



# Static nets in motion: Evaluating seabed interactions of trammel nets deployed in two Mediterranean artisanal fisheries

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## ARTICLE INFO

### Keywords:

Small-scale fishery  
Spiny lobster fishery  
Environmental impact  
Sensitive benthic habitats  
Interaction area

## ABSTRACT

Static fishing gears, such as trammel nets, are traditionally considered to have minor physical impact on benthic habitats and communities. However, some studies suggest notable but poorly quantified interactions with the seabed. This fact can be especially concerning when fishing occurs over complex and sensitive habitats, as is the case of fisheries targeting spiny lobster (*Palinurus elephas*) in the Mediterranean. Understanding these interactions is crucial for assessing ecological impacts and promoting sustainable practices in small-scale fisheries. This study evaluated the interaction of the trammel nets targeting cuttlefish (*Sepia officinalis*) and spiny lobster with the seagrass *Posidonia oceanica* and rhodolith bed (i.e., formed by nodules of coralline red algae) habitats, respectively, using underwater time-lapse cameras, motion sensors, GPS, and catch data. The results confirmed that nets remained static during the soaking, but caused considerable displacement and collapse over the seabed during hauling. These processes increased the contact surface, leading to organism displacement and entanglement. Interaction area between nets and seabed significantly increased with the depth and net length; however, shorter nets generated larger interaction areas when standardized by netting walls. Entanglement of *P. oceanica* in cuttlefish fishing increased with interaction area, while no such pattern was observed for rhodoliths in lobster fishing, likely due to habitat heterogeneity. The acquired knowledge in this study about the interactions between trammel nets and sensitive benthic habitats facilitates the assessment of fishing impacts and the development of mitigation measures in conservation-focused areas.

## 1. Introduction

Small-scale fisheries (SSFs) play a major role in providing food and ensuring security for coastal communities globally (Berkes et al., 2001). In some regions, such as the Mediterranean, they constitute a substantial segment of the fishing industry (Maynou et al., 2011; Palmer et al., 2017). Despite their geographical reach and importance, SSF have historically been overlooked in formal evaluations and fisheries research (McClenachan et al., 2012; Pita et al., 2019). Nonetheless, the modification of the European Union's discard policies in 2013 (Regulation EU No1380/2013 of the European Parliament and the Council on the Common Fisheries Policy) led to a marked increase in research of this sector (Ganias et al., 2023a; Gil et al., 2018; Marengo et al., 2023; Maynou et al., 2018; Papageorgiou and Moutopoulos, 2023). These

studies have provided new insights into the environmental and economic sustainability of this sector (Lloret et al., 2018; Russo et al., 2017).

While most studies have primarily concentrated on discards of commercial fish or protected species (Brownell et al., 2019; Coelho et al., 2005; Purbayanto et al., 2001), a research gap remains in understanding gear interactions with biogenic habitats (Catanese et al., 2018). Traditionally, SSFs have been considered more sustainable than industrial fisheries because they typically use static gears, such as trammel nets, gillnets, or traps, that are assumed to have a low impact on benthic habitats (Maynou et al., 2011). Nevertheless, some studies have reported notable discard levels of habitat-forming invertebrates, algae, or plants for some of these gears (Catanese et al., 2018; Ganias et al., 2023b; Gil et al., 2018; Gonçalves et al., 2008; Sardo et al., 2023; Shester

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<https://doi.org/10.1016/j.fishres.2025.107397>

Received 18 September 2024; Received in revised form 29 April 2025; Accepted 2 May 2025

Available online 15 May 2025

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and Micheli, 2011), suggesting significant interactions between some static gears and biogenic habitats. Given this implication, it becomes particularly important to examine the environments in which these gears operate. In fact, a large fraction of Mediterranean trammel net fisheries is conducted on sensitive benthic habitats such as *Posidonia oceanica* meadows and rhodolith beds (Catanesi et al., 2018; Gil et al., 2018; Ramos-Esplá, 2007), which are included in the Habitat and Species Directive 92/43/EEC and EC Council Regulation 1967/2006 EC.

Some studies have documented the interaction of static fishing gears, such as trammel nets, with sensitive habitats (Aydin et al., 2013; Barbera et al., 2003; Catanesi et al., 2018; Purroy et al., 2014; Sardo et al., 2023); however, they have neither detailed the mechanisms by which the nets interact with the seabed nor quantified the area of interaction. Whether the interaction with the seabed and the capture of benthic organisms occur predominantly during soaking or hauling processes remains unknown. In consequence, there is an acute lack of data on the ecological impact of static fishing gears (Grabowski et al., 2014; Sala et al., 2023), though the magnitude of these impacts will depend on the intensity of fishing operations and the degree of sensitivity of the benthic communities (Hinz, 2017). Obtaining these data will be vital to accurately describe the environmental consequences of SSF and incorporating them into fisheries management and conservation.

The present study focused on describing the interaction of trammel nets with the seabed in the context of the two principal SSFs, in terms of fishing effort (Palmer et al., 2017), in the Balearic Islands (western Mediterranean): A) the cuttlefish (*Sepia officinalis*) fishery in *Posidonia oceanica* meadows, and B) the spiny lobster (*Palinurus elephas*) fishery in rhodolith beds. For the first time, underwater time-lapse video cameras, accelerometers and GPS were used to quantify when, how and to what extent nets interact with sensitive habitats. Furthermore, the vulnerability of most benthic species caught by the gear was analysed from an ecological perspective, focusing on the damages caused by fishing procedures. The insights gained in this study, combining advanced technologies and ecological assessments, are instrumental for shaping future fisheries and conservation strategies, promoting a balanced coexistence between SSF and the preservation of essential marine habitats.

2. Materials and methods

2.1. Experimental fishing design

A total of 46 trammel net fishing trials (20 for cuttlefish and 26 for spiny lobster) were conducted on board 4 different commercial boats along the Mallorcan coasts from February 2021 to June 2022. The fishing trials were carried under commercial conditions, in accordance with the regulations in force at that time. In each fishing trial, 2 or 3 sets of trammel nets with varying numbers of nets (between 8 and 41 netting walls of approximately 50 m length) were deployed (Table 1). In the case of the cuttlefish fishery, the mesh size of the trammel nets has a minimum legal dimension of 67 mm in the inner panel, although fishers often use nets with an 80 mm mesh size. In the case of the spiny lobster fishery, fishers generally use mesh sizes ranging from 133 to 160 mm in

the inner panel. The soak time was approximately 24 h in the cuttlefish fisheries, while in the case of lobster fisheries it usually ranged between 10 and 48 h. However, in some circumstances, nets soaked for a longer period due to adverse maritime conditions delaying net retrieval, reaching values of up to 175 h. The cuttlefish trammel nets are generally deployed at shallow depths of approximately 10–40 m, close to the shore in areas usually protected from strong winds and currents. On the contrary, the spiny lobster trammel nets are deployed at greater depths, ranging from 50 and 150 m, in areas usually subject to strong winds and currents.

Each fishing trial had at least one scientific observer on board, recording all relevant information related to each trammel net deployment, including the depth, the number of netting walls, and the catch composition of each netting wall. The initial and end position for each trammel net (considering the moment at which the anchoring weight at the ends of the trammel entered or left the water) was registered with a GPS. Also, the complete trajectory of the boat during setting and hauling of the nets were recorded in 1 s intervals. As the net was hauled aboard, most of the catch, both commercial or large specimens of discard species, were assigned to a specific netting wall, measured for total length (TL), and identified to the lowest possible taxonomic level (usually to species level). Small invertebrates and fragments of sessile organisms, which continuously fell from the net and could not be assigned to a specific netting wall, were collected separately, identified, and weighed at the trammel net level.

