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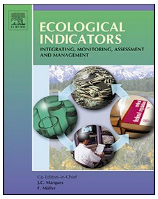

The impact of trammel nets as an MPA soft bottom monitoring method

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ABSTRACT

With the global increase of marine protected area (MPA) implementation, the need for monitoring and the evaluation of their effectiveness becomes ever more important. Currently there is a severe lack of information about the protection effects of soft-substrate ecosystems. While many different methods have been established for the monitoring of hard-substrate ecosystems, most of these minimally invasive methods prove ineffective for soft- bottom habitats. Information and quantification of the impact of monitoring methods is needed to provide decision makers with the necessary knowledge to choose appropriate and feasible monitoring methods. In this study we quantify the impact of experimental trammel net fishing as a monitoring method of the soft-substrate demersal fish community using the Arrábida MPA (Portugal) as a case study. Over the 14 biannual sampling campaigns (between 2010 and 2019) 21,873 individuals and 5.61 tonnes of fish were caught. The gear is highly effective with an average catch per unit effort higher than reported for commercial fisheries in adjacent areas. When excluding the pelagic species, mortality rates are 41.2% and 30.4% in numbers and biomass, respectively. Most of the dead individuals belong to small, non-protected species with relatively little commercial value while MPA conservation target groups such as Soleidae and Rajidae have high survival rates. Due to its low size- and species-selectivity and the high survival rate of protected valuable species, the trammel net experimental fishing proved to be an effective monitoring method for soft-substrate demersal fish communities. Given their relatively low impact on the local ecosystem experimental trammel nets are a good alternative for areas where non-extractive methods are not effective. Nevertheless, quantification of the impact of other monitoring methods is necessary to enable the determination of the methods with the lowest mortality and impact for future soft-substrate MPA monitoring.

1. Introduction

As anthropogenic pressures such as overfishing, climate change, habitat destruction and pollution are threatening the global marine biodiversity and abundance, the role of marine protected areas (MPA) has gained serious international attention in the last decades (Boonzaier and Pauly, 2016; COP, 2010; Wells et al., 2008; Wood et al., 2008). With the rising implementation of these protected areas to meet international conservation targets (Aichi Target 11, Sustainable Development Goal 14), the scientific community emphasizes the need for their appropriate design and subsequent adaptive management (De Santo, 2013; Wood et al., 2008). Marine ecosystems are intricate networks that show diverse and complex responses to established protection over time (Claudet et al., 2010; Lester and Halpern, 2008; Zupan et al., 2018). In order to attain the conservational and socioeconomic goals of the protected areas, regular monitoring is essential to elucidate the responses of the ecosystem and rationalize adaptive management for the future (Fraschetti et al., 2002; Gerber et al., 2005).

In the framework of MPAs the acquired information are primarily biological state-variables such as the dynamics of abundance, species richness, diversity, and size over the course of the protection. Data series for this monitoring can be produced from fisheries-dependent and fisheries-independent surveys. While fisheries-dependent data record the discard and catch of the present fisheries to draw conclusions about parameters such as demographic structure and population dynamics, fisheries-independent surveys are specifically designed to investigate the parameters of interest (Murphy and Jenkins, 2010; Pennington and Strømme, 1998).

In MPAs, where fishing is regulated or prohibited, scientists often must collect data using fisheries-independent methods. Designing fisheries-independent monitoring surveys demands the consideration of efficiency, costs and impact to choose a sustainable and informative method (Gerber et al., 2005; Rotherham et al., 2007). An efficient and feasible monitoring method should present the following characteristics: i) a reduced impact on the ecosystem, ii) a low mortality rate of the monitored organisms, iii) a selectivity of species to monitor and iv)

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Table 1
Overview of common fish assemblage monitoring methods, their advantages and disadvantages, biases and relevant literature (modified from Murphy and Jenkins (2010)).

