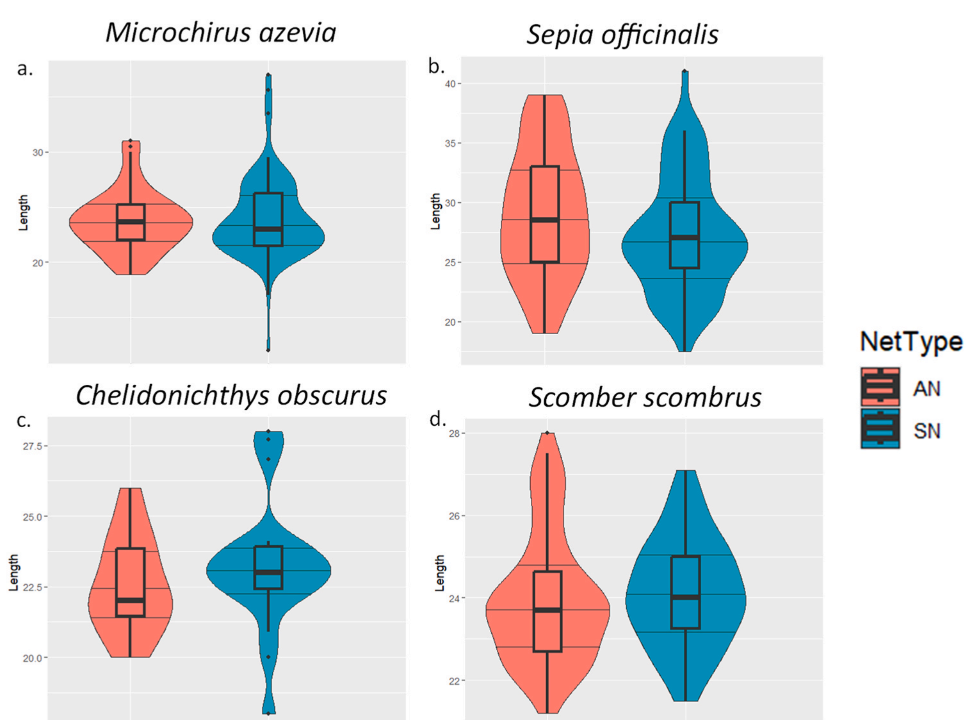

Fig. 5. The length distributions with the quantiles in violin plots for the four main species a. bastard sole, b. cuttlefish, c. longfin gurnard, and d. Atlantic mackerel [AN = "aranha" modified net and SN = standard net].

referred to as "animal forests" which influence hydrodynamics, release nutrients and promote particle retention and carbon fixation (Rossi et al., 2017). Studies regarding by-catch of corals are more common regarding deep-sea fishing, including gillnets and trawls which tend to strip coral coverage (Clark and O'Driscoll, 2003; Dias et al., 2020). While some studies on gillnets were carried out, there are few that highlight the incidental capture of habitat-forming structure species in trammel nets, which could be even more harmful than gillnets towards these species (Gonçalves et al., 2008; Karakulak and Erk, 2008; Shester and Micheli, 2011; Catanese et al., 2018; Dias et al., 2020). The environmental impact of removing these species is either direct, by reducing shelter and food sources for other organisms that rely on these habitat-forming species, increasing competition among them; or indirect, by reduction of filter feeders. There is a need for a better understanding of the ecological roles of the local species and the results of the impacts of extractive activities on them and on the health of the associated ecosystems (Wulff 2001, Fuller et al., 2008).

Similarly to previous studies, specifically those in which guarding nets have been used to reduce by-catch (Metin et al., 2009; Aydin et al., 2013; Catanese et al., 2018), the results of this study show that lifting the

Table 3
Results from the interviews including the métier, the port, the category of boat, the inner mesh side of the respective trammel net, the cost of the panel, and the response (negative or positive) of the vessels from each métier.

