



# Can pots be an alternative fishing gear to gillnets? A Mediterranean case study

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Received: 19 February 2024 / Accepted: 3 September 2024  
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**Abstract** Small-scale coastal fisheries in the Mediterranean often employ gillnets, a widely used gear worldwide. The disadvantages of gillnets in this fishery include high bycatch levels of unwanted species and consequent discards. Moreover, spatial conflict with other gears and dolphin depredation often results in considerable economic loss. Alternative fishing methods are being tested. This study investigated whether, in small-scale fisheries in the Adriatic Sea, pots can ensure sustainable harvest of mantis shrimp (*Squilla mantis*), a major target demersal species in terms of landings, and possibly replace traditional gillnets. We adopted a multidisciplinary approach to

investigate the catch efficiency, biological impact, and socio-economic effects of the two fishing methods. We found different species compositions in gillnet and pot catches. Gillnets yielded a greater number of discarded species of no commercial value, whereas pots caught a greater amount of mantis shrimp. Finally, a profit analysis indicated that pot fishery has the potential to increase profits for the commercial fishing industry. This study suggests that pots provide a more sustainable fishing method, both in terms of revenue and environmental impact.

**Keywords** Sustainable Fisheries · Coastal Fisheries · Alternative Fishing Gear · Bycatch and Discard Reduction · *Squilla mantis*

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M. Virgili and A. Petetta have contributed to this equally.

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**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s11160-024-09893-9>.

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## Introduction

Small-scale fisheries (SSFs) play a major socio-economic role within the Mediterranean fishing sector, accounting for 82% of the total fishing fleet (FAO 2023). These fisheries typically involve small vessels (LOA < 12 m) and operate either full- or part-time throughout the year, employing a diverse array of fishing strategies and gears in coastal areas and targeting multiple species (Grati et al. 2018; Calò et al. 2022; Papageorgiou and Moutopoulos 2023). Passive nets, particularly gillnets, are the most common gear used in Mediterranean SSFs (Lucchetti et al. 2020).

In the North-Western Adriatic Sea (FAO Geographical Sub-Area 17), one such fishery is operated by bottom-set gillnets, mainly targeting mantis shrimp (*Squilla mantis*) and common sole (*Solea solea*), but they also frequently capture and land other species due to their commercial value and additional income (Fabi and Grati 2005). However, this fishery is no longer profitable in the region for several reasons. Spatial conflicts, i.e. when several fishing activities operate simultaneously on the same fishing grounds (Bergh et al. 2023), are common in the overexploited areas of the Adriatic Sea (Farella et al. 2021; Grati et al. 2022; Tasseti et al. 2023), and can have a negative impact. Furthermore, the dolphin depredation on gillnets is a matter of concern in the area (Pardalou et al. 2022). It is caused primarily by the common bottlenose dolphin (*Tursiops truncatus*), which ‘steals’ fish from the net, resulting in catch loss, damage to the gear, and accidental entanglements of dolphins. Overexploited fish stocks may have increased the frequency of depredation (Reeves et al. 2013). Additionally, the economic crisis experienced by SSFs may have exacerbated fishers’ perceptions of dolphins as competitors (Li Veli et al. 2023).

Gillnets often exhibit poor species selectivity, which, in a multispecies fishery, can result in considerable bycatch levels and consequent discards (Tsagarakis et al. 2014, 2017). Discards for bottom gillnets in the Adriatic Sea are generally around 20% of the total catch in weight, with a potential increase in some seasons (Fabi and Grati 2005; Lucchetti et al. 2020). Moreover, gillnets in the area are responsible for relevant bycatch rates of marine megafauna, such as marine mammals (Đuras et al. 2021), sharks (Di Lorenzo et al. 2022), and turtles (Casale 2011; Lucchetti 2021; Virgili et al. 2024a).

Given these premises, it is crucial to guarantee socio-economic sustainability for SSFs i.e. landings, profits, and incomes, while ensuring sustainable exploitation of resources. Recently, the European Commission funded various scientific initiatives to investigate and promote pots as potential alternatives to traditionally used gear (Petetta et al. 2021), while also addressing the perspectives of stakeholders.

Pots can have a higher potential to reduce bycatch in some fisheries when compared to passive set nets (Petetta et al. 2021; Suuronen et al. 2012). Moreover, the removal of any discards from pots upon gear retrieval has considerably improved the survival probability compared to gillnets, as the trapped animals are kept alive in the water during the pot soaking time (i.e., the time between setting and hauling when gears are fishing; Barragán-Méndez et al. 2020; Lorenzon et al. 2013). For the same reason, several pot fisheries provide higher quality catches compared to other gear types (Olsen 2014). Additionally, pots are less susceptible to depredation (e.g., by dolphins and seals; Königson 2011; Pusch 2011), as access to the catch is limited for large-bodied animals, especially in the small pots employed in the Mediterranean basin (Petetta et al. 2020). Nevertheless, according to the last available data (year 2021), the weight and value of landings generated by Mediterranean pot fisheries account for approximately 3,200 tons and € 24 million, respectively, representing 1% of total fishery landings and 1.6% of their revenues (STECF 2023). Therefore, Mediterranean fishers can be encouraged to use pots as a method of capturing certain target species, at least in some areas and seasons. This approach would diversify the fishing fleet and mitigate the impact on non-target species (Petetta et al. 2021).

Mantis shrimp is one of the top-target demersal species in terms of landings for the Italian national fleet and, specifically for the SSFs, ranking among the top 6 species in 2021 and representing around 10% (in weight) of gillnet landings (STECF 2023). The aim of this study was to assess whether pots can be used in small-scale mantis shrimp fisheries to replace gillnets. Although mantis shrimp pots have been used since the second half of the last century, their expansion in the past was restricted due to competition with active gears targeting the same species (Froglia 1996). However, in recent years, these pots have increasingly been used along the entire Western

Adriatic coast, especially in the summer and early autumn, when trawling in coastal areas is forbidden. Therefore, this study was aimed at answering the following questions:

- Does species composition differ between gillnet and pot catches in a small-scale coastal fishery targeting mantis shrimp?
- Is there any difference in catch efficiency between pots and traditional gillnets in this fishery?
- Does the economic value of the catch differ between gillnets and pots, and could pots be used in this fishery as an alternative gear without negatively affecting the profit of this SSF?

## Materials and Methods

### Experimental design and sea trials

The study used a conventional bottom-set gillnet (hereinafter GNS, following FAO fishing gear catalogue; ISSCFG 2016) as a *control*. The GNS was composed of multiple netting panels made of transparent polyamide monofilament (diameter 0.20 mm) joined in the same gang. Each panel was 50 m in length and 3.6 m in stretched net drop (50 meshes in height), although the real vertical opening during fishing was relatively low (< 1 m), due to the low floatability of the float line. The mesh size was 72 mm. The float line and lead line were polypropylene (diameter 5.5 and 4.5 mm, respectively); the lead line weighed 60 g/m. The horizontal hanging ratio, i.e. the slack of the netting panel, was 0.33 for the float line and lead line, which are common values in Mediterranean gillnets (Lucchetti et al. 2015). The tested GNS was the same in all fishing operations.

The pots targeting *S. mantis* were used as a *treatment* (hereinafter FPO, ISSCFG 2016), and they presented similar characteristics to those commercially used along Western Adriatic SSFs. Each FPO had a semi-ellipsoidal shape with dimensions of 32 cm length, 30 cm width and 14 cm height. It had a volume of 12.1 L and a weight of 0.55 kg. The FPO frame (diameter 2 mm; rectangular mesh size, 10 mm length and 22 mm width) was made of galvanized metal with green plastic coating to give more resistance to oxidation. The frame of the entrance was oval-shaped

(internal surface: 18.8 cm<sup>2</sup>) and positioned in the front side. The entrance funnel was 12 cm long and made in plastic of the same colour of the FPO. On the opposite side of the entrance, sideways, there was a box, made of plastic, which served as bait container. The FPO structure was made so that the opening placed on the upper side is regulated by means of an internal elastic rope; this mechanism allowed ease baiting and emptying the pot with a quick operation of lifting and closing. Fresh sardines were used as bait: 3 individuals per pot for a total of about 40 gr. FPO were attached to a propylene main line (diameter 8 mm) by 1.5 m branch lines (diameter 5 mm) with a quick release swivel. This allowed to ensure a correct setup depending on the force and direction of bottom water current. Considering that FPO once lowered the first time were no longer brought ashore until the end of the fishing season (except for some washing and descaling operation) the use of anchors (Danforth<sup>®</sup>, United Arab Emirates) was required to face periods of strong wave motion and bad seawater conditions. FPO were placed at 15 m intervals according to the traditional rigging used by the local fishers (Petetta et al. 2020; Virgili et al. 2024b).

Each fishing trial utilized a range of 500 to 750 m of GNS (corresponding to 10–15 panels) and a gang of 40 FPO (Fig. 1) to obtain equal total length for each gear. The GNS and FPO deployments were paired, as each deployment consisted of setting and retrieving GNS and FPO gangs on the same fishing grounds and were spaced around 0.25 nautical miles apart (Fig. 1). The soaking time varied from half a day to almost a whole day for GNS and from a few hours to days for FPO.

A typical commercial vessel with a crew of two fishers was used for sea trials. Activities were conducted during the late summer or autumn of two consecutive years (September–November 2021 and September–October 2022), when the maximum yield of the target species (Grati et al. 2018) and dolphin depredation on set nets (Li Veli et al. 2023) were expected. Fishing operations were conducted in shallow waters (depth < 15 m) at 1–3 nautical miles off the Pedaso coast (Western Adriatic Sea, Italy), where fishing grounds are characterized by sandy bottoms inhabited by *S. mantis*.