Method	Advantages	Disadvantages	Biases	Literature
Gill net	No depth restrictions, Works in turbid water	Extractive – unknown mortality rate	Low species selectivity, Size-selectivity depends on mesh size	Fabi et al. (2002); Gray et al. (2005); Karakulak and Erk (2008)
Line and hook	No depth restrictions, Works in turbid water	Extractive – low catch mortality (mean 4.8%, 1.3 – 22.5%); mortality depends on hooks, fishing depth and species (Götz and others 2007)	Very size- and species selective, Selectivity depends on bait, inter- and intraspecific competition	Alós et al. (2008); Erzini et al. (1996); Götz et al. (2007); Løkkeborg and Bjordal (1992); Willis et al. (2000)
Purse Seine	No depth restrictions, Works in turbid water	Extractive – unknown mortality rate	Samples either pelagic or disrupts benthos for demersal sampling	Cailliet et al. (1979); Erzini et al. (2002); Tsagarakis et al. (2012)
Trammel Net	No depth restrictions, Works in turbid water	Extractive –mortality rate explored in this study	Low size- and species selectivity	Batista et al. (2009); Borges et al. (2001); Depestele et al. (2009); Karakulak and Erk (2008); Sousa et al. (2008)
Trap	No depth restriction, Works in turbid water	Extractive – low mortality rate depending on deployment time (not quantified), Less recordings than BRUV	Size- and species selective, Selectivity depends on bait	Harvey et al. (2012); Mahon and Hunte (2001)
Trawl	No depth restrictions, Works in turbid water	Extractive – unknown mortality rate, More epifauna bycatch than trammel Nets, Large impact on benthos	Mainly size selective, Large mobile species avoid trawls	Cappo et al. (2004); Depestele et al. (2009)
VISUAL: Baited remote underwater video (BRUV)	Depth limitation depends on camera case (large depths possible, Minimal impact on ecosystem and fish, Habitat feature info, Reliable size measurements with Stereo-BRUVs	Needs high water clarity, Battery and data storage limitations	Attracts scavengers and predators, Recounting	Cappo et al. (2004); Lowry et al. (2012); Willis et al. (2000)
Remote operated vehicle (ROV)	No depth restrictions, Minimal impact on ecosystem and fish, Habitat feature info, Flexible transect alteration	Needs high water clarity	Attraction and repulsion of fish, Recounting	Sward et al. (2019)
Underwater visual census (UVC)	Habitat feature info	Needs high water clarity, Trained divers, SCUBA limitations (depth and time), Influences fish behaviour	Size and distance bias, depending on experience, Recounting	Lowry et al. (2012); Willis et al. (2000)
Diver operated video (DOV)	Minimal impact on ecosystem, Habitat feature info, Reliable size measurements with stereo-video	Needs high water clarity, Trained divers, SCUBA limitations (depth and time), Influences fish behaviour	Attraction and repulsion of fish, Recounting	(Goetze et al., 2015; Boavida et al., 2016)

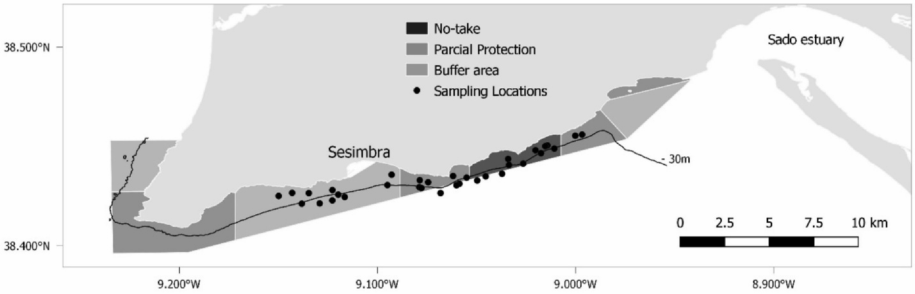

Fig. 1. Map of the Trammel net sampling points in the different protection levels of the Prof. Luiz Saldanha Marine Park (PLSMP).

a low cost of both effort and finance. Even though soft-substrate ecosystems make up over 75% of the global inner shelf area (Hayes, 1967) and the majority in most MPAs (Caveen et al., 2012; Fetterplace, 2017), Caveen et al. (2012) identified a severe lack of MPA effect research of soft-sediment habitats. Soft-substrate ecosystems provide a habitat for many fish species, both specifically adapted (such as many ray, skate and flatfish species) and during transition between hard-substrate habitats. More recent research furthermore indicates that soft-substrate fish populations respond differently to protection than hard-substrate ones (Fetterplace, 2017; Sousa et al., 2018).

While there are many low-impact monitoring methods for hard-substrate ecosystems that are non-extractive and minimally invasive (Murphy and Jenkins, 2010) most of them are not suitable for soft-substrate monitoring. This is mainly due to the low visibility, lower fish density and extension to deeper waters (Caveen et al., 2012). Alternative methods, which are not based on high water clarity, diving surveys or high species density, are mostly extractive thus causing a higher impact on the surveyed ecosystem (Table 1). Experimental fishing is a common fisheries-independent monitoring method, where a fishing gear is used to assess the biological parameters of a fish stock or assemblage (Pennington and Strømme, 1998). In contrast to commercial fishing, the catch is released back into the water and dead individuals are only taken if needed for identification purposes or for fisheries biology and ecology research. Thus, these extractive monitoring methods differ significantly from their commercial analogue and their effectiveness cannot be evaluated using the same parameters (Rotherham et al., 2007). For example, discard and by-catch rates, which are regularly evaluated for fishing métiers, elucidate the selectivity of the used gear but generally do not distinguish between dead target species and non-commercial species that are discarded alive. The vitality of the caught individuals is of crucial importance for evaluating the economic and ecological impact of an extractive monitoring method.