All the discarded benthic specimens were assessed using a vitality scale (Benoît et al., 2010) to estimate their health condition or status as a proxy for the likelihood of survival after being removed from the nets and returned to the sea. The scale ranges from: 1 (excellent, no external injuries), 2 (good, minor external injuries), 3 (poor, significant external injuries), to 4 (moribund, severe and life-threatening injuries). It serves as an indicator of species' vulnerability to fishing practices.

Subsequently, benthic organisms, belonging to the discarded fraction, were identified and classified depending on their vulnerability category. These categories were established using the available information in the database World Register of Marine Species (WoRMS, <https://www.marinespecies.org/>). Specifically, information about the importance to society according to the IUCN Red List and the MSFD (Marine Strategy Framework Directive) indicators of the Good Environmental Status (GES), and the ecological importance using AMBI ecological groups (Borja et al., 2000), was registered.

All data were organized in a hierarchical database, classified by fishing trip, trammel net, and netting wall.

2.2. Underwater time-lapse cameras and accelerometers

In order to analyse the movement of the nets during fishing operations, some of the nets were equipped with underwater time-lapse cameras and accelerometer sensors. A total of 228 underwater camera deployments were made during the experimental fishing trials (Table 1). Within each trial, between 4 and 6 cameras were positioned on the flotation line of the trammel net (Fig. 1A), with the camera lens pointing downwards, thus allowing to record the lower section of the netting wall (i.e., the weighted part of the net) and the seabed.

Cameras were low-cost bespoke time-lapse systems (see Appendix A), composed of a Raspberry Pi Zero W single-board computer with an 8 MegaPixel Raspberry Pi camera module v2 (Raspberry Pi Foundation, Cambridge, United Kingdom). A Pimoroni Unicorn pHAT, with a 4 × 8 RGB LED matrix was attached on top of the Raspberry Pi Zero as lighting system for night-time recordings. The system was powered by a portable and rechargeable power bank of 6700 or 10000 mAh (depending on the soak time), which was plugged into the system via a dongle usb. Finally, the Raspberry Pi Zero was equipped with a 128 Gb microSD memory card for storing of the recorded videos and for installing the software that controlled the operation of the cameras. This software, developed by the company OceanDrivers (Ocean Connection SL, Spain), allowed

**Table 1**  
Summary of experimental fisheries surveyed on Mallorca during 2021–2022.

Metier	Year	Num. trials	Num. trammel nets	Num. netting walls	Num. cameras	Num. sensors
Cuttlefish trammel net	2021	10	23	366	60	18
	2022	10	20	200	39	0
	TOTAL	20	43	566	99	18
Spiny lobster trammel net	2021	16	31	854	75	32
	2022	10	30	240	54	0
	TOTAL	26	61	1094	129	32
TOTAL		46	104	1660	228	50

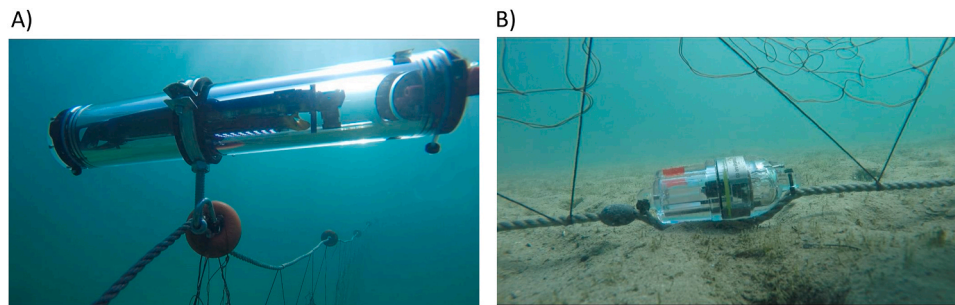


Fig. 1. A) Underwater video camera installed on the top (floating line) of the net. B) Accelerometer sensor located at the bottom of the net (lead line).

programming the power-on time, work and rest periods, and other settings of the camera (as day or night mode). In the cuttlefish fisheries, the cameras were programmed to record for 5 min every half hour, while in the spiny lobster fisheries, due to the longer duration of the fishing trials, they recorded for 5 min every hour. However, in both cases, the cameras initiated continuous recording shortly before the hauling process to capture in detail the net's interaction with the seabed during this operation.

The entire system was mounted to the housing cover using a custom two-piece structure, specifically designed and 3D-printed for this purpose. Finally, the system was inserted in a pressure housing (rated to 150 m depth) from Blue Robotics Inc (USA) consisting of an acrylic plastic tube with a length of 300 mm and a diameter of 50 mm.

A total of 50 MetaMotionR (Mbleintlab Inc., USA) accelerometer meta-sensors were deployed during fishing trials. Two to three sensors were mounted on the lead line of trammel nets in selected fishing trials. These sensors monitored net movement (Table 1; Fig. 1B) using a 3-axis accelerometer that recorded data to an 8 Mb internal memory. A Windows-based command line base software was developed by Ocean-Drivers to set the movement sensors: activating/deactivating, modifying logging frequency, and downloading data. The accelerometers were programmed to log at 5–2 Hz, depending on soak time, to conserve storage capacity. The sensors were placed in waterproof deep-sea fishing light casings with a 3D-printed support.

During the 2021 fishing trials, cameras and sensors were attached to a single trammel net in each trial to evaluate differences in catch composition between nets with and without these devices. To minimize their effects on fishing performance, the cameras were designed with slight positive buoyancy, while sensors were small and neutrally buoyant.

### 2.3. Estimation of net movements during soaking

The movement of the nets during soaking was analyzed using video and accelerometer sensor data recorded during the experimental fishing conducted in 2021. The process of setting the nets became somewhat more intricate with the underwater cameras attached to the flotation line. Consequently, certain cameras became entangled in the nets, resulting in suboptimal positioning for recording the lead line of the net and the seabed. As a result, some recordings had to be excluded from the analysis. Videos from properly positioned cameras were visually inspected, paying special attention to the location and position of the lead line at the beginning and at the end of the soak time. Thus, for each camera, the presence or absence of movement was visually recorded. ImageJ software was then used to measure the distances between the lead line and a specific reference point (e.g., any easily identifiable structure such as a stone or burrow), with pixel measurements converted to centimetres using the size of the motion sensor in the captured images as a reference scale.

Data from the accelerometer sensors recovered after fishing were downloaded. Acceleration values were expressed in units of *g*, with 1 *g* corresponding to the acceleration due to gravity. Under static

conditions, accelerometer readings reflect only the gravitational force acting on the sensors. Consequently, the sensor output corresponds to the sum of gravitational acceleration and the inertial acceleration produced by the net's movement. The calculation of Dynamic Acceleration ( $DA_i$ ) involves subtracting the static acceleration component from the raw acceleration data collected by the accelerometer along each of the three orthogonal axes (*x*, *y*, and *z*). To achieve this, we first applied a smoothing process to the raw acceleration values for each axis, using a 2 s running mean (Shepard et al., 2008). Subsequently, the dynamic acceleration for each axis was determined by subtracting the smoothed values, which represent the static acceleration component (Shepard et al., 2008), from the original raw acceleration data. These dynamic portions of the signal were then converted into the Vectorial Dynamic Body Acceleration, i.e. *VeDBA* (Gleiss et al., 2011; Qasem et al., 2012; Wilson et al., 2006) derived by:

$$VeDBA = \sqrt{(DA_x^2 + DA_y^2 + DA_z^2)}$$

After data processing, the maximum *VeDBA*, average acceleration (mean *VeDBA*) and its standard deviation were calculated for each analysed device. All acceleration data were processed using the *filter()* function from the *stats* package to calculate the running mean, and the *reshape2* package from the R software ([www.r-project.org/](http://www.r-project.org/)).