After retrieving the GNS and FPO, the crew proceeded to sort the catch on board separately for each gear type. The *total catch* for each gear was thus

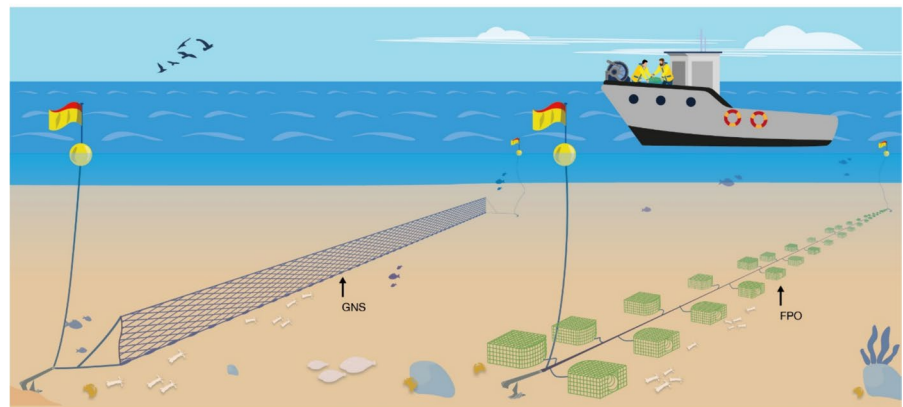
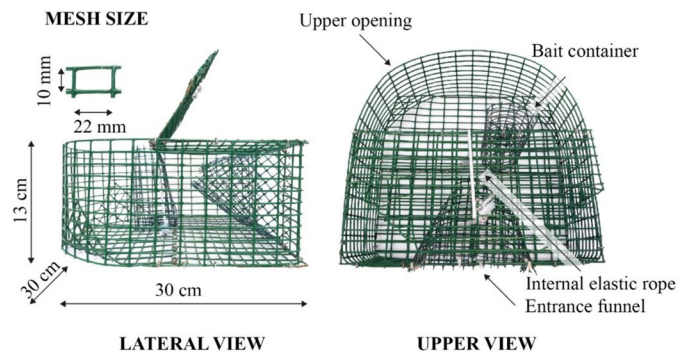
**Fig. 1** TOP: Technical design and specifications of the two gears tested: conventional gillnet (GNS) used in Adriatic SSFs to target *S. mantis* and other demersal species, and pot for *S. mantis* (FPO). BOTTOM: Illustration of the sampling method: commercial vessel (LOA 6.8 m; gross tonnage 1 GT; gasoline-powered engine 100 HP) with a crew of two fishers, equipped with a net winch to haul 500–750 m of GNS and 40 FPO

### GNS

50 m PP Ø 5.5 mm	E=0.33	
50	PA Ø 0.20 mm	72 mm
		1666
		1666
50 m PP Ø 4.5 mm	E=0.33	60g/m



### FPO



divided into: a *landed catch* consisting of the main target species and other species that have commercial value; *discards* consisting of species with no commercial value such as invertebrates and fish species and commercial individuals under the minimum landing size or in poor condition; and, *bycatch* of protected, endangered, and threatened species (PET species included in EU regulations and international lists such as the EU Habitat Directive and the IUCN Red List), which were discarded if dead or released alive. Observers on board identified all individuals to the lowest taxonomic level possible, counted them,

weighed them to the lowest 1 g on a small balance scale with marine compensation, and measured them to the nearest 0.5 cm for total length (TL; fish) or mantle length (ML; cephalopods), and to the nearest 0.1 mm for carapace length by means of a calliper (CL; *S. mantis* and other crustaceans). No sub-sampling was conducted in this study. The economic value of the commercial species caught by each fishing gear was daily recorded. The value was determined by the local market price and expressed as €/kg.

Preliminary data analysis

A preliminary data check and analysis were performed to ensure that the data could be treated as paired, as the deployments were paired between the two gears. Initially, the deployments of both GNS and FPO with soaking times that significantly deviated from the average were excluded from further analyses. A linear model (*lm*; R-package) (Pinheiro et al. 2018) was then applied to assess the potential effect of soak time on the mantis shrimp catch for each gear. In case no significant effect was detected, data was treated as paired.

Comparing the species composition between gillnets and pots

We performed a catch dominance analysis to quantify and compare the species composition observed in the catches of GNS and FPO, respectively (Herrmann et al. 2022; Petetta et al. 2023). This methodology enables an evaluation of the impact of fishing gear from a species-community perspective, measuring how much each species caught dominates in the sample (Warwick et al. 2008). The catch dominance analysis was performed to evaluate the relative abundance of each species in both the total catch, the discarded catch, and the landed catch.

The species dominance for GNS and FPO was estimated for each of the gear types separately, and the estimation of the species dominance pattern was averaged over deployments of pots and gillnets, respectively. Following the procedure described in (Petetta et al. 2023), a fixed rank was assigned to each single species caught in the sea trials by including it in one of the following four categories: 1) ‘Target species’, i.e. the main commercial species targeted by GNS and FPO; 2) ‘Other species of commercial value’, i.e. additional landed species with a commercial value; 3) ‘Other species of no commercial value’, i.e. those species usually discarded by fishers; 4) ‘PET species’.

The estimation of the catch dominance in the number of individuals ( $dn_i$ ), weight ( $dw_i$ ), and economic value ( $dv_i$ ) was carried out separately for FPO and GNS and for each fraction of the catch (total, discarded, and landed) (Cerbule et al. 2022; Herrmann et al. 2022; Madhu et al. 2023; Petetta et al. 2023):

$$\begin{aligned} dnt_i &= \sum_{j=1}^m \left\{ \frac{nt_{ij}}{\sum_{i=1}^Q \{nt_{ij}\}} \right\} \\ dwt_i &= \sum_{j=1}^m \left\{ \frac{\rho_{ij} \times nt_{ij}}{\sum_{i=1}^Q \{\rho_{ij} \times nt_{ij}\}} \right\} \\ dvt_i &= \sum_{j=1}^m \left\{ \frac{\sigma_{ij} \times nt_{ij}}{\sum_{i=1}^Q \{\sigma_{ij} \times nt_{ij}\}} \right\} \end{aligned} \tag{1}$$

where  $j$  represents the deployment and  $i$  is the species rank defined previously.  $n_{ij}$  is the count number for each species  $i$  in deployment  $j$ . Parameter  $\rho_{ij}$  is the average weight of species  $i$  in deployment  $j$  in a given fraction of the catch; it is obtained from the total weight and number of individuals. Parameter  $\sigma_{ij}$  is the average value of species  $i$  in deployment  $j$  in a given fraction of the catch.  $Q$  is the total number of species observed, and  $m$  is the total number of paired deployments considered in the analysis.

Furthermore, the cumulative dominance curves were estimated in the number of individuals ( $Dnt_I$ ), weight ( $Dwt_I$ ), and economic value ( $Dvt_I$ ) to represent the cumulative proportional abundances of the species (Cerbule et al. 2022; Herrmann et al. 2022; Madhu et al. 2023; Petetta et al. 2023):

$$\begin{aligned} Dnt_I &= \sum_{j=1}^m \left\{ \frac{\sum_{i=1}^I nt_{ij}}{\sum_{i=1}^Q nt_{ij}} \right\} \text{ with } 1 \leq I \leq Q \\ Dwt_I &= \sum_{j=1}^m \left\{ \frac{\sum_{i=1}^I \rho_{ij} \times nt_{ij}}{\sum_{i=1}^Q \{\rho_{ij} \times nt_{ij}\}} \right\} \text{ with } 1 \leq I \leq Q \\ Dvt_I &= \sum_{j=1}^m \left\{ \frac{\sum_{i=1}^I \sigma_{ij} \times nt_{ij}}{\sum_{i=1}^Q \{\sigma_{ij} \times nt_{ij}\}} \right\} \text{ with } 1 \leq I \leq Q \end{aligned} \tag{2}$$

In Eq. (2),  $I$  is the species index summed up in the nominator. The fixed species ranking in all catches in the cumulative dominance curves allows the comparison of the steepness of the cumulative dominance curves. Specifically, steeper sections in dominance curves will imply that some species are more dominant than other species in the fishing gear (GNS or FPO, respectively), while the horizontal parts show that the particular species are not abundant (Cerbule et al. 2022; Herrmann et al. 2022; Petetta et al. 2023).

The Efron percentile 95% Confidence Intervals (CIs; Efron 1982) were used to provide the uncertainty of the values of dominance patterns obtained following the procedure described in (Herrmann et al. 2022). This procedure enables the estimation of uncertainties around the dominance values at the species level induced by the limited sample sizes at a

single deployment as well as the between-deployment variation in species dominance.

Furthermore, the difference  $\Delta d$  in species dominance  $d$  between FPO ( $p$ ) and GNS ( $g$ ) was estimated for the number of individuals, weight, and economic value (Herrmann et al. 2022; Petetta et al. 2023):

$$\Delta d = d_p - d_g \quad (3)$$

The CIs for Eq. 3 were obtained based on separate bootstrap populations for  $d_p$  and  $d_g$ , as described in (Cerbule et al. 2022; Herrmann et al. 2022). The significance was detected by inspecting the CIs for the difference; if the 0.0 value was within the CIs, no significant difference was detected.

### Comparing the *mantis* shrimp catch efficiency between gillnets and pots

We estimated the relative length-dependent *mantis* shrimp catch efficiency of GNS and FPO to quantify the effect of gear changes on catch efficiency. We used the method described in Herrmann et al. (2017) to compare the catch data for the two gears. This method models the length-dependent catch comparison rate ( $CC_l$ ) summed over pot and gillnet deployments by:

$$CC_{cl} = \frac{\sum_{j=1}^m \{np_{cl,j}\}}{\sum_{j=1}^m \left\{ np_{cl,j} + \frac{ng_{cl,j}}{qg_j} \right\}} \quad (4)$$

where  $np_{cl,j}$  and  $ng_{cl,j}$  are the numbers of *mantis* shrimp caught in each size class  $cl$  for the pots and GNS, respectively, in deployment  $j$ .  $qg_j$  is a sampling factor that accounts for the fact that some of the gillnet deployments used less than 750 m of net. For example, if deployment  $j$  used  $ml_j$  m of gillnets,  $qg_j$  is  $ml_j/750$ . Parameter  $m$  is the number of paired deployments considered. We estimated the catch comparison rate  $CC(cl, \nu)$  expressed by Eq. (4) by minimizing the Expression (5) (maximum likelihood estimation):

$$- \sum_{cl} \left\{ \sum_{j=1}^m \left\{ np_{cl,j} \times \ln(CC(cl, \nu)) + \frac{ng_{cl,j}}{qg_j} \times \ln(1.0 - CC(cl, \nu)) \right\} \right\} \quad (5)$$

where the outer summation is over the length classes  $cl$  and the inner summation is over the deployments  $m$ . Parameter  $\nu$  describes the catch comparison curve

defined by  $CC(cl, \nu)$ . The experimental  $CC_{cl}$  was modelled by:

$$CC(cl, \nu) = \frac{\exp(f(cl, \nu_0, \dots, \nu_k))}{1 + \exp(f(cl, \nu_0, \dots, \nu_k))} \quad (6)$$

In Eq. (6),  $f$  is a polynomial of order  $k$  with coefficients  $\nu_0$  to  $\nu_k$ . We considered  $f$  up to an order of 4 with parameters  $\nu_0, \nu_1, \nu_2, \nu_3$ , and  $\nu_4$ ; leaving out one or more of the parameters  $\nu_0 \dots \nu_4$  led to 31 additional models for the catch comparison function  $CC(cl, \nu)$ .

