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CATCHABILITY AND SURVIVAL OF THE RESOURCES DURING FISHING OPERATION

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Summary

Abstract

The Strait of Sicily (central Mediterranean Sea) is considered one of the most productive areas for demersal fishing in the Mediterranean basin. In the Strait of Sicily, such as many Mediterranean fisheries, bottom trawling fleets predominate, being responsible for a high amount of total catches and, in many cases, yielding the highest earnings among all the fishing sub-sectors. In particular, the most practiced bottom trawl fishery of the area is the crustacean one such as the deep-water rose shrimp (*Parapenaeus longirostris* Lucas, 1846) and the giant red shrimp (*Aristaeomorpha foliacea* Risso, 1827) trawl fisheries. However, in the Strait of Sicily, the landing of *P. longirostris* is higher compared to the other fishable resources. In this bottom trawl fisheries, *P. longirostris* is the main target species, *Merluccius merluccius* Linnaeus, 1758 is the main commercial by-catch, and *Trachurus trachurus* Linnaeus, 1758, is the main unwanted by-catch. Considering that, in the Strait of Sicily, according to the most recent assessments, *M. merluccius* is in overexploitation and overexploited status whereas *P. longirostris* is in overfishing, the present Ph.D. thesis aims to test and evaluate by-catch reduction devices (BRDs) that minimize the retention of undersized fish and do not penalize revenues of the fishing industry. Considering that a fraction of fish that escape from fishing gear or that are rejected at the sea probably does not survive (unaccounted mortality), it is a major concern for sustainable fisheries management, as unaccounted mortality may lead to biased stock assessment since they will tend to underestimate fishing mortality and overestimate stock size. In this context, in the present Ph.D. thesis, the escape survival (i.e. survival of the fish escaped through the trawl net codend) of the *Mullus barbatus* Linnaeus 1758 and the discard survival (survival of fish rejected at the sea after being hauled on deck) of *T. trachurus* were evaluated for the first time in the central Mediterranean Sea.

The effect of artificial lights mounted on the headrope trawl net on the catch of *P. longirostris*, *M. merluccius*, and *T. trachurus* was tested in a survey carried out onboard a commercial trawler. Overall, the test net catch rates were not significantly higher than those of the control net (Kruskal-Wallis test, $p > 0.05$), except for *P. longirostris* ($p < 0.05$). Conversely, the two-tailed Kolmogorov–Smirnov test revealed statistical differences in the size structure of *P. longirostris*, *M. merluccius*, and *T. trachurus* between the test and control nets ($p < 0.05$). Using generalised linear mixed models, the test net was found to yield higher catches of undersized individuals of the three species and adults of *P. longirostris* than the control net.

In paper 2, two types of BRDs, i.e. a sorting grid (herein Grid-T45 40 mm) and a T90 50 mm codend, were compared to a typical commercial bottom trawl net (control), in terms of size structures and catch per unit effort. Results showed that the landing per unit effort (LPUE) of *P. longirostris* was higher for the net with Grid-T45 40 mm although they did not differ significantly from the control

net. Conversely, the discard per unit effort (DPUE) of the control net were significantly higher than both BRD configurations. For *M. merluccius*, slightly higher LPUE were recorded using the T90 50 mm codend when compared to the control but this result was not statistically significant. The lowest DPUE was found for T90 50 mm codend with significant differences if compared to the control and Grid-T45 40 mm. The catch comparison on the size structures analysed through generalised linear mixed models, highlighted that the Grid-T45 40 mm was more effective in catching adults of *P. longirostris* whereas T90 50 mm codend resulted more selective for adults *M. merluccius*.

As for escape survival concerns, it has been shown that *M. barbatus* individuals from control sampled by demersal trawl net, with open codend, have high survival 94% probability (87-97%, 95% Confidence Interval, CI) and minimal injuries, while fish escaping through codend meshes had significantly increased injuries and reduced survival 63% (55-70%, 95% CI). During 7 days of captive monitoring, mortality was highest in the treatment group in the first 24 hours, while all mortality for both groups ceased within 48 hours.