### 2.4. Estimation of net movements during hauling

The movements of the nets during the hauling process were evaluated by visually analysing the underwater videos recorded during this process and with the data registered with the GPS of the boat's trajectories during the setting and hauling of the nets.

For all the cameras that were well positioned and recorded the entire hauling process in 2021 and 2022, including 66 cameras for the cuttlefish fishery and 46 for the spiny lobster fishery, the initiation and ending of the hauling process were documented. The process was considered to start when the net began moving or started collapsing (this process is described in more detail in the Results and Discussion sections). The end was determined when the net was lifted off the seafloor. Additionally, for all cameras analyzed, the degree of net collapse was categorized as follows: no collapse (when the distance between the camera and the seafloor remained constant), slight collapse (when the camera moved closer to the seafloor but remained about a meter away), or complete collapse (when the camera came within a few centimetres of the seafloor or made contact).

The GPS data recorded during the setting and hauling process were processed using the QGIS 3.8 software (<https://www.qgis.org>). In this case, the boat's position during the setting and hauling processes was used as an approximation of the position of the net. The trajectory data for each trammel net were selected using the initial and end position recorded with the GPS (Appendix B). For each net, the area between the dotted line corresponding to the trajectory of the setting and the trajectory of the hauling was measured with the *Measure Area* tool. This measured area was considered as the interaction area (IA) or the



displacement of the nets over the seabed. Also, the impact area of the anchoring weight of the trammel net was estimated. The trammel net has an anchor or weight at each end to fix the net to the seabed. This weight is usually formed by a concrete block of about 5–10 Kg. During the hauling process, this weight travels a certain distance over the seabed prior to being retrieved. The distance between the last point in the setting trajectory and the last point in the hauling trajectory was measured with the *Measure Line* tool, as an approximation of the distance travelled by the anchoring weight (DTAW).

## 2.5. Statistical analysis

Statistical analyses were performed to identify the factors influencing IA and DTAW. All analyses described below were carried out using the R software.

First, the relationships between IA or DTAW and fishing type (cuttlefish or spiny lobster fishery) were statistically assessed. The Shapiro-Wilk test for normality and Bartlett's test for homogeneity of variance were applied to evaluate whether the data met the assumptions required for ANOVA. If these assumptions were not met, the non-parametric Kruskal-Wallis test was employed instead.

Since cuttlefish and spiny lobster fishing were carried out under different conditions, a more in-depth analysis was carried out to identify the variables that affect the IA and the DTAW. The variables considered in this study were: depth, number of netting walls (reflecting the total trammel net length, with each netting wall measuring approximately 50 m), net recovery time (i.e., hauling time, in min), wave height (m), wind speed (m/s), and weight of benthic organisms (g). The meteorological data was obtained from the official website of *Puertos del Estado* (*Ministerio de Transporte y Movilidad Sostenible*, <https://www.puertos.es/es-es>). The correlation between explanatory variables and the IA and DTAW were analysed using a correlation matrix with the function *cor()* from the *corrplot* package. The matrix showed a high correlation between net recovery time and the number of netting walls, so net recovery time was excluded from the model. The maximum complexity models (assessed through Multiple Linear Regression Models) for the estimation of IA and DTAW were simplified using backward stepwise selection based on Akaike's Information Criterion (AIC; *Zuur et al., 2009*), using

the *stepAIC()* function from the *MASS* package. A log-transformation was applied to the IA and DTAW data to improve normality and stabilize variance. Additionally, the normality and homoscedasticity assumptions of the models were checked plotting the residuals (Q-Q plot, scale-location plot). To express the model's predictions in the original data scale, we used the *predict()* function and applied an exponential transformation to the predicted values. Analyses of variance and post-hoc Tukey's tests were used to identify significant differences among the factors.

Linear regressions were used to examine how benthic and commercial catch weights were influenced by IA and soak time. Soak time was analyzed only for spiny lobster fisheries, as it was constant across all cuttlefish fisheries. A log-transformation was applied to normalize data when necessary.

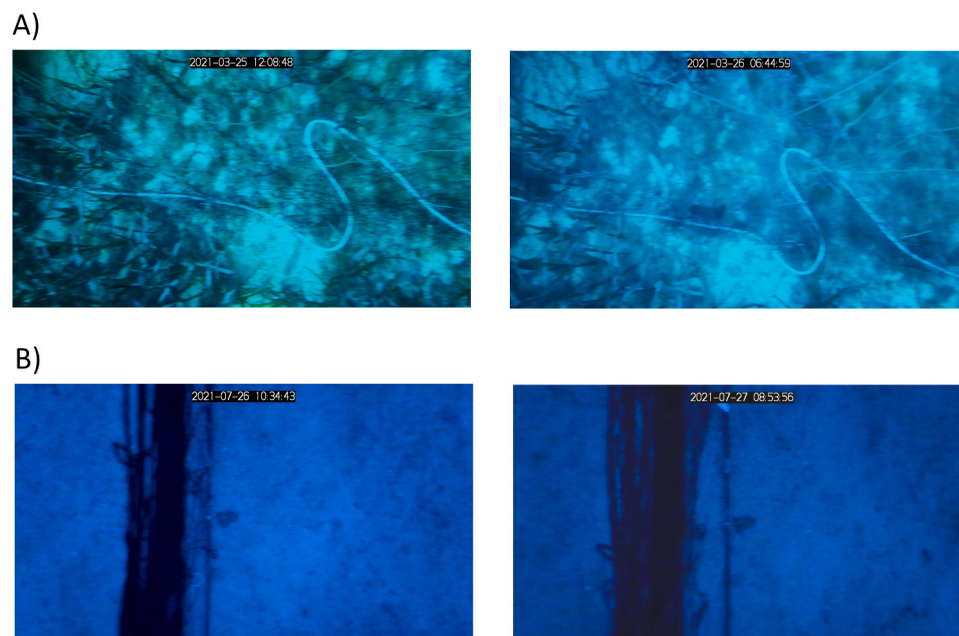
## 3. Results

### 3.1. Movement of the nets during soaking

Of the 60 cameras placed in the cuttlefish trammel nets during 2021, 38 of them were deployed in a suitable position to observe the movements of the lead line on the bottom.

Most of the analysed cameras (79 %) showed the nets remaining in the exact same position during the entire soak time, with the lead line maintaining its shape and location (Fig. 2A). This was confirmed by the environmental reference points. The rest of the cameras (21 %) evidenced a slight displacement of the lead line or a change in its shape while staying in the same place. For the images that showed movement, the measurements made between the lead line and a reference point presented a value of  $16.6 \pm 15.7$  cm (mean  $\pm$  SD). For the images with no movement, this value was of  $4.3 \pm 2.1$  cm, probably caused by slight camera position changes in the flotation line.