Métier	Port	Boat Category	Inner mesh used (mm)	Net panel cost (€)	Fishers' opinion		No. of vessels
					-	+	
1	Olhão	Artisanal	66	100		2	2
2	Olhão, Quarteira	Artisanal	80	25–100	1	2	3
3	Quarteira, Sagres	Artisanal, Coastal	100	66–120	3	1	4
4	Quarteira, Tavira	Artisanal	110	26–75	1		2
5	Olhão, Portimão, Sagres	Coastal	120	15–70	3	1	3
6	Sagres	Coastal	200	80		1	1
7	Sagres	Coastal	240	N.A.		1	1
Total					8	8	16

standard trammel net off the seabed tends to reduce non-commercial invertebrate by-catch, while maintaining the catch rates of demersal target species such as the cuttlefish, with non-significant effects on the catch rates of other commercial benthic species, including various species of soles.

In the present study, results of the modified nets showed there was a non-significant increase in the catch of cuttlefish by weight, and thereby value. A corresponding non-significant decrease in catches was also recorded for flatfish, specifically the bastard sole (*M. azevia*). It is worthy of note that although cuttlefish are the primary target species of this fishery, bastard soles, with high catch rates and value, are an important commercial by-catch in this fishery. While this was expected due to the nature of the net, as it was lifted from the seabed and flatfish are more likely to be entangled near the bottom of a trammel net, it was a smaller difference when compared to that previously observed by Szynaka et al. (2018) when using a modified trammel net equipped with a guarding panel ("greca") between the leadline and the net. The reason may be either due to the difference in height in the net bottom section, 30 cm versus 20 cm in the current study, or perhaps due to the net standing differently in the water column than the one used in previous studies. However, the net behavior could not be compared between the two designs due to the lack of underwater footage data of the modified net from the previous study (Szynaka et al., 2018).

The CPUE ratios of cuttlefish and bastard sole of the standard net to the modified net were 1:0.93 and 1:0.79, respectively, which indicates that the raised modified net was successful in maintaining acceptable catch rates of these commercial species, while in Martínez-Baños and Maynou (2018) more cuttlefish were caught in the modified "greca" net. Size differences were not significant between the two net types regarding cuttlefish, although the modified raised net could have caught larger individuals as these are more likely to move further up the water column than smaller individuals during the night, when they feed (Castro and Guerra, 1989; Quintela and Andrade, 2002).

Regarding discarded catch, some sea sponges, corals, and sea fans were caught during specific trips. Other species were not strongly related to any trips, seasons, or net type. The main discards were sponges and one fish species, the Atlantic mackerel (*Scomber scombrus*). The Atlantic mackerel is sometimes sold as a commercial species when caught in large quantities with other types of gear but is usually discarded when caught in relatively small numbers and sizes by static gears, as was the case in this study. The two most discarded species were the sponges *Axinella polypoides* and cf. *Desmacidon fruticosum*, representing 19.7% of the total discards in numbers. Destroying these types of habitat structures can be problematic for the local environment and the species that depend on them as sponges fill many ecological niches (Folkers and Rombouts, 2020). Destroying the complex, three-dimensional structure of benthic habitats by the direct removal of biological features (e.g., sponges, corals, bryozoans, shell aggregates) has a negative impacts on local ecosystems (Torres-Pulliza et al., 2020). While the IUCN classifies the Atlantic mackerel as a species of least concern (LC), species of sponges are classified as "not evaluated", which means that not only are the impacts of fishing activities on these species poorly known, but also that there is no information on whether these species are vulnerable or threatened by other anthropogenic activities. A sign of concern should be pointed out here, as it is known that sponge aggregations are an important marine habitat, being currently protected in the deep sea, as part of the Vulnerable Marine Ecosystems (VME; FAO, 2016).