Among these models, the estimations of the catch comparison rate were made by using multi-model inference to obtain a combined model (Burnham and Anderson 2002; Herrmann et al. 2017). We evaluated the ability of the combined model to describe the experimental data based on the  $p$ -value, calculated by the ratio between the model deviance and the degrees of freedom (DOF; Herrmann et al. 2017; Wileman et al. 1996). A  $p$ -value  $> 0.05$  implies that the combined model describes the experimental data sufficiently well. In cases of poor fit statistics ( $p$ -value  $< 0.05$  and deviance/DOF  $> 1$ ), the residuals were inspected to determine whether the results were due to structural problems when modelling the experimental data or data over-dispersion (Wileman et al. 1996).

With similar catch efficiency between gears, the catch comparison rate would be 0.5; thus, the application of this baseline allows us to judge whether there is a difference in catch efficiency between FPO and GNS. Since the results of  $CC(l, \nu)$  do not provide a direct relative value of the catch efficiency between gears, we further estimated the catch ratio  $CR(l, \nu)$  (Herrmann et al. 2017) as follows:

$$CR(l, \nu) = \frac{CC(l, \nu)}{(1 - CC(l, \nu))} \quad (7)$$

When the catch efficiency between FPO and GNS is similar, the value of  $CR(cl, \nu)$  would be equal to 1.0. If the  $CR(cl, \nu)$  is significantly larger than 1.0, it would show that FPO are catching significantly more *mantis* shrimp with  $cl$  compared to GNS.

The  $CR(cl, \nu)$  values provided by Eq. (7) are specific to the number of FPO versus meters of GNS used in the experiment, based on 40 FPO versus 750 m of GNS, which corresponds to 5.33 FPO per 100 m of GNS

deployed. However, a typical vessel with two crew members would realistically deploy 3,000 m of GNS or 270 FPO (*real scenario*), which corresponds to 9 FPO per 100 m of GNS deployed. Therefore, the results provided by Eq. (7) can be scaled by a factor of 1.69 ( $\approx 9/5.33$ ) to obtain a realistic comparison. For completeness, we additionally scaled the results obtained by Eq. (7) to provide estimates for 1 to 10 FPO per 100 m of GNS deployed.

The 95% CIs for  $CC(cl, v)$  and  $CR(cl, v)$  were estimated using a double bootstrapping method (Herrmann et al. 2017). The bootstrapping method accounts for between-deployment variability as well as within-deployment variability. However, contrary to the double bootstrapping method (Herrmann et al. 2017), the outer bootstrapping loop used in the current study (accounting for the variability between deployments) was conducted in pairs to take full advantage of the experimental design of deploying GNS and FPO simultaneously. By using multi-model inference in each bootstrap iteration, the method also accounted for the uncertainty in model selection. We performed 1,000 bootstrap repetitions and calculated the Efron 95% CIs.

Furthermore, length frequency distribution and cumulative length frequency distribution analyses were used to quantify the proportion of the total catch of mantis shrimp for each carapace length class  $cl$  and up to a given carapace length class  $CL$ , captured with gear type i.e. GNS ( $t=g$ ) or FPO ( $t=p$ ). The analysis was conducted using the following equation (Cerbule et al. 2021):

$$\begin{aligned}
 fnt_{cl} &= \frac{\sum_{j=1}^m m_{cl,j}}{\sum_{j=1}^m \sum_{cl} m_{cl,j}} \\
 Fnt_{CL} &= \frac{\sum_{j=1}^m \sum_{cl=0}^{CL} m_{cl,j}}{\sum_{j=1}^m \sum_{cl} m_{cl,j}}
 \end{aligned}
 \tag{8}$$

By incorporating the evaluation of Eq. (8) in the double bootstrap described above, we obtained 95% CIs. Further, to compare the length distribution of mantis shrimp captured by both gears, the differences in length frequency  $\Delta fn_{cl}$  and cumulative length frequency  $\Delta Fn_{CL}$  between GNS ( $g$ ) and FPO ( $p$ ) were estimated as follows:

$$\begin{aligned}
 \Delta fn_{cl} &= fnp_{cl} - fng_{cl} \\
 \Delta Fn_{CL} &= Fnp_{CL} - Fng_{CL}
 \end{aligned}
 \tag{9}$$

The Efron 95% CIs for the  $\Delta fn_{cl}$  and  $\Delta Fn_{CL}$  were obtained using the double bootstrapping method,

as described above. All the analyses described in Sects. "Preliminary data analysis" and "Comparing the species composition between gillnets and pots" were conducted using the SELNET software (Herrmann et al. 2012, 2016, 2017, 2022).

### Comparing the profits

An economic assessment was performed to determine the feasibility and economic sustainability of implementing the alternative gear in comparison to the traditional one.

To assess the profits at the gear level for each fishing operation, the main costs related to fuel consumption, staff, working time, and other additional costs, such as gear maintenance and bait, were collected. Cost items varied according to the gear used and were related to fuel consumption, additional staff (personnel for cleaning the GNS and personnel dedicated to logistics for FPO transport at sea), and other factors (e.g., maintenance of the gear and bait for FPO). The daily gasoline costs per liter, available online at the Italian Ministry of the Environment, were multiplied by the liters consumed. The additional staff costs were calculated based on the hourly cost communicated by the boat owner and the required hours of work. Finally, the profits were estimated by subtracting costs from the revenues obtained from the direct sale of fish.

The European Regulation (EU 2019) establishes that the maximum length for GNS is to be set at 6 km, whereas there is no legislation in force for pot fisheries. The length of commercially used GNS depends on the capabilities and dimensions of the fishing vessel and the strategy and attitude of the fishers. Therefore, for a crew consisting of two members, we considered the *real scenario* outlined in Sect. "Comparing the mantis shrimp catch efficiency between gillnets and pots" involving the deployment of 3 km of GNS and 270 FPO, i.e., the average amount of nets and pots employed by vessels similar to the one used in the study. We investigated whether there was any significance when comparing the profit obtained with the two gears, first considering profits solely from *S. mantis* and then from all the catch sold.

A non-parametric bootstrap method with replacement was utilized to undertake statistical comparisons of profit data between GNS and FPO (Efron and

Tibshirani 1993). The variability of the profit difference means (derived from catches), considering both *S. mantis* alone and all the species caught, was evaluated using the non-parametric bootstrap with replacement in the following manner. From the profit data, 2,000 replicates of the same dimension (30 values) with replacement were bootstrapped for each gear. From these replicates, 2,000 values of the mean difference between GNS and FPO were derived. On this set of 2,000 differences, the 95% Efron CIs of the true difference were then calculated according to the improved BCA percentile method (Efron and Hastie 2022). If the 95% CIs did not capture the zero value, the difference was deemed statistically significant. All the calculations were carried out using the free statistical software R (R Core Team 2023). The BCA interval was calculated with the function *bca* of the R package “coxed” (Kropko and Jeffrey 2019).

## Results

### Preliminary data analysis

A total of 30 valid fishing operations were conducted in the two-year period (Table 1). The preliminary analysis excluded GNS and FPO deployments with extreme soak times. The average range of GNS soak times was 11–17 h, in accordance with common fishers’ practices. Therefore, we excluded two GNS hauls that had a soak time of 22 h, along with the corresponding FPO deployments. The average range of FPO soak time was 14–48 h; thus, five FPO hauls with soak times of 1, 72, 74, 78, and 95 h, respectively (and the corresponding GNS hauls), were excluded. Consequently, 23 out of 30 paired deployments were considered for further catch analyses.

The *lm* results revealed that, within the 23 paired deployments, soak time had no effect on the mantis shrimp catch, either for GNS (estimate=2.76; *p*-value=0.39) or for FPO (estimate=-0.06; *p*-value=0.98).

### Comparing the species composition between gillnets and pots

GNS and FPO captured 40 different species during the fishing operations (Fig. 2, top). Only 3 species were considered as “Target species” i.e., mantis

shrimp for both gears and two sole species (*Solea solea* and *Pegusa impar*) for GNS. The majority of species (25) belonged to the “Other species with commercial value” category and were mostly fish, except for the octopus (*Octopus vulgaris*), caramote prawn (*Penaeus kerathurus*), and changeable nassa (*Nassarius mutabilis*). The “Other Species without commercial value” category included 9 species: 5 mollusc species, 2 crab species, and 2 fish species. The “PET species” category only included the elasmobranch species caught by the GNS, i.e., the blue shark (*Prionace glauca*, 1 individual), sandbar shark (*Carcharhinus plumbeus*, 1 individual), and pelagic stingray (*Pteroplatytrigon violacea*, 1 individual). Additional results on catches are reported in Supplementary Material 1.

The cumulative curves of the total catch show that, in FPO, the species with commercial value (species IDs S1-S28) account for an average of 83% (CIs 77–87%) in terms of the number of individuals and 92% (CIs 89–94%) in terms of the weight of all the species caught (Fig. 2 bottom, *a, d*). These percentages are significantly lower in GNS i.e. 33% (CIs 23–44%) in terms of the number of individuals and 74% (CIs 64–82%) in terms of weight. Therefore, for this gear, the catch was primarily dominated by species that did not have a commercial value (Fig. 2 bottom, *b, e*, and Table S1).