Of the 75 cameras placed in the spiny lobster trammel nets during 2021, 31 of them were correctly deployed. The visual inspection of these videos, showed that in most cases (96.8 %) the nets remained in the same exact position during the soak time (Fig. 2B), which corresponded to a distance of  $4.5 \pm 3.2$  cm (mean  $\pm$  SD) using the measurements made between the lead line and a reference point. Only one of the



**Fig. 2.** Images recorded by the underwater cameras: A) During a cuttlefish fishery (fishery IDP10 and camera T8) at the beginning (photo on the left) and at the end (photo on the right) of the soak time (more than 18 hours). B) During a spiny lobster fishery (fishery IDP19 and camera T6) at the beginning (photo on the left) and at the end (photo on the right) of the soak time (more than 22 hours).

cameras showed some movements of the net that consisted of a small displacement of the lead line in the same area. This displacement was estimated as a distance of 7.7 cm.

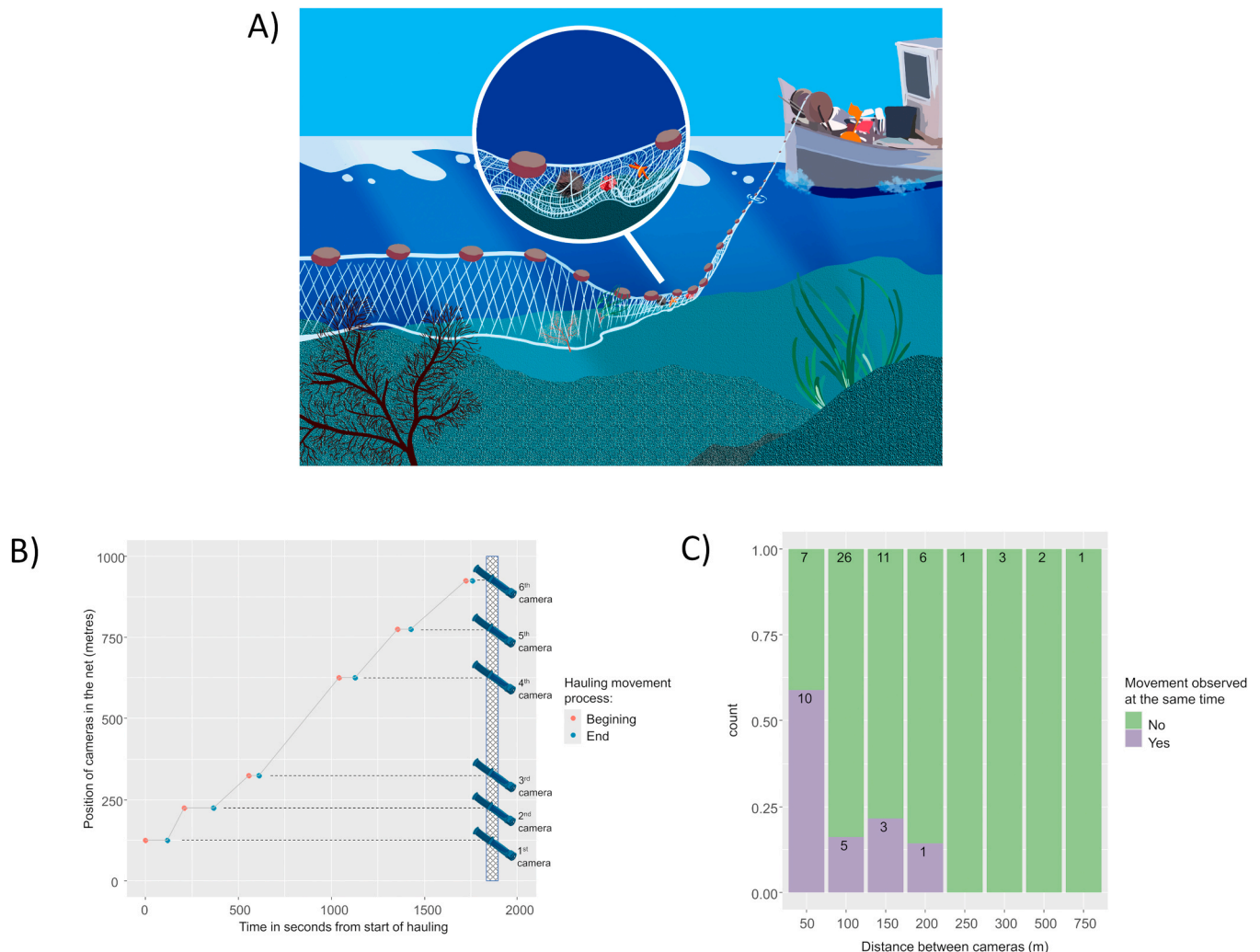
However, in all cases, the movement recorded by one camera was not registered in the other cameras in the same trammel net, indicating that the movement was specific to individual netting walls.

Furthermore, the movement of the nets during soaking was analysed from the data recorded by the accelerometer sensors. Of the total number of sensors installed, a random subsample of 14 sensors from each fishery was analysed. All the analysed accelerometer sensors presented very low values of VeDBA (Appendix C1), with the mean values of VeDBA ranging between 0.001 and 0.011 g (Appendix D). The maximum VeDBA values were also generally low (Appendix C2), for both cuttlefish and spiny lobster fisheries, although 5 of the sensors showed high values ( $> 0.1$  g). In these cases, videos from the cameras placed on the sensors were inspected. Two of the cameras did not record images while the high VeDBA values were recorded, so they were discarded. The other three cameras showed movement of the net caused by strong currents or an entangled catch, although the videos showed that those movements did not carry over to the lead line.

### 3.2. Movement of the nets during hauling

Different types of net interactions with the seabed were observed in video recordings during the hauling phase. One of the interactions involved the forward and lateral movements of the nets over the seabed. Additionally, a previously undescribed phenomenon was detected: the vertical collapse of sections of the net. This process was captured by the cameras attached to the flotation lines, which recorded footage that progressively got closer to the seabed and, in some instances, interacted with it. During this process, sections near the retrieval point were observed collapsing, causing all the netting material, including floats, to be dragged across the seafloor. These collapsed nets moved for a certain distance before being fully lifted from the bottom and hauled onto the boat's deck (Fig. 3A).

During the visual inspection of the recorded videos, it was observed how the nets interacted with benthic organisms during the hauling process (Appendix E). This interaction is caused by a combination of the two aforementioned processes: the collapse of the nets, which increases the contact area with the seabed, and the horizontal displacement of the nets over the seafloor. The affected organisms are sometimes merely knocked over or displaced, but in other instances, they are entangled in the nets and extracted with the catch. This phenomenon primarily occurs with organisms that have hard, protruding structures, such as sea



**Fig. 3.** Net movement processes during the hauling: A) Drawing that represents the vertical collapse of a section of the net before being lifted from the bottom during the hauling process (art by Llorenç Vidal). B) Example of how the movement of the net is progressively observed by the cameras according to its position in IDP8. C) Proportion of cameras that present (in purple) and do not present (in green) movement simultaneously as a function of the distance (in m) between them. Each consecutive camera located on the trammel nets were considered. Numbers on the bars correspond to the number of cameras considered.

urchins and calcareous algae.