However, some other invertebrate species that were caught in these nets are now protected by the Portuguese law and under VME in the deep sea, including species that are pulled up, including the hard coral *Dendrophyllia ramea*, and gorgonians, or soft corals, *Eunicella verrucosa,* and *Paramuricea* cf. *grayi*. Although the catch rates of these vulnerable corals were relatively low over the course of 16 trips, the nets were relatively short compared to the longest possible trammel nets used in Portugal, which can be as long as 20000 m (according to DGRM) or approximately 13.5 times as long as the net in this study, meaning that large quantities can be caught over a short period of time. This clearly requires a need for by-catch and discards management to extend beyond vertebrates. In general, this also produces a positive outcome for the fishers as the reduced catch of such organisms reduces the time spent cleaning of the nets and reduces net damage associated with the catch of these species (Martínez-Baños and Maynou, 2018).

Regarding the other notable by-catch, the vulnerable taxon of Elasmobranchii that were caught in this study are not targeted. Individuals are kept if the fisher sorting the catch considers them fit for selling or for personal consumption, or they are discarded, which is often due to the individual being undersized. These latter include various *Raja* species, the bottlenose skate, *Rostroraja alba*, and two *Torpedo* spp. It is particularly important to note that the undulate ray, *Raja undulata*, and the bottlenose skate are prohibited to be caught and retained according to articles 10 and 13 in the Portuguese Ordinance No. 14/2014. However, the CPUEs of both commercial and discarded individuals are fairly low. By comparison, in a previous study focusing on by-catch reduction in a flatfish trammel net fishery, the main by-catch consisted of elasmobranchs and it was found that decreasing the mesh size of the outer panels resulted in lower catch rates, specifically for the marbled electric ray *Torpedo marmorata,* while maintaining the catch rates of the commercial species (Ganias et al., 2023b).

4.2. Video analysis

It is easier to observe commercial catch as each individual is retrieved from the net and measured. However, depending on the hauling speed, and because the fishers rarely remove the invertebrate by-catch during hauling, but rather at a later time, it is more difficult to assess by-catch efficiently. Despite only being able to analyze the video footage of 10 of the 16 trips due to technical issues with the GoPros, it was possible to improve the accuracy of the invertebrate by-catch analysis. Onboard, 816 individuals from the three classes were observed versus the 1260 individuals observed in the video analysis. Thus, about one-third of the catch was not originally observed in real time. The by-catch of invertebrates was significantly different among the two net types ($p < 0.05$), with the modified lifted net catching 36% less invertebrates of the main by-catch classes.

4.3. Interviews

By-catch can make the work harder for the fishers during hauling periods. Cleaning operations, whether they be onboard or following a trip, can be tedious and time consuming. The presence of by-catch also often results in net damage, reducing the efficiency over time, or the lifespan of the fishing gear. Sartor et al. (2018) reported that the fishers in Ligurian Sea (western Mediterranean) in the caramote prawn fishery discussed how by-catch is a limiting factor to net efficiency, taking up to two days to clean nets, which resulted in an increase of fishers relying on guarding nets. Szynaka et al. (2018) recognized that the results need to be convincing in order to persuade fishers to adopt a new gear or fishing practice. Despite the promising results achieved in the present study, the fishers' perception towards the performance of the modified net, expressed in the interviews, were split. Most fishers were concerned about the reduction in catch of various sole species, and despite showing them that this reduction was not significant, any decrease in earnings was found to be unacceptable. However, taking both cuttlefish and the bastard sole into consideration, the ratio of the landed value of the standard net to the modified net is 1:1.04, and the results of the video analysis point out to a significant decrease in the capture of species that require net cleaning. These results are found to be important for the future adoption of such a modified net. However, since the difference in price between the two types of nets is approximately 22 euros, we do not know if there would be an economic benefit regarding the use of the modified net considering the reduction in net damage compared to the standard net, as this is often what is associated with high costs of fixing or replacing entire panels of the net.