The catch composition in FPO was dominated by *S. mantis*, which accounted for more than 80% and 90% of the total and landed catch in weight, respectively, with a small contribution from other species in the catch composition. *S. mantis* almost saturates the cumulative curve of the landed fraction in both the number of individuals and weight; 100% is reached at species 21 (black goby, *Gobius niger*, around 5% in weight on average; Fig. 2 bottom, *a, d*). In terms of weight, none of the other species with a commercial value reached an average dominance of 3% in the total catch (Table S1). Regarding the discarded fraction, the highest proportion was observed for the purple dye murex (*Bolinus brandaris*; around 41% in number and 49% in weight), followed by changeable nassa (*Nassarius mutabilis*; around 47% in number and 22% in weight; Table S1). In the latter case, despite being a commercial species with a dedicated pot fishery in the area (Grati et al. 2010), the entire catch was



**Table 1** An overview of the catches obtained from the deployment of gillnets (GNS) and pots (FPO). The black horizontal line divides the deployments of two fishing seasons (2021, 2022)

ID	GNS					FPO										
	Soak time (h)	GNS (m)	Total catch (Kg)	Landed catch (Kg)	Dis-carded catch (Kg)	PET catch(Kg)	<i>S. mantis</i> catch (Kg)	<i>S. mantis</i> catch (Nr)	Soak time (h)	Pot numbers	Total catch (Kg)	Landed catch (Kg)	Dis-carded catch (Kg)	PET catch(Kg)	<i>S. mantis</i> catch (Kg)	<i>S. mantis</i> catch (Nr)
1	12	500	2.38	1.51	0.88	0	0.98	25	15	40	4.90	4.15	0.76	0	4.05	97
2	12.5	500	3.00	2.06	0.94	0	0.53	14	23	40	3.79	3.38	0.40	0	3.27	95
3	12.5	500	4.66	3.78	0.88	0	1.69	42	23	40	4.60	4.49	0.11	0	4.40	125
4	12	500	4.33	3.44	0.89	0	0.86	33	48	40	3.53	3.42	0.12	0	3.24	82
5	13	500	1.94	0.71	1.23	0	0.18	4	15	40	1.60	1.10	0.50	0	1.02	30
6	12	500	1.28	0.76	0.52	0	0	0	23	40	3.54	2.61	0.93	0	2.45	58
7	12	500	4.34	1.77	2.57	0	0.15	4	23	40	2.71	2.29	0.41	0	2.09	55
8*	12	500	1.18	0.86	0.32	0	0.21	7	95	40	2.85	1.68	1.17	0	1.68	41
9	15	500	7.18	6.16	1.02	0	0.79	17	16	40	4.09	3.03	1.06	0	2.85	58
10	15.5	500	6.04	5.02	1.01	0	0.39	11	24	40	5.09	4.71	0.39	0	4.59	90
11	12	750	12.96	10.40	2.56	0	0.15	5	26	40	3.48	2.67	0.81	0	2.64	61
12	16	750	10.46	9.11	1.36	0	1.71	37	16	40	4.77	4.43	0.34	0	4.43	102
13	15	500	3.46	2.27	1.19	0	0.39	10	24	40	4.25	3.89	0.36	0	3.87	85
14*	17	600	17.39	13.34	4.05	0	0.24	6	1	40	0.61	0.61	0.00	0	0.61	14
15	12	500	6.03	5.70	0.33	0	3.07	72	14	40	2.46	2.26	0.21	0	1.67	38
16*	12	500	4.56	4.08	0.48	0	1.41	36	78	40	3.31	2.87	0.44	0	2.86	68
17	14	500	5.32	4.83	0.49	0	2.08	52	15	40	2.97	2.94	0.03	0	2.81	85
18	11	500	2.96	2.10	0.85	0	1.07	29	24	40	4.11	3.92	0.20	0	3.92	100
19*	14	500	104.90	3.46	1.44	100.00	1.00	27	74	40	1.27	1.14	0.13	0	1.06	31
20	16	500	7.04	3.58	1.06	2.40	2.83	64	24	40	3.13	2.35	0.78	0	2.35	75
21	12	500	3.77	2.31	0.81	0.66	0.27	7	23	40	3.14	2.35	0.79	0	2.35	76
22	13	600	3.92	3.04	0.88	0	0.17	5	46	40	2.16	1.75	0.41	0	1.75	50
23	12	600	5.92	4.95	0.97	0	0.63	15	23	40	1.71	1.50	0.21	0	1.50	45
24*	12	600	3.66	2.55	1.12	0	0.54	11	72	40	0.84	0.73	0.11	0	0.66	14
25	15	600	5.33	1.96	3.34	0	0.66	12	24	40	3.12	2.50	0.62	0	2.50	50
26*	22	600	4.24	4.24	0	0	1.29	25	24	40	2.06	2.03	0.04	0	1.89	39
27*	22	600	4.04	2.30	0	1.75	2.03	40	24	40	4.31	4.22	0.09	0	3.11	61
28	15	600	22.20	14.23	0.88	7.10	4.30	80	48	40	2.23	2.19	0.04	0	2.13	45
29	13	600	6.16	4.71	1.46	0	1.92	41	47	40	2.96	2.77	0.18	0	2.75	60

Table 1 (continued)

ID	FPO															
	Soak time (h)	GNS (m)	Total catch (Kg)	Landed catch (Kg)	Dis-carded catch (Kg)	PET catch(Kg)	<i>S. mantis</i> catch (Kg)	<i>S. mantis</i> catch (Nr)	Soak time (h)	Pot numbers	Total catch (Kg)	Landed catch (Kg)	Dis-carded catch (Kg)	PET catch(Kg)	<i>S. mantis</i> catch (Kg)	<i>S. mantis</i> catch (Nr)
30	13	600	10.06	8.72	1.33	0	4.00	61	30	40	2.93	2.91	0.02	0	2.85	62

\*Denotes the deployments that were excluded from the analysis. PET: Protected, Endangered, and Threatened Species

discarded due to a lack of demand in the autumn season.

The proportion of *S. mantis* in the catch was significantly less dominant in GNS than in FPO, reaching only 19% and 26% of the total and landed catch in weight, respectively (Fig. 2 bottom, e). The same average percentages were observed for common sole (*S. solea*). Among the other commercial species, high proportions in the catches were observed for tub gurnard (*Chelidonychthys lucernus*) and Mediterranean starry ray (*Raja asterias*), with an average of 12% and 16% of the total and landed catch in weight, respectively (Table S1). The discarded portion was dominated by two species (*B. brandaris* and swimming crab, *Liocarcinus* spp.), each representing, on average, 27% of the proportion in weight. High percentages in the discarded fraction are also observed for PET species due to the substantial weight of the few individuals caught (Fig. 2 bottom, e and Table S1).

The same trend between gears was observed when considering the economic value, since *S. mantis* represented more than 99% (CIs 98–100%) of the total catch in FPO (Fig. 2 bottom, g), versus 29% (CIs 19–78%) in GNS. The species with the highest economic value in GNS was *S. solea* (45%; CIs 11–63%), with significant contributions from other commercial species such as *C. lucernus*, *R. asterias*, and flathead grey mullet (*Mugil cephalus*; Fig. 2 bottom, h, and Table S1).

Delta plots between the total catch dominance curves of the two gears provide a detailed insight at each single species level (Fig. 2 bottom, c, f, i). The plots showed a marked dominance of *S. mantis*, picarel (*Spicara maena*), *N. mutabilis*, and conger eel (*Conger conger*) in the FPO catches compared to GNS in the number of individuals, weight, and economic value. By contrast, the proportion of several commercial and discarded species (species IDs S2 to S6; S8; S12; S30; S31) was significantly larger in the GNS total catch.

Comparing the *mantis* shrimp catch efficiency between gillnets and pots

Table 1 reports the number of *S. mantis* individuals measured in each deployment in both gears. The fit statistics of the combined model used in the catch comparison by pooling the deployments of the two years ( $p$ -value=0.06; Deviance=48.15; DOF=34)

indicated the model's good fit to the experimental data.

Compared to GNS, FPO were significantly more efficient at capturing mantis shrimp for most length classes, except for the 29–30 mm CL classes, where the increase in catch efficiency when using FPO was not statistically significant (Fig. 3 a, b). On average, FPO caught 1.5 to 3 times more mantis shrimp than GNS when considering the most abundant length classes (22 to 32 mm; Fig. 3 b). The FPO catch efficiency was even higher than GNS in a *real scenario*, with FPO catching, on average, 2.5 to 5 times more mantis shrimp for the same length classes (Fig. 3 c). The catch ratio estimates in mean curves (Fig. 4), considering 1 to 10 FPO per 100 m of GNS deployed, highlighted that 4 FPO are sufficient to guarantee a higher mantis shrimp catch than 100 m of GNS. Additional results are reported in Supplementary Material 1.

### Comparing the profits

The cost items and incomes (in mean values) for the two fishing gears are reported in Table 2. The major FPO costs were represented by fuel and bait (43% and 46%, respectively). For GNS, the major costs were fuel and additional staff (53% and 32%, respectively).

On average, the mean price per kilo for *S. mantis* was € 12.7 and € 18.0 for GNS and FPO, respectively. Figure 5 illustrates the profit comparison between the two gears. When only considering the profit obtained from *S. mantis* catches, we observed significantly higher profits for FPO (mean profit: € 253.4) than GNS (mean profit: € 19.2). The 95% CIs for the mean profit difference calculated according to the non-parametric bootstrap were CIs € [-174.3, -297.5]. When considering all the species caught, the mean FPO profit (€ 256.5) was slightly higher than the mean GNS profit (€ 192.8); however, the bootstrap 95% CIs for the mean profit difference were CIs € [-32.3, -146.7], highlighting that this difference was not significant.