This process was not simultaneously recorded by all cameras positioned along a trammel net. Initially, the collapse and/or displacement became evident in the camera positioned closest to the side of the net where hauling begins, and then progressively appeared in subsequent cameras (Fig. 3B). The duration of the nets' interactions with the seabed, including the displacement and collapse of the net, varied from 5 s to 19 min. This duration tended to be shorter for cuttlefish compared to lobster nets, with average times of  $2.4 \pm 1.7$  and  $4.7 \pm 4.4$  min (mean  $\pm$  SD), respectively. The length of the trammel net that was affected by the collapsed or folding process was estimated to be generally lower than 100 m, however, maximum length of over 200 m was occasionally recorded (Fig. 3C). The collapse process also presented a certain level of variability. In most instances, an intense collapse was observed (65 % for the cuttlefish and 51 % for the spiny lobster fishery), with the nets completely lying on the seabed. However, there were instances where no collapse occurred (26 % for cuttlefish trammel nets and 28 % for spiny lobster nets). In the remaining instances, only a minor collapse was observed (9 % and 21 % respectively).

Video recordings showed clear lateral and forward movement of the net over the seabed during the hauling phase. These movements were estimated in 95 of the 104 trammel nets (due to GPS recording failures), using the GPS data collected on board to quantify the DTAW and to estimate the IA. The IA was significantly higher in the spiny lobster fishery than in the cuttlefish fishery (Chi-square = 26.80, df = 1,  $p < 0.001$ ). IA for spiny lobster fishery was of  $31247.8 \pm 45881.7$  m<sup>2</sup> (mean  $\pm$  S.D.), while it was  $5569.8 \pm 7753.4$  m<sup>2</sup> for cuttlefish fishery. The DTAW was also significantly higher in the spiny lobster trammel nets (Chi-square = 29.66, df = 1,  $p < 0.001$ ). The averaged estimated distance was  $234.4 \pm 231.9$  m in the spiny lobster fisheries and  $72.3 \pm 57.1$  m in the cuttlefish fisheries.

After the AIC selection process, the IA final model includes the variables depth and length of trammel nets (expressed as number of netting

walls, *N.of.nets*).

The regression equation was:

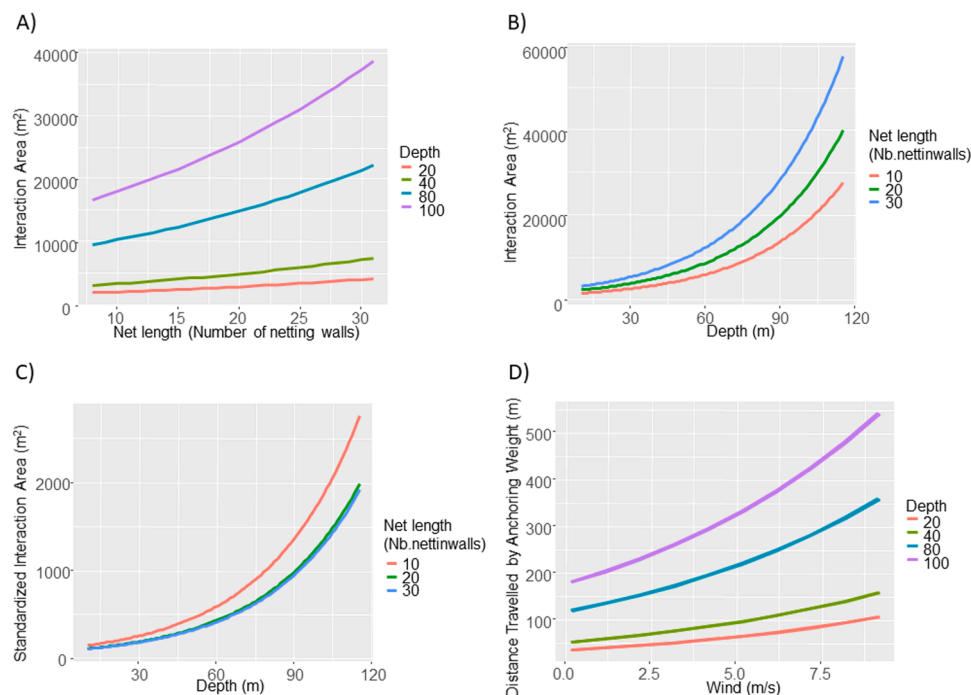
$$\log(IA) = 6.645 + 0.0278 \times \text{Depth} + 0.0366 \times \text{N.of.nets}$$

The multiple linear regression model was statistically significant ( $F_{2, 91} = 28$ ,  $p < 0.001$ ), and the multiple R-squared value was 0.367, thus 36.7 % of the variability in  $\log(IA)$  could be explained by depth and net length. The results of the model were summarized in the Appendix F1. As the number of nets increases, the IA increases for depths of 20, 40, 80 and 100 m (Fig. 4A). The post-hoc test suggested significant differences in the predicted IA among all these different Depth levels ( $p < 0.05$ ). Likewise, the predicted IA increased with depth considering nets of different length (10, 20 and 30 netting walls; Fig. 4B). A Tukey post-hoc test showed significant differences between these net length levels ( $p < 0.001$ ). Finally, the analysis was repeated by standardizing IA based on the number of netting walls to assess the relative effect of each panel depending on trammel net length. The IA for nets with 10 netting walls was significantly higher than for longer nets (Fig. 4C). A post-hoc test confirmed that IA for trammels with 10 netting walls was greater than for those with 20 or 30 walls ( $p < 0.001$ ).

For the DTAW, the most parsimonious model included depth and wind speed, resulting in the following regression equation:

$$\log(DTAW) = 3.104 + 0.0207 \times \text{Depth} + 0.1226 \times \text{Wind}$$

The model was statistically significant ( $F_{2, 92} = 45.18$ ,  $p < 0.001$ ), with an R-squared value of 0.484, indicating that 48.4 % of the variability in  $\log(DTAW)$  was explained by these variables. The results of the model were summarized in the Appendix F2. DTAW increased with wind speed at depths of 20, 40, 80, and 100 m (Fig. 4D). Post-hoc tests indicated significant differences in DTAW across depth levels ( $p < 0.001$ ), except between 20 and 40 m ( $p = 0.297$ ).



**Fig. 4.** A) Linear regression model to predict the Interaction Area (IA, in m<sup>2</sup>) based on the predictor variables Number of netting walls (which express the trammel net length) and Depth (in m), treating Depth at the levels of 20, 40, 80 and 100 m. B) Predicted IA by the linear regression model using the variable Number of netting walls at the levels of 10, 20 and 30 netting walls of length. C) Linear regression model using the standardized IA (i.e., the predicted IA of each netting walls) to estimate the relative effect of trammel nets with different lengths. D) Linear regression model to predict the Distance Travelled by the Anchoring Weight (DTAW, in m) based on the predictor variables Wind Speed (in m/s) and Depth (in m), where Depth is considered at the different levels. Note that, in all the cases, a linear model was fitted to the log-transformed response variable, resulting in a nonlinear trend when back-transformed to the original scale.