Only few extractive methods have been tested, characterized, or quantified thoroughly in the scope of MPA monitoring (Bennett et al., 2009; Götz et al., 2007). This knowledge gap can lead to time-series surveys that may cause unnecessary disturbance of the ecosystems, which were initially managed to be protected from such anthropogenic pressures. To sustainably manage MPAs, the performance, potential impact on the ecosystem and the resulting effectiveness of monitoring methods should be evaluated critically.

Trammel nets are an important artisanal gear in southern European countries and their by-catch, discards (Aydin et al., 2013; Coelho et al., 2005; Gonçalves et al., 2007), selectivity (Erzini et al., 2006; Gray et al., 2005) and impacts (Depestele et al., 2009) have been assessed thoroughly in the context of commercial fisheries. Because of their low species- and size-selectivity (Erzini et al., 2006), while causing little benthic disturbance (Depestele et al., 2009), trammel nets have been used successfully to identify protection effects (Seytre and Francour, 2008; Sousa et al., 2018) and have the potential of being effective monitoring methods for soft-substrate assemblages. Nevertheless, mortality and impact remain to be quantified and compared empirically to other alternatives to evaluate their feasibility.

In this study we quantify the impact of the experimental trammel net monitoring program of the Prof. Luiz Saldanha Marine Park (Arrábida, Portugal). Both hard- and soft-substrate habitats have been monitored using various monitoring methods over the years (Henriques et al., 1999, 2013; Horta e Costa et al., 2013; Sousa et al., 2018). Here we assess the impact of using experimental trammel nets as a monitoring tool for soft-substrates. We analysed the fish catch data from 14 trammel net survey campaigns that were conducted between 2010 and 2019. The ecological and economic impact of trammel net monitoring on the ecosystem and the region is evaluated and these implications are subsequently compared with other alternative methods. Finally, conclusions are drawn for monitoring soft-substrate habitats in other marine protected areas of the world.

2. Material and methods

2.1. Study area

The Prof. Luiz Saldanha Marine Park (PLSMP) is located off the coast of Arrábida, Portugal and encompasses a total area of 53 km^2 along 38 km of coastline. This multi-use MPA was designated in 1998 (no-take zone implemented in 2009) as part of the Natura 2000 Network reaching from the Cabo Espichel (38° 27′ N, 9° 12′W) to the mouth of the Sado estuary (38° 29′N, 8°57′W; Fig. 1). Most of the coastline is exposed towards the South, thus sheltering it from the prevailing north-northwest winds and swells. Located in proximity of the northern limit of the north-east-Atlantic upwelling events (Wooster et al., 1976) and cold temperate water masses, this MPA lies in an oceanographic and biogeographic transitional zone (Henriques et al., 2009). Thus, Arrábida combines the northern distribution limit for some subtropical species and the southern limit for temperate northern species (Henriques et al., 2009), making it a unique biodiversity hotspot (Henriques et al., 1999). The abundance of many marine organisms has been exploited by small-scale artisanal fisheries from the harbours of Sesimbra and Setúbal for centuries. With many livelihoods depending on the productivity of the PLSMP and its surrounding areas, monitoring the development of the ecosystem and the effects of the different levels of protection is essential. Comprehensive data is the foundation to inform decision makers and stakeholders about the status of the MPA and adaptive management measures to attain the socio-economic and conservation goals.

2.2. Experimental trammel net fishing

In this study the fisheries-independent data set from 342 experimental soft-substrate trammel net deployments was analysed to determine the ecological impact of this survey method. In the framework of several monitoring programmes (BIOMARES, BUFFER, INFORBIOMARES), a total of 14 experimental fishing campaigns were conducted in spring (March – May) and autumn (October – December) from 2010 to 2019 except from summer 2015 to summer 2018 due to lack of funding. A sampling design to sample each protection level with several replicates, divided into shallow - sand (12–20 m) and deeper - mud (28–56 m) within the marine park, and outside of the protection in a deeper area (70–83 m) was implemented (Fig. 1).

The fishing was done on board a licensed commercial fishing vessel from Sesimbra with the help of local fishermen. Trammel nets (500 m in length, 1.6 m high, 500 mm stretched mesh outer panels and 100 mm inner panel) were deployed parallel to the coast for a maximum of 24 h. This set-up was selected as it corresponds to the one most commonly used by the local artisanal fisheries (Batista et al., 2009) and due to its low size-selectivity (Erzini et al., 2006). Time of deployment, water temperature, location, start and end of retrieval were recorded. During the retrieval of the nets, two observers identified all individuals and recorded total length (to the lower half cm) and vitality before releasing them back into the water. Fish were considered "alive" if they showed respiratory clues, unimpaired reflexes (Davis, 2010) or were seen swimming actively after being released. If none of these applied or there was visible damage, fish were recorded as "dead". For this study only records of fish identified to species level were used and their biomass was calculated using length – weight relationships from FishBase (Froese and Pauly, 2010). Catch per unit effort (CPUE) was calculated as abundance and biomass per 1000 m and 24 h for each deployment. From the fish biomass, an estimated market value was calculated according to the average 2017 species market value per kilogram of the Sesimbra fish auction, obtained from the general directorate of natural resources, security and maritime services (DGRM – Direção-Geral de Recursos Naturais, 2018). Species were furthermore classified by their IUCN red list protection status (Red-List, 2019) and if targeted by local fisheries or not. A students *t*-test for paired means was used to assess differences between the mortalities of the overall fish catch and excluding pelagic species. An unpaired *t*-test assuming unequal variances was used to evaluate the differences between the mean mortality of deployments over muddy and sandy substrate. For all statistics a significance level of $\alpha = 0.05$ was applied. All analyses were performed using R (R Core Team 2019).