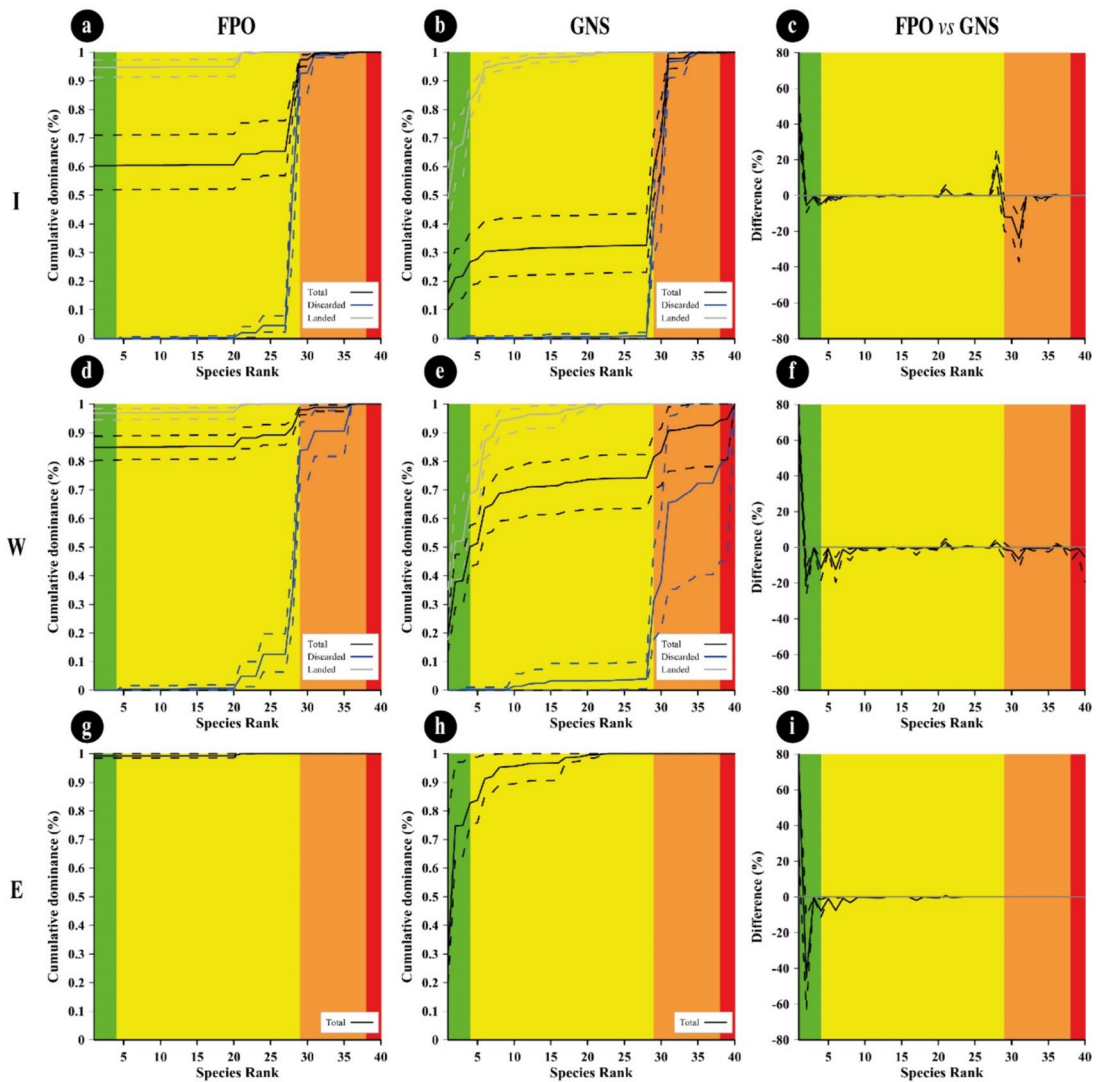
## Discussion

The purpose of this study was to test the catch efficiency and profitability of pots targeting mantis shrimp in the Adriatic Sea and comparing them with

traditionally used gillnets. Specifically, the study evaluated whether pots could provide a more sustainable alternative to traditional gillnets, examining their ability to mitigate current issues in these fisheries, such as reducing bycatch and discards, and enhancing profitability.

The findings from the catch dominance and catch comparison analyses demonstrate that pots targeting *S. mantis* are highly selective for the target species, resulting in few discards and no PET species bycatch. This has been observed in earlier studies for other pot fisheries targeting cephalopods and shrimps (Castriota et al. 2004; Fabi and Grati 2005), and fish (Petetta et al. 2020). In contrast, the lower species selectivity of gillnets produced more discards of species with no commercial value (e.g., crabs), raising conservation concerns due their potential to capture primarily elasmobranchs and sea turtles (Lucchetti et al. 2017). High discard rates are already reported in several fisheries employing set nets, such as gillnets targeting hake (*Merluccius merluccius*) in the Ionian Sea (29.5%; Tzanatos et al. 2007), trammelnets targeting prawns in Izmir Bay (Gökçe and Metin 2007), and spiny lobster (*Palinurus elephas*) in Tunisia and Spain (Quetglas et al. 2004), where discards may exceed 40%. In terms of bycatch, set nets in the Mediterranean Sea are responsible for the annual capture of approximately 31,000 sea turtles (mostly *C. caretta*) with a mortality rate of 30–50% (Lucchetti 2021; Virgili et al. 2024a, b). Much less is known about elasmobranchs and their interactions with SSFs (Di Lorenzo et al. 2022), although in the Northern Adriatic, gillnets called "cagnolare" are specifically employed to catch demersal sharks (e.g., *Squalus* spp., *Mustelus* spp.) (Bargione et al. 2019; Lucchetti et al. 2023). Low bycatch and mortality rates are observed for coastal cetacean species, particularly *T. truncatus* (i.e., 0.14 animals per year per vessel in Italian waters; Li Veli et al. 2023), although a strong interaction with set nets is known (Lauriano et al. 2009). Another difference resides in the discarding practices observed. While the unwanted organisms caught by pots were usually alive and promptly discarded at sea, increasing their chances of survival, the bycatch individuals in gillnets were dying or already dead when the net was retrieved. Typically, these individuals were not immediately discarded due to the additional time needed to free them from the meshes. These organisms were always removed once

Target Species	Other Species (€)	Other Species (no €)	PET Species
S1 <i>Squilla mantis</i>	S11 <i>Scorpaena porcus</i>	S21 <i>Gobius niger</i>	S31 <i>Liocarcinus sp</i>
S2 <i>Solea solea</i>	S12 <i>Trachurus spp.</i>	S22 <i>Auxis thazard</i>	S32 <i>Hexaplex trunculus</i>
S3 <i>Solea impar</i>	S13 <i>Boops boops</i>	S23 <i>Penaeus kerathurus</i>	S33 <i>Galeodea echinophora</i>
S4 <i>Chelidomychthys lucernus</i>	S14 <i>Diplodus annularis</i>	S24 <i>Spicara maena</i>	S34 <i>Mitilus galloprovincialis</i>
S5 <i>Mullus barbatus</i>	S15 <i>Pagellus erythrinus</i>	S25 <i>Arnoglossus laterna</i>	S35 <i>Rapana venosa</i>
S6 <i>Raja asterias</i>	S16 <i>Lithognathus mormyrus</i>	S26 <i>Citharus linguatula</i>	S36 <i>Conger conger</i>
S7 <i>Liza aurata</i>	S17 <i>Octopus vulgaris</i>	S27 <i>Pagellus bogaraveo</i>	S37 <i>Serranus hepatus</i>
S8 <i>Mugil cephalus</i>	S18 <i>Platichthys flesus</i>	S28 <i>Nassarius mutabilis</i>	S38 <i>Prionace glauca</i>
S9 <i>Scophthalmus rhombus</i>	S19 <i>Scomber scombrus</i>	S29 <i>Bolinus brandaris</i>	S39 <i>Carcharhinus plumbeus</i>
S10 <i>Merluccius merluccius</i>	S20 <i>Mullus surmuletus</i>	S30 <i>Goneplax rhomboides</i>	S40 <i>Pteroplatytrigon violacea</i>



◀**Fig. 2** TOP: Assigned ranking (S) of the species caught, divided by category: target species, other species with commercial value (€), other species without commercial value (no €), and Protected, Endangered, and Threatened species (PETs). BOTTOM: Cumulative species dominance in the catch of pots (FPO: *a, d, g*) and gillnets (GNS: *b, e, h*). The curves (solid lines) with 95% CIs (dashed lines) represent the cumulative species dominance for catches in the number of individuals (I), weight (W), and economic value (E). Delta plots (*c, f, i*) resulting from the comparison of single species dominance in the total catch between FPO and GNS in the number of individuals (I), weight (W), and economic value (E). The curves (solid lines) with 95% CIs (dashed lines) represent the comparison between gears at the single species level. The grey horizontal line at 0 represents an equal proportion between the two gears. The green, yellow, orange, and red areas represent target species, other species with commercial value, species without commercial value, and PET species, respectively

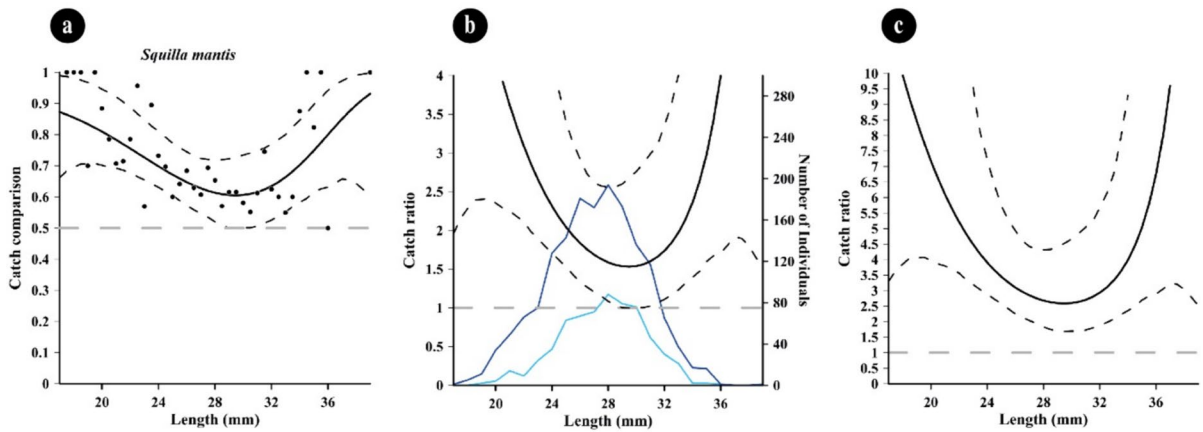
hauled onto the deck, without any possibility of survival. However, there are strategies in set nets that can reduce discards by increasing mesh sizes (Karakulak and Erk 2008; Lucchetti et al. 2020), reducing netting twines (Ayaz et al. 2011; Grati et al. 2015), adjusting hanging ratios (Kumova et al. 2015), and using the “guarding net” (i.e. a strip of monofilament net with large meshes placed in the lower part of trammel nets (Martínez-Baños and Maynou 2018; Sartor et al. 2018)).