### 3.3. Assessment of benthic catches

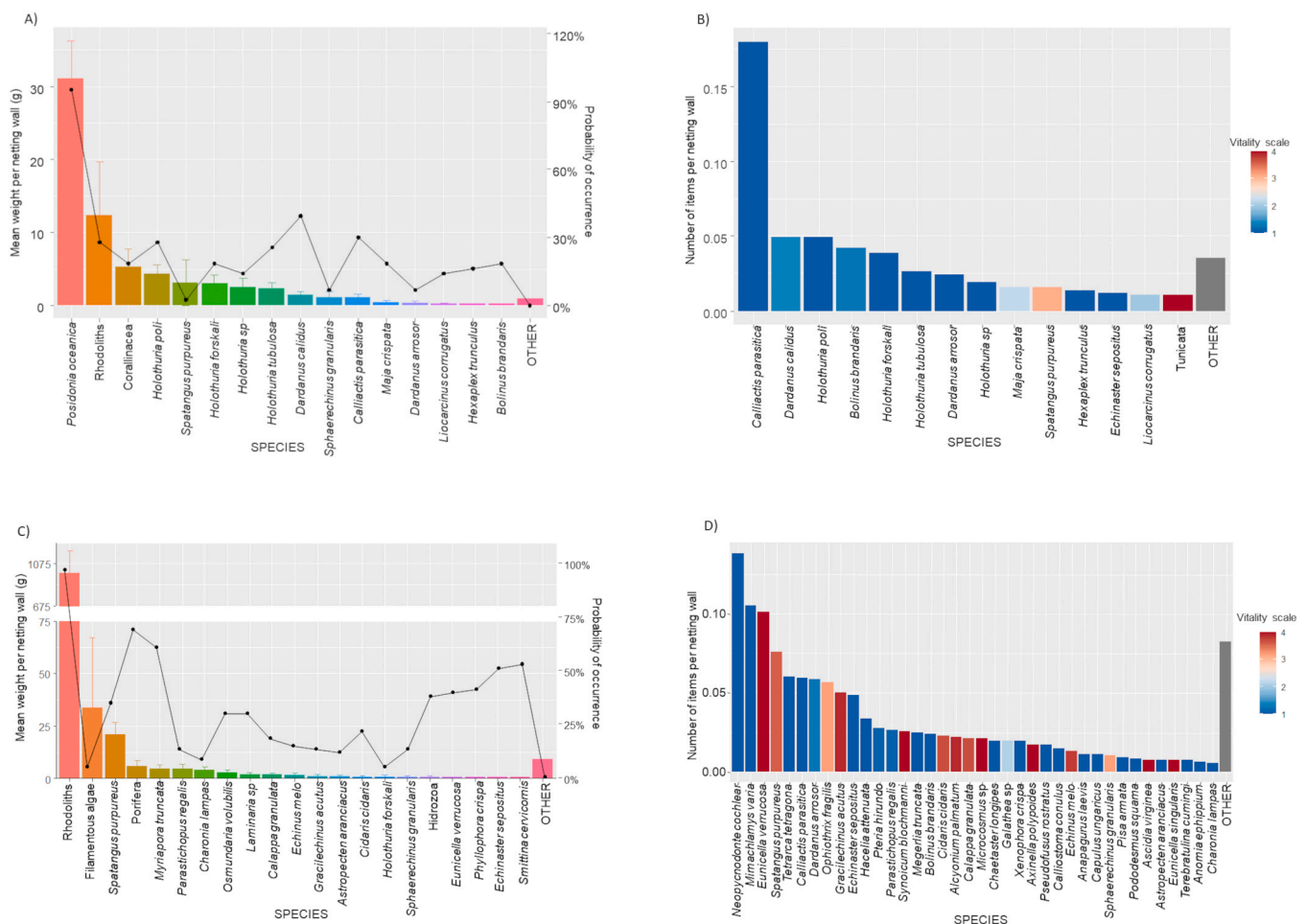
Benthic species' catches in cuttlefish fisheries represented an average weight of  $69.9 \pm 84.3$  g per netting wall. These catches were classified into 35 taxa, 26 of which were identified at the species level, while the rest were classified at higher taxonomic levels. The most abundant category (in weight; Fig. 5A) was *Posidonia oceanica*, followed by free nodules of red calcareous algae (rhodoliths, composed of multiple species such as *Lithothamnion* spp.) and some species of the sea cucumber genus *Holothuria*. The most frequently captured invertebrates (Fig. 5B) were the anemone *Calliactis parasitica*, and their hosts *Dardanus calidus* and *D. arrosor*, and various species of *Holothuria*. The health status estimated for these species were high (near to 1 in the vitality scale), however other more fragile animals such as the sea urchin *Spatangus purpureus* or specimens of the Tunicata subphylum showed poorer health status (vitality scale higher than 3; Fig. 5B).

A total of 17 of the 27 identified benthic species have been classified according to their vulnerability (Fig. 6A), which represents the 86.6 % of the total weight of benthic catches per netting wall in the cuttlefish fishery. The most abundant vulnerability category (61.3 %) was “MSFD indicators of GES”, represented mainly by the species *Posidonia oceanica*, but also by rhodoliths. Benthic species allocated to the vulnerability category “AMBI very sensitive to disturbance” accounts for 14.9 % of the weight, and mostly correspond to the echinoderm species *Holothuria forskali*, *Spatangus purpureus*, *Holothuria tubulosa* and *Sphaerechinus*

*granularis*.

Benthic catches for the spiny lobster fisheries were classified into 121 taxa, 95 of which were identified at species level and the rest at higher levels. In total, these catches represent 675.9 g of weight per netting wall. The most abundant capture (in weight; Fig. 5C) was rhodoliths. The following most abundant capture was an unidentified filamentous alga and the sea urchin *Spatangus purpureus*. The analysis focused only on invertebrate categories (Fig. 5D) showing a large variety of different species. The most abundant categories are species from the class Bivalvia as *Neopycnodonte cochlear* or *Mimachlamys varia*, the gorgonian *Eunicella verrucosa*, and the sea urchin *Spatangus purpureus*. These last two species also presented a low health condition (vitality scale higher than 3), with a very low likelihood of survival.

A total of 48 of the 95 identified species were classified according to their vulnerability (Fig. 6B), which represent the 88.3 % of the total benthic captured weight. The most abundant category, with an 81.9 % of the total weight, was “MSFD indicators of GES” and was mainly represented by algal species of the genus *Lithothamnion* (i.e., main species forming the rhodolith beds), but also by the algae *Osmundaria volubilis* and *Laminaria rodriguezii*. The second most abundant category represented just the 3.9 % of the total weight and was composed mainly by the sea urchins *Spatangus purpureus* and *Gracilechinus acutus*, and the starfish *Astropecten aranciatus*. Finally, the IUCN category “Vulnerable” and “Near threatened” in the Balearic Islands, which represented the 1.0 % and 0.1 % of the total weight, was composed mainly by the



**Fig. 5.** Benthic catches in cuttlefish trammel nets estimated as A) abundance (mean weight, in g, per netting wall with the error bar), and their probability of occurrence represented with black points; and as B) frequency of benthic catches expressed as number of items per netting wall where the colour scale represents the vitality estimated on board. Benthic catches in the surveyed trammel nets of spiny lobster fishery estimated as C) abundance (mean weight, in g, per netting wall with the error bar), and their probability of occurrence represented with black points; and as D) frequency of benthic catches expressed as number of items per netting wall where the colour scale represents the vitality estimated on board.