3. Results

During the 14 campaigns, a total of 21 873 fish were caught making up a total biomass of 5.61 tonnes (Fig. 2). With a summed net length of 186 500 m, this translates to an average CPUE of 117 individuals/1000 m per 24hrs and 30.1 kg/1000 m per 24hrs. Of all fish, 8 570 (39.2%) were released alive and 13 197 (60.3%) discarded dead, while 106 (0.5%) were missing the vitality record. Of the total biomass, 3.22 t (57.4%) were released alive, 2.33 t (41.5%) dead and 0.06 t (1.1%) without vitality record (Fig. 2). Excluding the pelagic fish, there was a highly significant decline of mean net mortality (*t*-test p-Value < 0.0001): 58.2% of the caught individuals were released alive and the mortality rate declined to 41.2%. This decline was also observed in the mean deployment mortality rates by biomass (*t*-test p-Value < 0.0001), with 68.4% of the total biomass being released alive and 30.4% dead (Fig. 3). The total estimated commercial value of the fish catch was 24 807 €, whereof an estimated value of 17 782 € (71.8%) was released alive and 6 769 € (27.3%) dead.

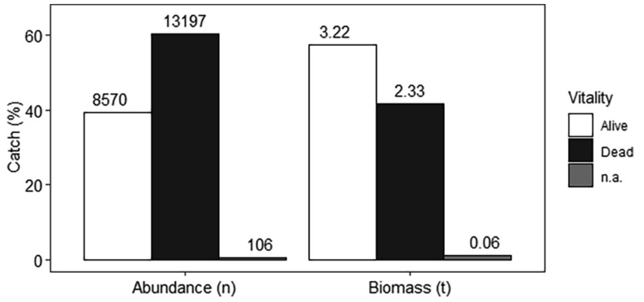

Fig. 2. Bar plot of the dead, alive and not recorded proportion of the total fish catch from 2010 to 2019 by abundance (n) and biomass in tonnes.

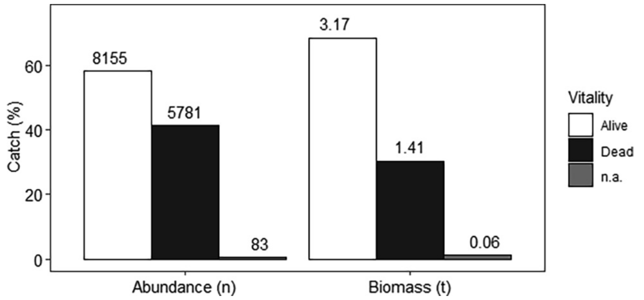

Fig. 3. Bar plot of the dead, alive and not recorded proportion of the fish catch excluding pelagic species from 2010 to 2019, by abundance (n) and biomass in tonnes.

To evaluate the overall catch proportion of commercially targeted species and the resulting survival rate, the biomasses and numbers of targeted and non-targeted species were computed (Table 2).

Commercially targeted fish made up 91.6% of the total fish catch in numbers and 95.3% in weight (Table 2). The mortality rate of targeted fish is higher in number (61.8% targeted, 44.3% non-targeted) but lower in biomass (41.2% targeted, 47.1% not targeted) than non-targeted species. The highest mortality rate can be observed for the one endangered species (EN), followed by species of least concern (LC). Near threatened (NT) species show large differences between the mortality by number (42.5%) and by biomass (4.1%), indicating a higher mortality of smaller individuals. Notably, critically endangered (CR) species present by far the lowest mortality rate ($< 5\%$), followed by data deficient (DD) ones.

As pelagic fish are not targeted by this fishing gear and reveal a strong difference in mortality, we separated pelagic fish and non-pelagic fish, looking at the most frequent species ($> 2\%$ of either total number or biomass) and their mortality rates. Non-pelagic fish made up 64.1% in numbers and 82.7% in weight of the total fish catch, being dominated by *Soleidae, Rajidae, Triglidae, Merluccidae* and *Batrachoididae* families in descending order of importance in terms of biomass. Most pelagic fish belonged to the *Scombridae* family (Table 3 and Supplementary Material Table ii).