Moreover, pots demonstrated a significantly higher catch efficiency and catch quality for mantis shrimp compared to gillnets. This could explain the increased use of pots along the Western Adriatic coasts in recent years (Virgili et al. 2024b). It is also clear that, apart from *S. mantis*, the two gears attract different species, despite fishing on the same grounds. Commercial fish like common sole, tub gurnard, starry ray, grey mullet, and most sparids do not enter the small mantis shrimp pots. However, they constitute an important catch fraction of gillnets. In contrast, pots are often approached by smaller fish with (e.g., black goby) or without (e.g., blotched picarel and conger eel) economic value, which, due to their size, are not caught by the gillnet meshes. For the same reason, pots retain a higher proportion of smaller mantis shrimp than gillnets, and these are potentially marketable since the species lacks a minimum landing size (EU 2019). However, their capture may raise concern regarding the sustainability of pots for this species, and regulations or recommendations for the establishment of either a minimum landing size, minimum pot

mesh size, or good practices on the release of smaller live specimens may be needed.

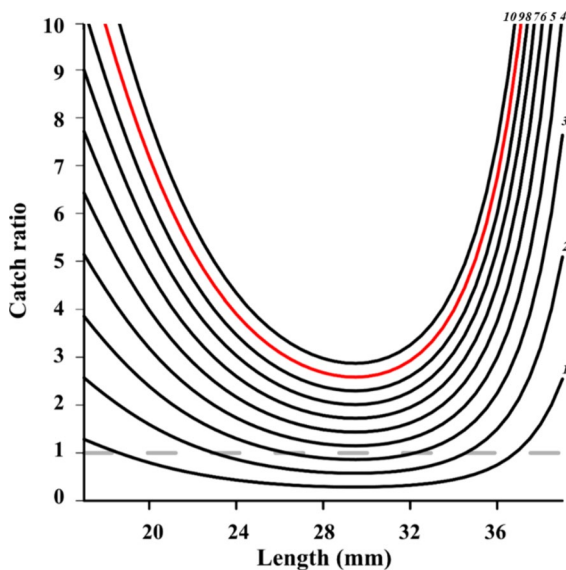
Pot fisheries can represent a valid strategy at the economic level, providing lower costs for personnel, fuel consumption, and other operating costs. Revenues are, in fact, comparable to those of traditionally used gillnets if the whole catch is considered, and even higher if the mantis shrimp alone is considered. In this study, GNS had a cost of around € 65 per panel, while FPO had a cost of € 9 per unit. In addition, some fishers produce pots by hand, recycling materials and components used in other fishing gear or those intended for other uses, further reducing costs. In contrast, fishing with gillnets requires an additional daily trip to set the nets, resulting in additional fuel costs. From the profit assessment, we can estimate that the initial pot costs could be amortized over the course of a quarter of the fishing season (typically of 3–4 months with an average of 10–15 fishing days per month). Of course, mantis shrimp pots require bait to effectively attract the prey, contrary to other pots employed in the area (e.g., for cuttlefish *Sepia officinalis*, and fish) (Petetta et al. 2020). However, the cost of sardines commonly used as bait is usually less than € 1.50 per kilo. Also, the space required on deck for pots is not an issue in this fishery since these pots are usually deployed in several trips at the beginning of the season and then left at sea throughout the season, with the movement of single gangs each time. The economic analysis includes the cited costs, demonstrating their lack of impact on FPO profits compared to GNS.

The conflict with other commercial or recreational fishers, increased fuel costs, and other fishing-related factors (e.g., dolphin depredation) disadvantage GNS more than FPO. These findings align with results coming from the “PRIZEFISH project” (2019), which highlighted a good trend in certain economic indicators such as net profit margin and return on investment (i.e., Return on Fixed Tangible Assets, RoFTA) and a general good performance of the mantis pot fisheries sector in GSA 17 (Supplementary Material 2). Pot fisheries are one of the few cases where the percentage of income from a single species is higher than 50%, compared to other passive gears that base their profit on multiple species. Price is the main factor that influences customers’ buying decisions, followed by the freshness of the product. As a result of the freshness and quality of the product, price derived



**Fig. 3** Results of the catch comparison analyses obtained for mantis shrimp between pots (FPO) and gillnets (GNS). *a*) modelled catch comparison rate (black line) with 95% CIs (black dashed curves); the black circles represent the experimental rate; the grey horizontal line at 0.5 represents the point at which both gears have equal catch rates. *b*) the catch ratio

(black line) with 95% CI (black dashed curves); the blue lines represent the length frequency distributions obtained with the two gears (light blue, GNS; dark blue, pots); the grey horizontal line at 1.0 represents the point at which both gears have equal catch rates. *c*) catch ratio curve with CIs scaled by a factor of 1.69 ( $\approx 9/5.33$ ) to obtain a realistic comparison



**Fig. 4** Catch ratio curves attained by scaling the results obtained by the catch ratio equation provide estimates for 1 to 10 pots (FPO) per 100 m of gillnets (GNS) deployed (numbers in italics). The red curve represents the *real scenario*, i.e., 9 FPO per 100 m of GNS deployed

from pots, as outlined in our paper, is almost double the average price obtained from other gears (i.e., trawling), and higher than that of set nets (PRIZE-FISH, 2019).

The use of pots as an alternative to gillnets has shown promising results at the socioeconomic level. At least in certain seasons, this could provide small-scale fishers, who earn less from fishing activities compared to large-scale fishers (STECF 2023), with an opportunity to increase their income from landings and improve overall sustainability.

The narrow entrance of mantis shrimp pots limits access to the catch, reducing the risk of depredation by large predators such as bottlenose dolphins, which do not include this species in their diet, as observed in Mioković et al. 1999, and Neri et al. 2023.

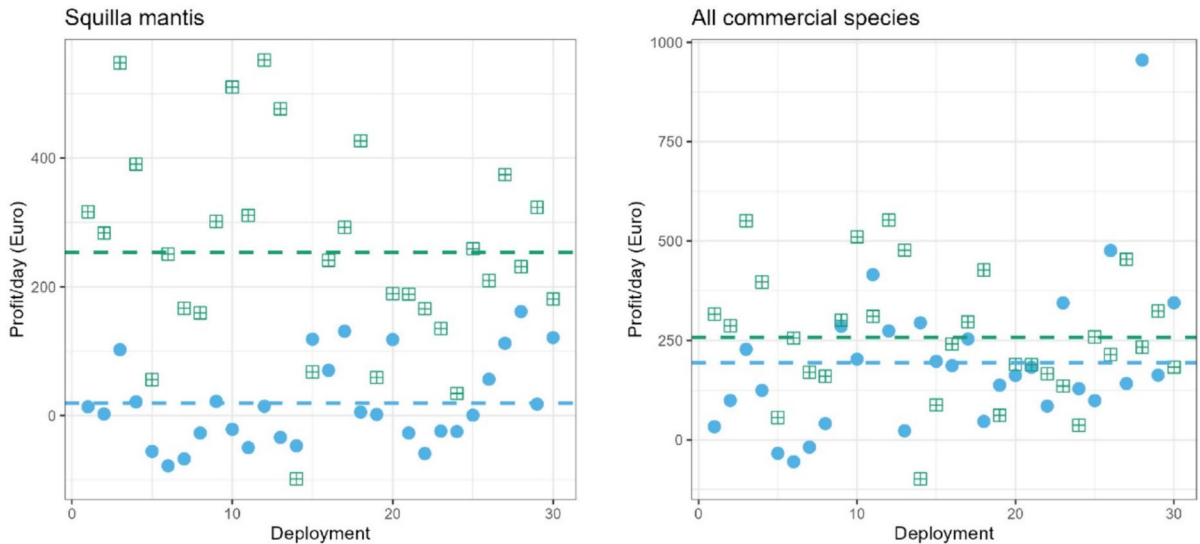
Increased pot fishing efforts may result in the overfishing of target species and the ongoing capture of marine animals when pots are lost at sea (so-called ghost fishing). The most recent results from SACWGSAD (2022) indicated that the Adriatic stock is sustainably exploited. However, it is recommended that: (1) fishing mortality is not to increase; and (2) a valid stock assessment for *S. mantis* is carried out in this area by improving data collection on this species (biological parameters, catches and landings, effort, and prices).

Ghost fishing is a critical problem in some Mediterranean fisheries. Ghost fishing mostly involves gillnets (Ayaz et al. 2006), longlines, and trawls (Ayaz et al. 2010). However, there is a dearth of research specifically focusing on lost pots (Petetta

**Table 2** Mean values (with standard errors) of cost items and incomes expressed in euros for the two fishing gears (GNS: gillnets; FPO: pots). The text reports values as percentages (Sect. "Comparing the profits"). Fuel: cost for fuel consumption during gear transport and fishing activities; Staff: cost for

additional staff other than crew members (i.e., for cleaning the set nets); Other: costs for gear maintenance and bait for pots; TOT: total costs; MTS Inc.: income obtained when only taking into account the sale of *S. mantis*; APS Inc.: income obtained when taking into account the sale of all commercial species

Gear	Fuel	Staff	Other	TOT	MTS Inc	APS Inc
GNS	€ 35.67 ± 1.64	€ 21.47 ± 2.13	€ 10 ± 6.94	€ 67.15 ± 7.94	€ 76.48 ± 11.99	€ 251.13 ± 35.04
POT	€ 28.36 ± 3.05	€ 6.75 ± 4.69	€ 30.66 ± 3.94	€ 65.78 ± 10.76	€ 313.71 ± 26.69	€ 318.35 ± 27.07



**Fig. 5** The profit comparison between gillnets (GNS, ○) and pots (FPO, □) is detailed. The profits shown only consider *S. mantis* income and those profits from income obtained from the sale of all the commercial species caught

et al. 2021). Generally, pots allow non-target species to escape relatively easily (Ungfors et al. 2013), and their fishing potential has been found to be low after bait consumption (Adey et al. 2008). In our study, the pots were securely rigged, preventing any loss due to adverse weather conditions and underwater currents.