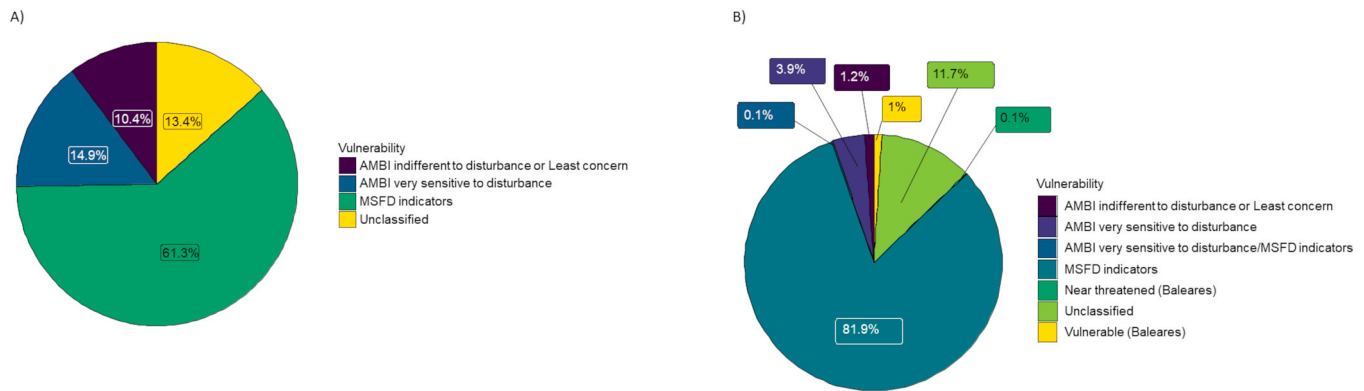


Fig. 6. Pie chart that represents the percentage of weight of benthic catches for the different vulnerability categories in A) cuttlefish fishery, and B) in spiny lobster fishery.

gastropod *Charonia lampas* and the sponge *Axinella polypoides*, respectively.

### 3.4. Factors affecting benthic catches

Linear regressions analyzed the relationship between benthic catch weight and IA for cuttlefish and spiny lobster trammel nets (Appendix G). Total benthic catches from cuttlefish fisheries showed a significant relationship with IA, including the dominant species, *Posidonia oceanica* ( $p < 0.001$ ). In contrast, this relationship was not significant for spiny lobster fisheries ( $p > 0.05$ ), where neither total benthic catches nor rhodolith catches were significant.

Additionally, soak time, which ranged from 10.4 to 174.8 h in spiny lobster fisheries, showed no significant relationship with either total benthic catches or the main commercial species, *Palinurus elephas* ( $p > 0.05$ ).

## 4. Discussion

### 4.1. Seabed interaction during different fishing phases

The interaction of static nets with the seabed has been evidenced in several studies through the capture of algae, seagrasses, or benthic invertebrates (Catanese et al., 2018; Shester and Micheli, 2011). However, until now, it was not clear how and when such interactions occurred. Contrary to what our results show, there was speculation that benthos (for example, rhodoliths) became more entangled the longer the nets remained on the seabed, suggesting a direct relationship between the soak time and the amount of benthos captured (Cabanellas-Reboredo et al., 2018). The present study evidenced that trammel nets remained largely static during the soaking phase and thus showed no significant interaction with the seabed. In fact, a similar study conducted by Savina et al. (2018), using underwater cameras to determine the movement of gillnets during soaking, also estimated limited lateral net displacement.

In our study, underwater cameras revealed that during hauling, nets significantly interacted with the seabed through two simultaneous processes: net collapse onto the seabed and net displacement caused by boat drift. Although experienced fishers had suspected these processes, they have not been scientifically demonstrated or quantified before. In a participatory workshop with the fishing sector, the results from the study were discussed, and one interpretation was that net collapse is likely caused by unequal retrieval of the lead and float lines within a netting panel. The float line, typically shorter and lighter, is retrieved faster, while the heavier lead line recovers more slowly due to friction with the seabed. This effect is exacerbated when boat drift, influenced by wind or currents, increases the angle of the net relative to the boat, adding tension to the float line and causing net collapse near the seabed.

In addition to the visual evidence obtained with underwater

cameras, the GPS tracks were used as an approximation of the area swept by the static nets while they are being retrieved. The area that is in direct contact with the fishing gear (i.e., footprint) was on average lower for trammel nets targeting cuttlefish than for those targeting spiny lobster (5569.8 m<sup>2</sup> and 31247.8 m<sup>2</sup> respectively). The average estimated footprint for the spiny lobster trammel net (0.03 km<sup>2</sup> for trammel nets with 20 netting walls, at a depth of approximately 100 m) was notably higher than estimates for other static fishing gears. For example, Kopp et al. (2020) observed a swept area of less than 2 m<sup>2</sup> for individual fishing pots during retrieval in the Bay of Biscay. While comparisons with gillnets deployed along the Danish coast show more similar values, Savina et al. (2018) estimated the swept area for lightweight gillnets at around 0.04 km<sup>2</sup> and 0.01 km<sup>2</sup> for heavier gillnets. Despite this, the average footprints estimated in this study were much smaller than the estimates obtained from towed gears such as trawls, seines, and dredges. Eigaard et al. (2016) concluded that Scottish seining has the largest overall gear footprint with a ~1.6 km<sup>2</sup> swept area estimated per hour, followed by otter trawling for *Nephrops* and mixed demersal fish (~1.2 km<sup>2</sup>) and beam trawling (~0.2 km<sup>2</sup>). Since these impacts are estimated per hour and mobile gears are generally towed for several hours a day (Kaiser et al., 1996; Sánchez et al., 2007), the magnitude of the impact area of the trammel nets is considerably lower when compared on the same temporal scale (considering 24 h of soak time). The significant impact of trawl nets on the seabed has led to their regulation and restriction under various legal frameworks. In fact, their use is strictly prohibited over particularly vulnerable habitats such as *Posidonia* meadows and rhodolith beds, according to the Council Regulation (EC) No 1967/2006, and the Spanish Order APA/254/2008.

The interaction area estimated in this study increased with the depth and with the trammel nets length. Nevertheless, when the IA was standardized by netting wall, the relative effect per panel was highest for shorter trammel nets (i.e. 10 netting walls). A possible explanation is that longer nets are heavier and provide greater anchoring during net retrieval, minimizing boat drift and reducing the displacement during hauling.

However, it is important to note that the estimates made for both the interaction area and the distance travelled by the anchoring weight are approximations, as the geo-referenced position is obtained from the boat and the actual positions of the nets are unknown. This approximation inherently carries some error, which can increase with depth and lead to an overestimation of its effects on IA and DTAW. This occurs because, at greater depths, retrieving the anchoring weight takes longer, allowing the boat to drift more in the absence of anchorage.