The results of the *T. trachurus* discard survival experiment showed that after a commercial bottom trawl fishing operation, its probability of surviving is very low. The most important factor affecting the probability of survival resulted be delta T, depth, and haul duration even if also condition factor, air exposure, season, and injuries affected significantly the probability of survival of the species.

In conclusion, the use of underwater lights in Mediterranean trawl fisheries should be carefully regulated through ad hoc measures that are currently lacking, to minimize the potential impacts of artificial light on some already overexploited stocks. Even if further works should be carried out in the future to test BRDs performances in different areas and seasons, the T90 50 mm codend and the Grid-T45 40 mm seem promising tools to reduce the catch of undersized individuals and contribute to mitigating the current overfishing of *P. longirostris* and *M. merluccius*. The escape survival of *M. barbatus* was high and thanks to an improved methodology the bias in the sampling was minimized. However, for improved stock assessment of *M. barbatus*, the experiment should be repeated to provide accurate escape mortality estimates. While the discard survival of *T. trachurus* was very low and according to the landing obligation (Reg. EU 1380/2013) all the juveniles of the species should be landed.

1. Introduction

1.1 The impact of the fishing activities from an ecological perspective

International efforts to address the sustainability of the world's fisheries have intensified in recent decades due to the increasing awareness of the poor status of global fish stocks (Vasconcellos and Unal, 2022). In particular, in the Mediterranean basin, despite concerted efforts to establish an effective legal framework and ensure the implementation and compliance of the fishery sector, 75% of the assessed stocks in the Mediterranean are still considered to be threatened by overfishing (FAO, 2022). Among the fisheries that mostly contribute to the overfishing of the stocks, bottom trawling can be considered one of the most impactful, also due to the significant quantities of organisms thrown back into the sea: the so-called discard. The definition of discards includes incidental catches of non-target and juvenile species that are discarded due to their low or null economic value or for legal reasons (GFCM, 2018). Discard' activity occurs because many fishing gears, mostly bottom trawl, are insufficiently size-selective (Tsagarakis et al., 2017) and they target species that often inhabit areas occupied by a wide range of other species (multi-species fishery) (Fiorentino and Vitale, 2021). Therefore, managing a multi-species fishery is fraught with difficulties because the different shapes, behaviors, sizes, etc of most fish and invertebrates prevent to select a single species in shared habitats. As a result, fish stock management in the Mediterranean is mainly based on input restrictions, i.e. closed areas and seasons, limitations of the fishing effort, minimum mesh size, minimum conservation reference sizes (MCRSs). It is worth recalling, as in bottom trawl fisheries, the MCRS of the organisms is the more important output restriction that can be considered (Lleonart and Maynou, 2003; Lucchetti et al., 2014; Nolde Nielsen et al., 2015; Fiorentino and Vitale, 2021). Indeed, the so-called landing obligation (or "discard ban") of the European Common Fisheries Policy (Reg. EU 1386/2013), introduced a ban on discards of regulated species, incentivizing the design and adoption of technical solutions that diminish the amount of discard. In addition, the resolution of the General Fisheries Commission for the Mediterranean GFCM31/2007/3 (GFCM, 2007) requires the Mediterranean Member States to replace the diamond mesh in the cod end with the 40 mm square mesh. The objective for such fisheries will be therefore to find a mesh or by-catch reduction device (BRD) that minimizes the retention of undersized fish and does not penalize revenues of the fishing industry. For a trawl gear to be truly selective, the fish entering the net should be filtered to ensure that those that are small enough to pass through the meshes can escape, whereas those above the MCRS are retained (Glass and Wardle, 1995; Glass et al., 1995).

1.2 The study area: Strait of Sicily

The Strait of Sicily is an important transitional area in the central Mediterranean Sea, separating the Eastern and Western basins (Figure 1). According to the definition by the General Fisheries

Commission for the Mediterranean (GFCM) of Geographical Sub-Areas (GSAs) (GFCM, 2009), the Strait of Sicily encompasses different fisheries areas: GSA12, GSA13, GSA14, GSA15, and GSA16.