Recently, there has been an increase in the use of *S. mantis* pots and other pots targeting fish and cuttlefish (Petetta et al. 2021; Virgili et al. 2024b) along the Italian coasts in terms of the number of boats involved (PRIZEFISH, 2019). This expansion is likely linked to the exclusion of active gear, especially from coastal areas, as established by current legislation. In fact, EU Regulation (2006) prohibits trawling within three nautical miles, while the Italian Ministerial DM 399/2019 extends this prohibition to six nautical miles for specific periods (following the summer fishing ban). Moreover, the use of AIS (Automatic

Identification System) has become mandatory for vessels over 15 m in LOA (Length Overall), ensuring greater control over fishing activities, particularly in certain coastal areas. The resulting reduction in gear conflicts with active gear has decreased the effective fishing effort, benefiting the SSF fleet (Bastardie et al. 2017) in terms of exploitable fishing grounds and fishing days. Therefore, diversification of the fleet on a spatio-temporal scale could be a solution, especially for the multispecies and multigear fisheries in coastal areas. Providing fishers with an ecolabeled fish product to access more lucrative markets is also a forward-looking strategy for those who voluntarily use low-impact fishing gear (Virgili et al. 2024a).

## Conclusion

The results of this study show that pots could replace gillnets and trammel nets following the seasonality of several SSF target species. A proposed solution is to replace the use of set nets with a year-round fishing method that involves the use of different types of pots. Specifically, pots would be used to catch cuttlefish from March to July, mantis shrimp from July to November, basket traps for changeable nassa from November to March, and occasionally, foldable fish pots for seabreams (i.e. *Diplodus* spp.), red mullet (*Mullus barbatus*), and octopus (Petetta et al. 2021). The diversification of the fleet ensures a lower fishing effort on a broader spectrum of demersal species and guarantees greater competitiveness on the fish market. The use of pots to replace traditionally used GNS in this *S. mantis* fishery constitutes an endeavor to achieve greater sustainability in terms of both economic viability and environmental impacts. To further improve sustainability in this pot fishery, it may be necessary to implement additional management measures, particularly by imposing regulations on the maximum number of pots to be deployed per vessel, setting a minimum mesh size for the pots, and defining spatio-temporal closures.

**Acknowledgements** This study was conducted with the contribution of the LIFE financial instrument of the European Community, namely the DELFI Project-Dolphin Experience: Lowering Fishing Interactions (LIFE18NAT/IT/000942). It does not necessarily reflect the European Commission's views and in no way anticipates future policy.

We express our utmost gratitude to the crew of MP Giamario GB and their family (Pedaso, Italy) for their effort in the fieldwork and data collection. We extend our sincere thanks to Monia Bonfilì (Bonfilì Design; [www.bonfilidesign.it](http://www.bonfilidesign.it)) for providing the illustrations for the figures, and Eurostreet for English language revision. We also thank the anonymous reviewer who helped us greatly improve the quality of the paper.

**Funding** Open access funding provided by Consiglio Nazionale Delle Ricerche (CNR) within the CRUI-CARE Agreement.

**Data availability** The authors can provide the data upon request.

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## References

- Adey JM, Smith IP, Atkinson RJA et al (2008) "Ghost fishing" of target and non-target species by Norway lobster *Nephrops norvegicus* creels. *Mar Ecol Prog Ser* 366:119–127. <https://doi.org/10.3354/meps07520>
- Ayaz A, Acarli D, Altinagac U et al (2006) Ghost fishing by monofilament and multifilament gillnets in Izmir Bay, Turkey. *Fish Res* 79:267–271
- Ayaz A, Ünal V, Acarli D, Altinagac U (2010) Fishing gear losses in the gökova special environmental protection area (SEPA), eastern Mediterranean, Turkey. *J Appl Ichthyol* 26:416–419. <https://doi.org/10.1111/j.1439-0426.2009.01386.x>
- Ayaz A, Altinagac U, Ozekinci U et al (2011) Effect of twine thickness on selectivity of gillnets for bogue, Boops boops, in Turkish waters. *Mediterr Mar Sci* 12:358–368
- Bargione G, Donato F, La Mesa M et al (2019) Life-history traits of the spiny dogfish *squalus acanthias* in the Adriatic Sea. *Sci Rep* 9:1–10. <https://doi.org/10.1038/s41598-019-50883-w>
- Barragán-Méndez C, González-Duarte MM, Sobrino I et al (2020) Physiological recovery after bottom trawling as a method to manage discards: the case study of *nephrops norvegicus* and *squilla mantis*. *Mar Policy*. <https://doi.org/10.1016/j.marpol.2020.103895>
- Bastardie F, Angelini S, Bolognini L et al (2017) Spatial planning for fisheries in the Northern Adriatic: working toward viable and sustainable fishing. *Ecosphere* 8:e01696. <https://doi.org/10.1002/ecs2.1696>
- Bergh Ø, Beck AC, Tassetti AN et al (2023) Analysis of spatial conflicts of large scale salmonid aquaculture with coastal fisheries and other interests in a Norwegian fjord environment using the novel GIS-tool SEAGRID and stakeholder surveys. *Aquaculture*. <https://doi.org/10.1016/j.aquaculture.2023.739643>
- Burnham KP, Anderson DR (2002) Model selection and multimodel inference. A practical information-theoretic approach, 2nd edn. Springer, New York
- Calò A, Di Franco A, Quattrocchi F et al (2022) Multi-specific small-scale fisheries rely on few, locally essential, species: Evidence from a multi-area study in the Mediterranean. *Fish Fish* 23:1299–1312. <https://doi.org/10.1111/faf.12689>
- Casale P (2011) Sea turtle by-catch in the Mediterranean. *Fish Fish*. <https://doi.org/10.1111/j.1467-2979.2010.00394.x>



- Castriota L, Falautano M, Romeo T et al (2004) Crustacean fishery with bottom traps in an area of the southern Tyrrhenian Sea: species composition, abundance and biomass. *Mediterr Mar Sci* 5:15–22. <https://doi.org/10.12681/mms.199>
- Cerbule K, Herrmann B, Grimaldo E et al (2021) The effect of white and green LED-lights on the catch efficiency of the Barents Sea snow crab (*Chionoecetes opilio*) pot fishery. *PLoS ONE* 16:1–13. <https://doi.org/10.1371/journal.pone.0258272>
- Cerbule K, Savina E, Herrmann B et al (2022) Quantification of catch composition in fisheries: a methodology and its application to compare biodegradable and nylon gillnets. *J Nat Conserv* 70:126298
- Di Lorenzo M, Calò A, Di Franco A et al (2022) Small-scale fisheries catch more threatened elasmobranchs inside partially protected areas than in unprotected areas. *Nat Commun* 13:4381. <https://doi.org/10.1038/s41467-022-32035-3>
- Douvere F (2008) The importance of marine spatial planning in advancing ecosystem-based sea use management. *Mar Policy* 32:762–771. <https://doi.org/10.1016/j.marpol.2008.03.021>
- Duras M, Galov A, Korpes K et al (2021) Cetacean mortality due to interactions with fisheries and marine litter ingestion in the croatian part of the Adriatic Sea from 1990 to 2019. *Vet Arh* 91:189–206
- Efron B, Hastie T (2022) Computer age statistical inference
- Efron B, Tibshirani RJ (1993) Chapter 17: Cross-Validation. *An Introd to Bootstrap* 436
- Efron B (1982) The jackknife, the bootstrap and other resampling plans. *Society for Industrial and Applied Mathematics (SIAM)*. <https://doi.org/10.1137/1.9781611970319>
- EU (2019) Regulation (EU) 1241/2019 of the European Parliament and of the Council of 20 June 2019 on the conservation of fisheries resources and the protection of marine ecosystems through technical measures. *Off. J. Eur. Union* 105–201
- EU (2006) Council regulation No 1967/2006 of 21 December 2006, concerning management measures for the sustainable exploitation of fishery resources in the Mediterranean Sea, amending Regulation (EEC) no 2847/93 and repealing Regulation (EC) no 1626/94. *Official Journal of the European Union*, 75 pp
- Fabi G, Grati F (2005) Small-scale fisheries in the maritime department of Ancona (Central Northern Adriatic Sea). *AdriaMed Tech* 64–84
- FAO (2023) The State of Mediterranean and Black Sea Fisheries 2023 -, Special. *General Fisheries Commission for the Mediterranean*, Rome
- Farella G, Tassetti AN, Menegon S et al (2021) Ecosystem-based MSP for enhanced fisheries sustainability: an example from the northern adriatic (Chioggia-Venice and Rovigo, Italy). *Sustain* 13:1–28. <https://doi.org/10.3390/su13031211>
- Fritz J-S (2010) Towards a “new form of governance” in science-policy relations in the European Maritime Policy. *Mar Policy* 34:1–6. <https://doi.org/10.1016/j.marpol.2009.04.001>
- Frogliola C (1996) Growth and behaviour of *Squilla mantis* (mantis shrimp) in the Adriatic Sea. (EU Study DG XIV/MED/93/016, Final Report)
- Gökçe G, Metin C (2007) Landed and discarded catches from commercial prawn trammel net fishery. *J Appl Ichthyol* 23:543–546. <https://doi.org/10.1111/j.1439-0426.2007.00832.x>
- Grati F, Polidori P, Scarcella G, Fabi G (2010) Estimation of basket trap selectivity for changeable nassa (*Nassarius mutabilis*) in the Adriatic Sea. *Fish Res* 101:100–107. <https://doi.org/10.1016/j.fishres.2009.09.012>
- Grati F, Bolognini L, Domenichetti F et al (2015) The effect of monofilament thickness on the catches of gillnets for common sole in the Mediterranean small-scale fishery. *Fish Res* 164:170–177. <https://doi.org/10.1016/j.fishres.2014.11.014>
- Grati F, Aladžuz A, Azzurro E et al (2018) Seasonal dynamics of small-scale fisheries in the Adriatic Sea. *Mediterr Mar Sci* 19:21–35. <https://doi.org/10.12681/mms.2153>
- Grati F, Azzurro E, Scanu M et al (2022) Mapping small-scale fisheries through a coordinated participatory strategy. *Fish Fish* 23:773–785. <https://doi.org/10.1111/faf.12644>
- Herrmann B, Sistiaga M, Nielsen KN, Larsen RB (2012) Understanding the size selectivity of redfish (*Sebastes* spp.) in North Atlantic Trawl Codends. *J Northwest Atl Fish Sci* 44:1–13. <https://doi.org/10.2960/J.v44.m680>
- Herrmann B, Sistiaga M, Santos J, Sala A (2016) How many fish need to be measured to effectively evaluate trawl selectivity? *PLoS ONE* 11:1–22. <https://doi.org/10.1371/journal.pone.0161512>
- Herrmann B, Sistiaga M, Rindahl L, Tatone I (2017) Estimation of the effect of gear design changes on catch efficiency: Methodology and a case study for a Spanish longline fishery targeting hake (*Merluccius merluccius*). *Fish Res* 185:153–160. <https://doi.org/10.1016/j.fishres.2016.09.013>
- Herrmann B, Cerbule K, Brčić J et al (2022) Accounting for uncertainties in biodiversity estimations: a new methodology and its application to the mesopelagic sound scattering layer of the high arctic. *Front Ecol Evol*. <https://doi.org/10.3389/fevo.2022.775759>
- ISSCFG (2016) *International Standard Statistical Classification of Fishing Gear*. *Handb. Fish. Stat.* 2
- Karakulak FS, Erk H (2008) Gill net and trammel net selectivity in the northern Aegean Sea. *Turkey. Sci Mar*. 72:527–540
- Königson S (2011) *Seals and fisheries: A study of the conflict and some possible solutions* (Thesis). University of Gothenburg, Sweden
- Kropko J, Jeffrey JH (2019) coxed: an r package for computing duration-based quantities from the cox proportional hazards model. *R J* 11:38
- Kumova CA, Altunağaç U, Öztekin A et al (2015) Effect of hanging ratio on selectivity of gillnets for bogue (*Boops boops*, L. 1758). *Turkish J Fish Aquat Sci* 15:561–567
- Lauriano G, Caramanna L, Scarnò M, Andaloro F (2009) An overview of dolphin depredation in Italian artisanal fisheries. *J Mar Biol Assoc United Kingdom* 89:921–929. <https://doi.org/10.1017/S0025315409000393>