The difference between the two mortality rates (by number and weight) of all frequently caught species is $< 6\%$ (Table 3). Of the 11 frequently caught non-pelagic species, 3 had mortality rates exceeding 50%, with *Merluccius merluccius* exhibiting the highest ($> 97\%$). Of the commercially commonly targeted species *Solea solea* and *Solea senegalensis,* over 85% were released alive in both number and biomass. Also, the two threatened, frequently caught ray species *Raja clavata* and *Rostroraja alba* have low mortality rates, with over 85% in number and biomass released alive.

Overall, the pelagic fish species have a very high mortality rate of 94.4% in numbers and 94.9% in weight with all 3 of the frequently caught species exhibiting mortality rates of over 85% in number and weight. *Scomber colias* was the most frequently caught pelagic fish, with over 95% mortality in numbers and in biomass.

To assess the impact of the trammel net method on sandy versus muddy soft-substrate fish assemblages, we compared the mortality rates between net deployments of the different substrates. The mean mortality of the deployments on mud were significantly higher (mean = 53.2%, p-value < 0.0001) than the ones on sandy substrate (mean = 43.3%).

4. Discussion

With a total fish catch of 21 873 individuals of 96 different fish

Table 2

Proportion of commercially targeted fish, non-targeted, and protected species by abundance and, biomass in tonnes and the corresponding mortality rates. Protection status as in IUCN Red-List (2019) with number of species in brackets: DD – Data deficient, LC – Least concern, NT – Near threatened, VU – Vulnerable, CR – Critically endangered, NA – no protection level established.

	Abundance (number of individuals)				Biomass (tonnes)				Total abundance	Total biomass
	Alive	Dead	NA	Mortality rate	Alive	Dead	NA	Mortality rate		
Non target	1003	811	17	**44.3%**	0.139	0.125	0.002	**47.1%**	8.4%	4.7%
Target	7567	12,386	89	**61.8%**	3.082	2.205	0.060	**41.2%**	91.6%	95.3%
Conservation status										
LC (n = 74)	6740	12,617	88	**64.9%**	1.582	2.078	0.015	**56.5%**	88.9%	65.5%
NT (n = 5)	348	259	3	**42.5%**	0.774	0.033	0.004	**4.1%**	2.8%	14.5%
VU (n = 6)	417	181	5	**30.0%**	0.240	0.155	0.004	**38.9%**	2.8%	7.1%
EN (n = 1)	6	39		**86.7%**	0.006	0.032	0.000	**85.1%**	0.2%	0.7%
CR (n = 1)	140	3	5	**2.0%**	0.249	0.003	0.034	**1.1%**	0.7%	5.1%
DD (n = 9)	919	98	5	**9.6%**	0.370	0.027	0.003	**6.8%**	4.7%	7.1%
Grand Total	**8570**	**13,197**	**106**	**60.3%**	**3.221**	**2.329**	**0.061**	**41.5%**		

Table 3

Mortality rate and proportion of the total fish catch (2010–2019) by number and biomass of the 14 most frequently (> 2% of the total abundance or biomass) caught species.

Species	Catch proportion		Mortality	
	Abundance	Biomass	Abundance	Biomass
Non-pelagic fish	**64.1%**	**82.7%**	**41.2%**	**30.4%**
Chelidonichthys lastoviza	4.0%	2.6%	35.1%	35.8%
Chelidonichthys lucerna	2.7%	3.4%	23.1%	22.8%
Chelidonichthys obscurus	4.3%	1.8%	76.6%	75.2%
Halobatrachus didactylus	2.1%	3.7%	1.3%	1.3%
Merluccius merluccius	4.6%	8.5%	97.5%	98.3%
Microchirus azevia	18.1%	12.4%	33.7%	27.8%
Mustelus mustelus	0.7%	4.7%	54.4%	54.7%
Raja clavata	1.3%	12.4%	2.1%	2.0%
Rostroraja alba	0.7%	5.1%	2.0%	1.1%
Solea senegalensis	3.8%	5.7%	6.0%	5.4%
Solea solea	2.5%	3.7%	14.0%	12.6%
Pelagic fish	**35.9%**	**17.3%**	**94.4%**	**94.9%**
Boops boops	2.7%	1.2%	87.9%	87.6%
Scomber colias	25.9%	13.1%	95.4%	95.8%
Trachurus trachurus	4.0%	1.2%	90.6%	89.1%
All fish species	**100%**	**100%**	**60.3%**	**41.5%**

species (some exclusively found on soft-substrates) with a size range from 1.5 cm to 140 cm, the trammel net soft-substrate monitoring method yielded a comprehensive data set with a robust sample size for the successful analysis of MPA effects (see Sousa et al., 2018). Of all fish, 60.3% of the individuals and 41.5% of the biomass died during the sampling and were discarded.