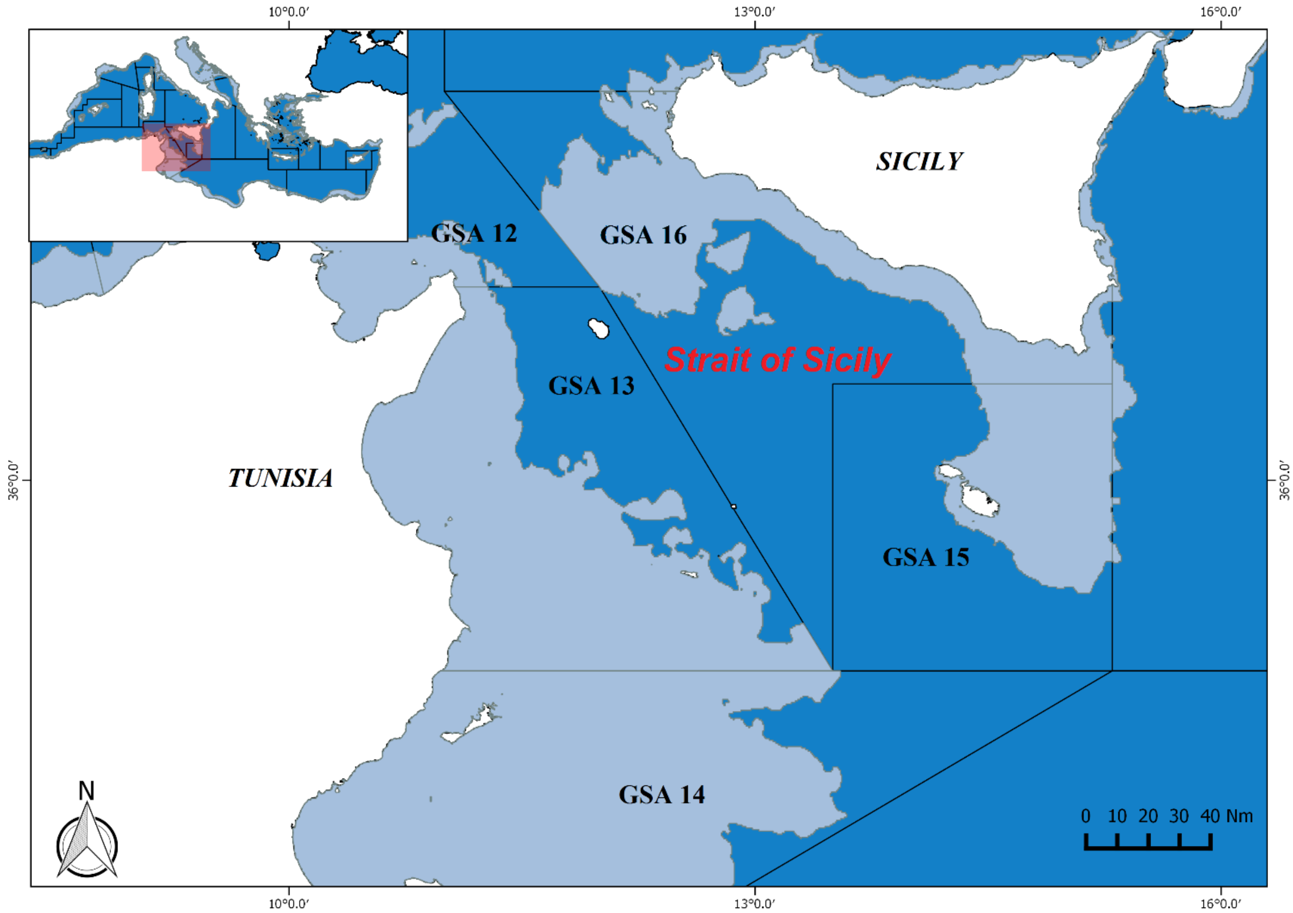

Figure 1 Geographical representation of the Strait of Sicily and its geographical sub-areas (according to GFCM 2009)