- Li Veli D, Petetta A, Barone G, et al (2023) Fishers' Perception on the Interaction between Dolphins and Fishing Activities in Italian and Croatian Waters. *Diversity* 15:133. <https://doi.org/10.3390/d15020133>
- Lorenzon S, Martinis M, Borme D, Ferrero EA (2013) Hemolymph parameters as physiological biomarkers for monitoring the effects of fishing and commercial maintenance methods in *Squilla mantis* (Crustacea, Stomatopoda). *Fish Res* 137:9–17. <https://doi.org/10.1016/j.fishres.2012.08.015>
- Lucchetti A, Buglioni G, Conides A et al (2015) Technical measures without enforcement tools: is there any sense? a methodological approach for the estimation of passive net length in small scale fisheries. *Mediterr Mar Sci* 16:82–89
- Lucchetti A, Vasapollo C, Virgili M (2017) An interview-based approach to assess sea turtle bycatch in Italian waters. *PeerJ* 5:e3151
- Lucchetti A, Virgili M, Petetta A, Sartor P (2020) An overview of gill net and trammel net size selectivity in the Mediterranean Sea. *Fish Res* 230:105677. <https://doi.org/10.1016/j.fishres.2020.105677>
- Lucchetti A, Petetta A, Bdioui M et al (2023) Catalogue of fishing gear in the Mediterranean and Black Sea region. FAO Fisheries and Aquaculture Technical Paper, Rome
- Lucchetti A (2021) Sea turtles. In: Carpentieri P, Nastasi A, Sessa M, Srour A (eds) Incidental catch of vulnerable species in Mediterranean and Black Sea fisheries – A review. Studies and Reviews No. 101 (General Fisheries Commission for the Mediterranean). FAO, Rome
- Madhu VR, Anand SB, Cerbule K, Herrmann B (2023) Simple pot modification improves catch efficiency and species composition in a tropical estuary mud crab (*Scylla serrata*) fishery. *Estuar Coast Shelf Sci* 288:108369
- Martínez-Baños P, Maynou F (2018) Reducing discards in trammel net fisheries with simple modifications based on a guarding net and artificial light: Contributing to marine biodiversity conservation. *Sci Mar*. <https://doi.org/10.3989/scimar.04710.03A>
- Mioković D, Kovačić D, Pribanić S (1999) Stomach content analysis of one bottlenose dolphin (*Tursiops truncatus*, Montague 1821) from the Adriatic Sea. *Nat Croat Period Musei Hist Nat Croat* 8:61–65
- Neri A, Sartor P, Voliani A, et al (2023) Diet of Bottlenose Dolphin, *Tursiops truncatus* (Montagu, 1821), in the Northwestern Mediterranean Sea. *Diversity* 15
- Olsen L (2014) Baited pots as an alternative fishing gear in the Norwegian fishery for Atlantic cod (*Gadus morhua*). Master Thesis. The Arctic University of Norway
- Papageorgiou M, Moutopoulos DK (2023) Small-scale fisheries discards in the eastern Mediterranean Sea: Discarding species, quantities, practices and drivers. *Fish Res* 267:106798. <https://doi.org/10.1016/j.fishres.2023.106798>
- Pardalou A, Adamidou A, Tsikliras AC (2022) Dolphin depredation and damage accumulation on different set nets in the northeastern Mediterranean Sea. *Estuar Coast Shelf Sci* 271:107866. <https://doi.org/10.1016/j.ecss.2022.107866>
- Petetta A, Vasapollo C, Virgili M et al (2020) Pots vs trammel nets: a catch comparison study in a Mediterranean small-scale fishery. *PeerJ* 8:e9287. <https://doi.org/10.7717/peerj.9287>
- Petetta A, Virgili M, Guicciardi S, Lucchetti A (2021) Pots as alternative and sustainable fishing gears in the Mediterranean Sea: an overview. *Rev Fish Biol Fish* 31:773–795. <https://doi.org/10.1007/s11160-021-09676-6>
- Petetta A, Herrmann B, Li Veli D et al (2023) Every animal matters! Evaluating the selectivity of a Mediterranean bottom trawl fishery from a species community perspective. *PLoS ONE* 18:e0283362. <https://doi.org/10.1371/journal.pone.0283362>
- Pinheiro J, Bates D, DebRoy S, Sarkar D (2018) R Core Team (2018). nlme: Linear and nonlinear mixed effects models. R package version 3.1–137
- PRIZEFISH project (2019). <https://programming14-20.italy-croatia.eu/web/prizefish>
- Pusch C (2011) Cod traps as an ecological sound fishing gear in German waters. In: International Marine Mammal-Gillnet Bycatch Workshop. BN Federal Agency For Nature Conservation, p 22
- Quetglas A, Gaamour A, Reñones O, et al (2004) Spiny lobster (*Palinurus elephas* Fabricius 1787) fishery in the western Mediterranean: A comparison of Spanish and Tunisian fisheries. *Bolleti la Soc. d'Historia Nat. les Balear*. 33
- R Core Team (2023) R: A Language and Environment for Statistical Computing. R Found. Stat. Comput.
- Reeves R, McClellan K, Werner T (2013) Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endanger Species Res* 20:71–97
- SAC, Scientific Advisory Committee on Fisheries (2022) Report of Working Group on Stock Assessment of Demersal Species (WGSAD). Rome, FAO, 12–17 December 2022
- Sartor P, Veli DL, De Carlo F, Ligas A, Massaro A, Musumeci C, Viva C (2018) Reducing unwanted catches of trammel nets: experimental results of the “guarding net” in the caramote prawn, *Penaeus kerathurus*, small-scale fishery of the Ligurian Sea (western Mediterranean). *Scientia Marina* 82(S1):131–140
- Scientific Technical and Economic Committee for Fisheries (STECF) (2023) Fisheries Dependent Information FDI. Publications Office of the European Union, Luxembourg, 2023, JRC136194.
- Suuronen P, Chopin F, Glass C et al (2012) Low impact and fuel efficient fishing—Looking beyond the horizon. *Fish Res* 119–120:135–146. <https://doi.org/10.1016/J.FISHRES.2011.12.009>
- Tasseti AN, Ferrà C, Manarini T et al (2023) The BlueBio project's database: web-mapping cooperation to create value for the Blue Bioeconomy. *Sci Data*. <https://doi.org/10.1038/s41597-023-02078-2>
- Tsagarakis K, Palialexis A, Vassilopoulou V (2014) Mediterranean fishery discards: review of the existing knowledge. *ICES J Mar Sci* 71:1219–1234
- Tsagarakis K, Carbonell A, Brčić J et al (2017) Old info for a new fisheries policy: discard ratios and lengths at discarding in EU mediterranean bottom trawl fisheries. *Front Mar Sci* 4:99

- Tzanatos E, Somarakis S, Tserpes G, Koutsikopoulos C (2007) Discarding practices in a Mediterranean small-scale fishing fleet (Patraikos Gulf, Greece). *Fish Manag Ecol* 14:277–285. <https://doi.org/10.1111/j.1365-2400.2007.00556.x>
- Ungfors A, Bell E, Johnson ML, et al (2013) *Nephrops Fisheries in European Waters*, 1st edn. Elsevier Ltd
- Virgili M, Petetta A, Barone G et al (2024a) Engaging fishers in sea turtle conservation in the mediterranean Sea. *Mar Policy* 160:105981. <https://doi.org/10.1016/j.marpol.2023.105981>
- Virgili M, Petetta A, Herrmann B et al (2024b) Efficient and sustainable: innovative pot design for a Mediterranean small-scale fishery. *Front Mar Sci* 11:1408036. <https://doi.org/10.3389/fmars.2024.1408036>
- Warwick RM, Clarke KR, Somerfield PJ (2008) k-dominance curves. In: *Encyclopedia of Ecology*. Elsevier BV Burlington, Massachusetts, pp 2055–2057
- Wileman D, Ferro R, Fonteyne R, Millar R (1996) Manual of methods of measuring the selectivity of towed fishing gears. *ICES Coop Res Rep* 215:132

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