4.1. Performance of the experimental trammel net monitoring

The overall CPUE in numbers (117.4/1000 m/24hrs) and biomass (30.1 kg/1000 m/24hrs) is almost threefold higher than the ones reported by Batista et al. (2009) for fishing vessels from Setubal and Sesimbra adjacent soft-substrates outside the MPA, and lies within the upper range of the CPUE reported for various European trammel net fisheries (Gonçalves et al., 2007). This high catch per unit effort is indicative of the combination of a high biomass within the MPA, protection effects, and the efficiency of the used trammel nets as a fishing method. The mortality of fish (60.3% by number and 41.5% by biomass) is far higher than the one presented by Götz et al. (2007) for selective hook and line surveys (see 4.3). For monitoring reserve effects in highly diverse fish assemblages, the impact is difficult to put into perspective due to the absence of information on fish mortality of the monitoring methods. No single critical evaluation of this parameter could be found in the literature for other extractive MPA monitoring methods, even though the mortality of individuals is an essential metric to assess the environmental impact and feasibility of monitoring methods.

The mortality rate decreases drastically when considering the biomass (from 60.3% by number to 41.5% by biomass). Such a decrease can be attributed to a higher mortality rate of small individuals compared to large ones. A similar pattern was found by Batista et al. (2009) in the form of damage. This could be caused by two factors i) the higher rate of gilling of small fish (Gray et al., 2005), and/or ii) the lower tolerance of physical extremes (Sogard, 1997). The minimum size of fish which are gilled is influenced primarily by the inner mesh size (Erzini et al., 2006; Gray et al., 2005). The size used in this study (100 mm) is the smallest allowed by Portuguese legislation and captures fish of even few centimetres total length. Gonçalves et al. (2007) found a decline in discards with increasing mesh size in the Algarve, southern Portugal. The choice of a larger inner mesh (e.g. 140 mm) could reduce the number of small individuals caught significantly (Gonçalves et al., 2007; Stergiou et al., 2006). If fished consistently this would still allow the monitoring of many target species especially rays and *Soleidae*. As the number of species is not significantly changed using larger mesh sizes, information on species composition and diversity should still be viable. Nevertheless, information about the relative abundance of juvenile life stages provides essential knowledge for evaluating recruitment and disentangling different MPA effects. Furthermore, the used mesh-size identical to regional commercial trammel nets allows for better comparison to fisheries dependent data.

Pelagic fish, which are highly mobile and are not targeted by trammel nets, made up 35.9% of the catch by number and 17.3% by biomass. Their lack of site fidelity and high mobility and abundance can produce confounding results when looking at MPA effects, for which reason they are often excluded from further analysis (Sousa et al. 2018). Pelagic fish can thus be considered a by-catch of this method.

4.2. Implications for the ecosystem and economy

The impact of the trammel net demersal fish monitoring can be divided into different aspects: i) the impact during the sampling on the benthic community, ii) the impact on the ecosystem through the individuals which were released alive and the ones that were discarded dead, and iii) the implications this monitoring method has for the local community and stakeholders.

As trammel nets are stationary and, in this case deployed on soft substrate, the damage of the benthic community is restricted to a minimal disturbance of the epibenthos during the deployment and the retrieval of the nets. Depending on the current and the experience of the skipper, the anchors, and the net itself can be dragged over the seafloor. This sometimes resulted in entangled epibenthic organisms (predominantly *Atrina pectinata*) on the deeper deployments. Overall, this impact is very low when deployed on homogeneous soft substrate. Due to the slow hauling time, low sampling depth, the high rate of entangling and the dispersed direct release of sampled fish in the same location where they were caught, the stress on the sampled fish is relatively low. As the fate of sampled fish and the error (type 1 and 2) of the vitality classification are highly complex and discussed thoroughly in other studies (Davis, 2010; Heath et al., 2014; ICES, 2014), this study is focused on the overall impact and efficiency. The by-catch of pelagic fish (35.9% by count and 17.3% by biomass) with high mortality rates (> 90%) is not ideal but it is assumed to have a low impact on the local ecology and economy. All three frequently caught pelagic fish are migratory species, with a high reproductive capacity and are not permanent residents of the area (see species parameters in Froese and Pauly (2010)). Compared to the commercial fishery targeting the same populations of *Trachurus trachurus* and *Scomber colias* with purse seine nets offshore, the average annual catch during the monitoring campaign of 130 kg is minute. Thus, the death of this amount of pelagic species has only minor effects on the coastal ecosystem of the MPA.