4.4. General discussion

Some of the strengths of this work included standardized materials and methods of the field work based on previous studies and experience in the region, permitting the researchers to focus on the objectives of the project instead of attempting to establish and test new methodologies, which is why it was possible to do fewer trips along the season. In general, an important part of experimental work on board a commercial fishing boat is establishing a proper relationship with the crew to be able to complete the work, and because the researchers have been working in the local ports over many years in previous projects, there was a good relationship with the fishers, allowing a smooth workflow. Due to the consistency in the data collection, it was possible to conduct an analysis focusing on the comparison of the two net types which produced results that show the modification is conducive for fishing within this specific fishery. Regarding the video collection, albeit having technical issues, it was possible to collect more data on species that are not so easy to account for onboard due to large numbers and that would have been otherwise missed and not recorded during real time observation. Interviews also gave some insight regarding the pricing of the typical trammel nets in the region, which is important to keep in mind for future developments of this or any other modifications, as it is well known that one of the main reasons for a new or modified fishing gear not being adopted is the higher cost of modified gear. Also, interviews and discussions with fishers permit dialogue and inform fishers of future changes, while also giving them the opportunity to state their opinions and ideas.

The limitations of the work mainly stemmed from time limitations due to delay in net production (which is dependent on the net makers and how they prepare nets). The weather during the fall and winter season was also a limiting factor, reducing the number of trips due to high winds, storms and rough seas. A net damage assessment was intended on being carried out after the work, but due to misunderstandings, the fishers continued to use the nets, resulting in the nets being further damaged or completely destroyed before any assessment could be made.

In terms of legislation, the Portuguese government currently permits the use of monofilament material for set nets, which is considered a short life span material, usually lasting between three and six months depending on where the nets are used (hard versus soft substrate). An attempt will be made in the future to aid fishers to transition to the use of the more durable, albeit more expensive, multifilament as well as to convince the fishers to use the "aranha" modification. Damaged multifilament nets are usually mended by the local fishers or by net repairers and are rarely thrown away due to damage because of the associated costs. Perhaps, one possible pathway will be subsidizing the first multi-filament "aranha" nets.

When discussing the study itself, similar fisheries that could potentially explore this modification include the cuttlefish and flatfish fisheries in the Mediterranean and in particular those where the greca net was not successful regarding commercial species. It is intended to further expand the studies to explore this modification in other trammel net fisheries as well as expanding to the other commonly used set net, the gillnet. Furthermore, this study exemplifies the need to use videos to collect data on abundance in the case of high volume catch rates in various fisheries to improve accuracy. This can also serve as scientific support for the production of an automated AI system that could identify individuals caught in fishing gear, extending previous work carried out for the Norway lobster (*Nephrops norvegicus*) from trawl video footages collected by IPMA off the Portuguese coast (Lau et al., 2012). Lastly, even though it was not possible to conduct a net damage assessment in this study, it is encouraged to observe damage in experimental fishing nets to explain potential differences in catch rates between the standard nets and experimental nets and loss of income associated with destroyed gear.

5. Conclusions

Using the modified net did not result in a significant decrease of commercial catch, showing even slightly higher sales values for the two target species, cuttlefish, and bastard sole, when combined. Additionally, the *aranha* net successfully contributed to reducing the discards of habitat-forming or bioengineering species, such as corals, gorgonians, and bryozoans, thereby contributing to the protection of bottom habitats and ecosystem. In future studies, it is suggested to use close up images onboard to better evaluate the true difference in by-catch if the individuals are not removed from the nets by the fishers during hauling. They should also include the evaluation of the net damage as it is crucial to understand if there is a difference in durability between the two net types. Finally, interactions with fishers to discuss results and concerns related to the use of the modified net can facilitate the effective adoption of such net modifications and lead to further improvements in fishing gears that can ensure the future of fisheries by actively minimizing environmental impacts.

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CRediT authorship contribution statement

Jorge M.S. Gonçalves: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Karim Erzini:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Aida Campos:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Pedro Monteiro:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Monika Jadwiga Szynaka:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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