### 4.2. Observed consequences of seabed interaction during hauling

The lateral movement and collapse of the net during hauling primarily affected benthic organisms. However, the impact of fishing gear



depends not only on the interaction area or footprint, but also on how it physically affects the seabed and its organisms. The interaction of the trammel net with the seabed appeared to be minimal when compared to other fishing gears such as trawls and dredges that have the potential to smother, damage and kill benthic organisms (Kaiser et al., 2006). Within the cuttlefish fishery, the recordings showed that the net generally passed over the seagrass without dislodging seagrass shoots. Despite this, the most abundant benthic organisms discarded were habitat forming plants and algae, *Posidonia oceanica* for the cuttlefish fisheries (31 g per netting wall) and rhodoliths (i.e., red coralline algae like *Lithothamnion*; 987.7 g per netting wall) for the spiny lobster fisheries. These amounts were consistent with previous studies, which reported 20.2 g and 41 g per netting wall/panel of *P. oceanica* for the cuttlefish fishery, as observed by Sardo et al. (2023) and Gil et al. (2018), respectively. Similarly, approximately 500 g per netting wall of rhodoliths were obtained by Catanese et al. (2018) in the spiny lobster fishery. Both seagrass and rhodoliths are particularly sensitive due to their slow growth rate. *Posidonia oceanica* horizontal rhizomes show elongation rates of 1–6 cm per year and vertical rhizomes 0.1–4 cm per year, being the lowest reported for marine angiosperms (Hemminga and Duarte, 2000). Nevertheless, the impact of trammel nets on *Posidonia* is considered minimal, as indicated by the low overall total bycatch biomass within the cuttlefish fishery. It remains unclear whether the captured *Posidonia* shoots were dislodged by the nets, or if they were merely loose fragments already present on the seabed, commonly accumulated after natural disturbances like storms (Di Carlo et al., 2005). While it is impossible to determine the precise origin of the shoots solely by examination, video observations during net hauling show infrequent uprooting of *Posidonia*. This suggests that the majority of captured shoots likely originate from these natural accumulations.

Similarly, rhodolith species are sensitive species due to their extremely slow growth rate of approximately 1 mm (0.5–1.5 mm) per year (Bosence and Wilson, 2003). Rhodoliths that reach the deck of the ship may undergo fragmentation due to net cleaning procedures. Although apparently this does not cause any adverse effects on their survival (Wilson et al., 2004), rhodoliths fragmentation in smaller pieces would reduce the habitat complexity and potentially its ability to store carbon (Tuya et al., 2023). Moreover, rhodoliths are not tolerant to desiccation due to their low water content and lack of protective mucilage, showing a significant decrease in survival when they are out of the water for longer than 5 min (Wilson et al., 2004).

As far as invertebrates are concerned, the video observations showed that some taxa, such as sea urchins, appeared to be pushed and dislocated by the gear, but not crushed or visibly damaged. Organisms initially reaching the deck were overall in good condition. However, once on board, they face the highest mortality risk due to prolonged air exposure, increased temperatures, and net clearing procedures. Fragile organisms like sea urchins that become entangled in the net are often fractured by clubs to speed up net cleaning. Those that remain intact have a higher chance of survival if not exposed to prolonged air and heat. Thus a prompt return of discards to the sea is recommended.

Nevertheless, sessile, less flexible, and highly branched species like gorgonians and sponges are prone to damage from entanglement and uprooting. This vulnerability was evident in bycatch data, particularly from the spiny lobster fishery, which operates in highly diverse biogenic seabeds (de Juan et al., 2023). For example, a 20-panel trammel net in this study captured an average of two *Eunicella verrucosa* gorgonians and 6 g of *Axinella polypoides* sponge, both with low survival rates upon return to the sea, as reflected by their high scores on the vitality scale. Therefore, in habitats with a high abundance of these organisms, such as coralligenous habitats, the impact of trammel nets may be particularly significant. Coralligenous habitats are important ecosystems in the Mediterranean Sea, due to their complex structures, high environmental heterogeneity, and rich biodiversity of algal and animal foundation species. Furthermore, their low growth rates make them especially vulnerable to physical disturbances (Ballesteros, 2006; Martin et al.,

2014). While the current study fishing trials did not occur over this habitat type a considerable impact would have been expected considering the mechanisms of net interactions described within this paper. These findings highlight the habitat-specific impacts of trammel nets.

Although traditionally considered to have minimal physical impacts, this study shows that trammel net effects cannot be ignored. Historically, traps and pots were widely used in the Mediterranean to catch spiny lobsters, that likely had lower habitat impacts. However, these methods were largely abandoned due to intensified fishing efforts, driven by fleet modernization and market demand (Amengual-Ramis et al., 2016; Goñi et al., 2003). Recent studies, however, emphasize the benefits of pots, including reduced discards and bycatch, seabed preservation, species and size selectivity, and improved catch quality (Petetta et al., 2021).

Despite this, the damage caused by trammel nets is still considerably less than the severe impacts of bottom trawling on biogenic habitats. These habitats often recover only over the long term after suffering the effects of bottom towed fishing gears, and in some cases, the damage can be irreversible. This is especially true for habitats dominated by slow-growing species, such as rhodolith beds, deep corals, and sponge bottoms (Barbera et al., 2003; Ordines et al., 2017).

#### 4.3. Conclusions and recommendations

Trammel nets, although less damaging than other fishing gears, can still impact sensitive benthic habitats and species, particularly during the hauling process. Net collapse and displacement caused by vessel drift during retrieval were identified as key contributors to these interactions. Effective mitigation strategies should focus on minimizing boat drift during hauling by keeping the vessel directly above the net. This can be achieved by synchronizing the boat's movement and winch speed to maintain an approximately 90° retrieval angle, although local factors such as wind, currents, and manual net handling may complicate this process. A promising mitigation approach could be the adoption of dynamic positioning systems, which use sensors to stabilize the vessel and reduce drift. These systems are now common on recreational boats but have yet to be adapted and tested for professional fishing operations.

Our results also showed that shorter nets have proportionally larger interaction areas than longer nets, suggesting that fisheries management could benefit from regulating fewer, larger nets rather than promoting shorter ones, which may increase benthic impacts. Furthermore, areas with high densities of sensitive taxa, such as sponges and gorgonians, as well as ecologically valuable habitats, should be avoided.

Ongoing efforts to regulate and mitigate the impacts of trammel nets are critical for sustaining biodiversity and the populations upon which fisheries depend. Additionally, future research should aim to identify threshold fishing intensities that compromise seabed integrity, facilitating better alignment with conservation goals, such as those outlined in the European Marine Strategy Framework Directive (MSFD; 2008/56/EC).

#### CRediT authorship contribution statement

**Catanese Gaetano:** Resources, Investigation. **Hinz Hilmar:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **de Juan Silvia:** Writing – review & editing, Conceptualization. **Disdier-Gómez José María:** Resources, Investigation, Data curation. **Gil María del Mar:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization.

#### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Chat GPT in order to improve language and readability of some sections. After using

this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

## 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.

## Acknowledgments

The authors are grateful for the invaluable collaboration of the fishers that collaborated in the on board surveys and contributed with their knowledge and perceptions to this study. Also, we would like to thank the *Federació Balear de Confraries de Pescadors* (FBCP) and Antoni M. Grau of the Direcció General de Pesca y Medio Marino of the Balearic Island for their collaboration and support. This study was funded by the Biodiversity Foundation of the Ministry for the Ecological Transition, through the FEMP Pleamar Programme, and the LIFE IP INTEMARES, as part of the project TRASMAR “Assessment of the impact of trammel net fishing on benthic habitats to innovate mitigation measures in collaboration with the fishing sector in the Balearic Islands”. This work is a contribution of the joint research unit “LIMIA-IRFAP”. Also, this research has been developed in the framework of the Centre of Excellence ‘Maria de Maetzu’ accredited to the IMEDEA (CEX2021-001198). SdJ was supported by a Ramon y Cajal postdoctoral grant funded by the Ministry of Science and Innovation (Plan Estatal I+D+I, 2017–2020; grant no. RYC2020-029062-I).

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.fishres.2025.107397](https://doi.org/10.1016/j.fishres.2025.107397).

## Data availability

Data will be made available on request.

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