The results for the different conservation status categories show a very high mortality rate of the endangered species *Cynoscion regalis* of over 85%. Even though this species is classified as endangered in the west Atlantic, it is a non-native species in Portugal. While further research is necessary to assess the effects of their introduction, the early maturity, and high fitness and appetite warrant a potential reduction of their prey species as well as the out-competition of native species (such as *Dicentrarchus labrax* or *Argyrosomus regius* – Gomes et al., 2017; Morais and Teodósio, 2016). We thus focus on the ecological impact on protected native species: High mortalities are found for species of low protection (LC, NT and VU) and the lowest mortalities for species classified as data deficient (DD) and critically endangered (CR). Thus, the most important species from a conservation point of view have high survival rates and remain in the ecosystem to grow and reproduce. Many of the threatened species (CR and VU) are elasmobranchs, with *Rajidae* being caught most frequently (see Supplementary Material Table iii). Due to their planar shape, the rays often got trammelled (trapped in large pockets of the trammel net, see Losanes et al. (1992)) and could be liberated without any damage. The large proportion and high mortality in numbers of the near threatened (NT) category can be mainly attributed to pelagic fish such as *Sardina pilchardus*.

The mortality rate of the 14 most frequently caught species highlights the strong interspecific variations of tolerance for capture and different capture mechanisms. The commercially frequently targeted species *Merluccius merluccius* exhibits a very high mortality of over 95% and was often found damaged and scavenged by invertebrates. Most hake move from deeper (100–200 m) to mid- and surface waters at night to feed (Hickling, 1927; Papaconstantinou and Caragitsou, 1987). It is thus probable, that they get caught by the trammel nets, either during this diel migration or when feeding in shallower waters at the beginning of the night. Thus, the time in the net is long, leading to increased damage and mortality. *Mustelus mustelus* also displays high mortality rates (> 50%) but was caught only rarely (0.7% of the total catch in numbers). In contrast, the two commercially important sole species *Solea solea* and *Solea senegalensis* were frequently released alive. These are two of the main target species fished by local trammel net fisheries (Batista et al., 2009). Using the same fishing gear in the same area, Abecasis et al. (2014) found a low post-release mortality using acoustic telemetry. The live-release of over 85% of all caught soles thus indicates that the ecological impact on the local *Solidae* populations is relatively low.

The comparison between sandy and muddy substrates showed an increased mean mortality of deployments on mud. We attribute this to a combination of two main factors: i) differences between the fish assemblages of the substrates (as shown by Sousa et al., 2018) and their inherent resilience to the method; ii) the deeper water depths of mud deployments resulting in more pronounced barotrauma effects. Both factors should be considered when designing a fish assemblage survey to reduce the impact of the monitoring.

The handling of fish can result in diverse lethal and sublethal post-release effects such as reductions in feeding, growth, or reproduction (Ellis et al., 2017; Wilson et al., 2014), which are not considered in this study. To provide more accurate information on long term ecological effects, post-release mortality should be investigated (e.g. using biotelemetry or cage experiments) and sublethal effects such as potential reduction of fitness and reproduction taken into account.

With the fishermen being the most directly impacted stakeholders of the MPA, an analysis of the effect on the exploitable fish stocks is relevant. Even though 90% of the fish caught are targeted by commercial fisheries and 2.33 t of the total catch were released dead over 14 sampling campaigns, a detailed exploration of the mortality rates and dead fish reveals a less impacting picture of this method. Looking at the estimated value of the catch, fish with a total value of 17,556 € (71.8%) were released alive and 6,796 € (27.4%) dead. This indicates that most of the valuable fish were returned alive, giving them the opportunity to grow, reproduce and multiplying the exploitable fish stocks and their value. This is demonstrated by the low mortality rates (< 25%) of frequently targeted and valuable species such as *Solea solea, Solea senegalensis, Chelidonichthys lucerna* and *Raja clavata.* Species with high mortality rates were mostly pelagic or wide-ranging ones (Scombridae, *Meluccius merluccius*), which can be and often are caught by fishermen offshore and outside of the surveyed area.

4.3. Comparison with other monitoring methods

With various factors complicating soft-substrate monitoring, these habitats and the effects of their protection have been lacking global scientific attention (Caveen et al., 2012). Several methods have been developed and refined to sample fish assemblages and parameters with minimal impact on the ecosystem (Table 1). Popular and cost-effective monitoring methods for MPAs often rely on visible observations, either in person (UVC, DOV) or with videos (e.g. BRUV, ROV). These methods are generally less size-selective than experimental fishing (Murphy and Jenkins, 2010) and are non-extractive. But for various reasons they can be ineffective for soft-substrate habitats. The visibility of soft-bottom habitats can be very limited due to disturbances of the sediment with strong hydrodynamic processes such as tidal currents, swell or even strong chop disturbing the unconsolidated particles sufficiently to make visual census unfeasible or unreliable. Secondly, soft-substrate habitats have on average lower fish abundances which, due to the uniformity of the habitat are dispersed and often rely on camouflage or burial. This can produce low counts and high coefficients of variation, demanding large sampling effort to attain robust data sets. Several studies have been conducted using UVC successfully for the monitoring of inshore, shallow depth rocky habitat fish in the PLSMP (e.g. Beldade et al., 2006; Gonçalves et al., 2002; Henriques et al., 2007; Horta e Costa et al., 2013). During some of these surveys, visibility restricted the sampling, which indicates that this method would not be feasible for the soft-sediment sections of the MPA.

As the aim of this survey was the monitoring of the entire soft-substrate demersal fish community (down to ~ 40 m) and its response to MPA effects, a method with a low size- and species selectivity was needed. Hook and line surveys are characterized by high size and species selectivity with a lower catch mortality (Table 1) and are an appropriate method for the monitoring of specific target species. Traps are species selective depending on the bait that is used and size selective depending on mesh size (Alós et al., 2008; Erzini et al., 1996; Løkkeborg and Bjordal, 1992; Mahon and Hunte, 2001). Thus, these extractive methods are feasible when monitoring specific target species. This can limit the by-catch of unwanted species and their mortality. Pelagic purse seine are high efficient for schooling pelagic species (Cailliet et al., 1979; Tsagarakis et al., 2012). Demersal application (such as Danish seine) can sample demersal and benthic communities but has a higher disturbance of the benthos through its active hauling on the bottom and increased mortality rates (Depestele et al., 2009). Trawl size selectivity depends on the mesh size of the codend (Erzini et al., 2002). Large, mobile species often escape the net and the disturbance of the benthic community has a high impact on the benthic ecosystem (Jones, 1992). Gill nets exhibit a relatively low size- and species selectivity, mainly determined by the mesh size and hanging ratio. Karakulak and Erk (2008) and Fabi et al. (2002) found a lower selectivity and higher catch efficiency for trammel nets in comparison with gill nets, which can be related to the additional trammelling mechanism.

While this study quantifies the catch and mortality of demersal fish, the thorough evaluation of monitoring methods should take the overall impact on the ecosystem into account. Trammel nets have been found to have a high catch of invertebrates and are often used to target commercially valuable cephalopods and crustaceans (Catanese et al., 2018; Stergiou et al., 2006). The vast majority of invertebrates caught in our study were released alive. Nevertheless, to further reduce the bycatch of species not targeted in the monitoring, various studies have found a decline of catch and mortality and discard through the use of guarding nets (Aydin et al., 2013; Catanese et al., 2018; Martínez-Baños and Maynou, 2018; Szynaka et al., 2018). While these can result in higher economic and time costs for fishermen (Szynaka et al., 2018), they could prove valuable for further lowering the impact of trammel net monitoring. Thus overall, trammel nets are characterized by low size- and species selectivity and limited impact on the benthos, while at the same time offering the opportunity to take morphometric measurements, determine condition or tag species of interest. These characteristics are desirable when sampling an entire demersal fish community and can provide a broad array of valuable data for MPA monitoring. To enhance the statistical power of the study, reduce biases and expand the data gathered, the combination of several monitoring methods (e.g. UVC and trammel net experimental fishing – Seytre and Francour, 2008) is advised (Murphy and Jenkins, 2010; Watson et al., 2005; Willis et al., 2000). To adapt the methodology and reduce mortality rates, a preliminary test study of the sampling methods and appropriate net configurations as performed by Rotherham et al. (2007) is useful. Furthermore, the selection of one or a few key species can limit the damage and impact on the monitored MPA and should be the objective once key indicator species have been identified (Gerber et al., 2005).

5. Conclusions

To the best of our knowledge, this study presents the first quantification of the impact of trammel net experimental fishing used to monitor soft-substrate demersal fish in an MPA. Over 14 sampling campaigns (between 2010 and 2019) a total of 21,895 fish with a total biomass of 5.62 tonnes were caught. The fishing method proved highly effective with a CPUE exceeding commercial effort of other trammel net studies (Batista et al., 2009; Stergiou et al., 2006). The impact on the soft-substrate fish community is relatively low as protected and demersal species have low immediate mortality rates. Shallow deployments over sand had lower mean mortality rates than deeper ones over mud. Large and valuable individuals were frequently released alive, being able to grow and reproduce after the survey. This contribution to the exploitable or potential spill-over biomass, limits the economic impact of the monitoring survey for local fishermen. Trammel nets combine low size and low species-selectivity with a limited impact on benthos and a moderate mortality of the extracted fish, making the method suitable for the monitoring of entire assemblages where non-extractive techniques are ineffective. This highlights the urgency to use and implement gained knowledge about the MPA effect in management and future implementation of the protection. Furthermore, this study reiterates the need for quantification of immediate and post-release mortality and impact of extractive survey approaches, especially in the context of soft-substrate MPA monitoring.

CRediT authorship contribution statement

C. Robert Priester: Conceptualization, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Lucas Martínez-Ramírez:** Investigation, Data curation, Writing - review & editing. **Karim Erzini:** Methodology, Writing - review & editing. **David Abecasis:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Supervision.

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.

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Appendix A. Supplementary data

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