Currently, the Strait of Sicily is defined as the entire marine area which separates Italy, Malta and Tunisia, and which extends to the western coast of Libya. The European and the African continental shelves are separated by deep water in the middle part of the Strait of Sicily. The shelf is wider off the south coast of Tunisia than it is off Sicily. In its narrowest part, between Cap Feto (Italy) and Cap Bon (Tunisia), the Strait of Sicily is 145 km wide. In oceanographic terms, the Strait of Sicily is characterized by the cold and less salty Atlantic waters coming from the western side of the Mediterranean, and the Levantine Intermediate Waters (warmer and saltier) coming from the east. The Atlantic waters entering the Strait of Sicily area originate in two streams, the Atlantic Tunisian Current in the south and Atlantic Ionian Stream in the north. These two streams respectively generate upwelling and down-welling along the Sicilian and Tunisian coasts. The Atlantic Ionian Stream also generates two main gyres or vortexes, namely the Adventure Bank Vortex and the Ionian Shelf Break Vortex. These oceanographic features contribute to making the Strait of Sicily one of the most productive areas for demersal fishing in the Mediterranean (Di Lorenzo et al., 2018; Jarboui et al., 2022).

1.2.1 The most important fishing activity in the Strait of Sicily: the crustacean trawl fishery

In the Strait of Sicily, such as many Mediterranean fisheries, bottom trawling fleets predominate, being responsible for a high amount of total catches and, in many cases, yielding the highest earnings among all the fishing sub-sectors (FAO, 2022). In this context, the Strait of Sicily constitutes an important fishing area for demersal resources in the central Mediterranean Sea and hosts several important marine fisheries. Among them, Mazara del Vallo is the main port for demersal fisheries; its fleet represents the main commercial fleet of trawlers in the Strait of Sicily and one of the most important fleet in the Mediterranean Sea (Milisenda et al., 2017). In particular, the most practiced bottom trawl fishery of the area is the crustacean one such as the deep-water rose shrimp (*Parapenaeus longirostris* Lucas, 1846) and the giant red shrimp (*Aristaeomorpha foliacea* Risso, 1827) trawl fisheries. However, in the Strait of Sicily, the landing of *P. longirostris* is higher compared to the other fishable resources (Maiorano et al., 2019). Importantly, in the *P. longirostris* bottom trawl fisheries of the Strait of Sicily, according to Milisenda et al. (2017) and Geraci et al. (2021), *P. longirostris* is the main target species, the European hake, *Merluccius merluccius* Linnaeus 1758, is the main commercial by-catch, and Atlantic horse mackerel, *Trachurus trachurus* Linnaeus 1758, is the main unwanted by-catch. Considering that, in the Strait of Sicily (Geographical Sub-Areas, GSAs 12-16), according to the most recent assessments, the *M. merluccius* is in overexploitation and overexploited status (Falsone et al., 2021) whereas *P. longirostris* is in overfishing (Gancitano et al., 2021), the GFCM, based on a proposal by the European Union, adopted Recommendation GFCM 44/2021/12 on a multiannual management plan for bottom trawl fisheries exploiting demersal stocks in the Strait of Sicily (geographical subareas 12 to 16). In particular, the aim of the Recommendation GFCM 44/2021/12 is to ensure the conservation and sustainable use, at the biological, social, economic, and environmental level, of marine living resources in the GFCM area of application; recalling that the GFCM shall give particular attention to measures to prevent overfishing and minimize discards as well as to the potential impacts on small-scale fisheries and local communities.

1.3 Unaccounted fishing mortality

Unaccounted fishing mortality is the mortality due to fishing activities that to date is not taken into account in the classical stock assessment models. Unaccounted fishing mortality can be classified into two main categories: discard and escape mortality. Discard mortality refers to animals that are caught and released back to sea after being brought to deck. Escape mortality is defined as the process that leads animals to die after contacting the fishing gear without being retained by it (Gilman et al., 2013). Escape mortality can include fish escaping through meshes during haul-in (Suuronen et al., 1996), unwanted catches released before brought on board (slipping) (Lockwood et al., 1983;

Stratoudakis and Marcalo, 2002), and fish lost when nets burst (Misund and Beltestad, 1995) (Figure 3).

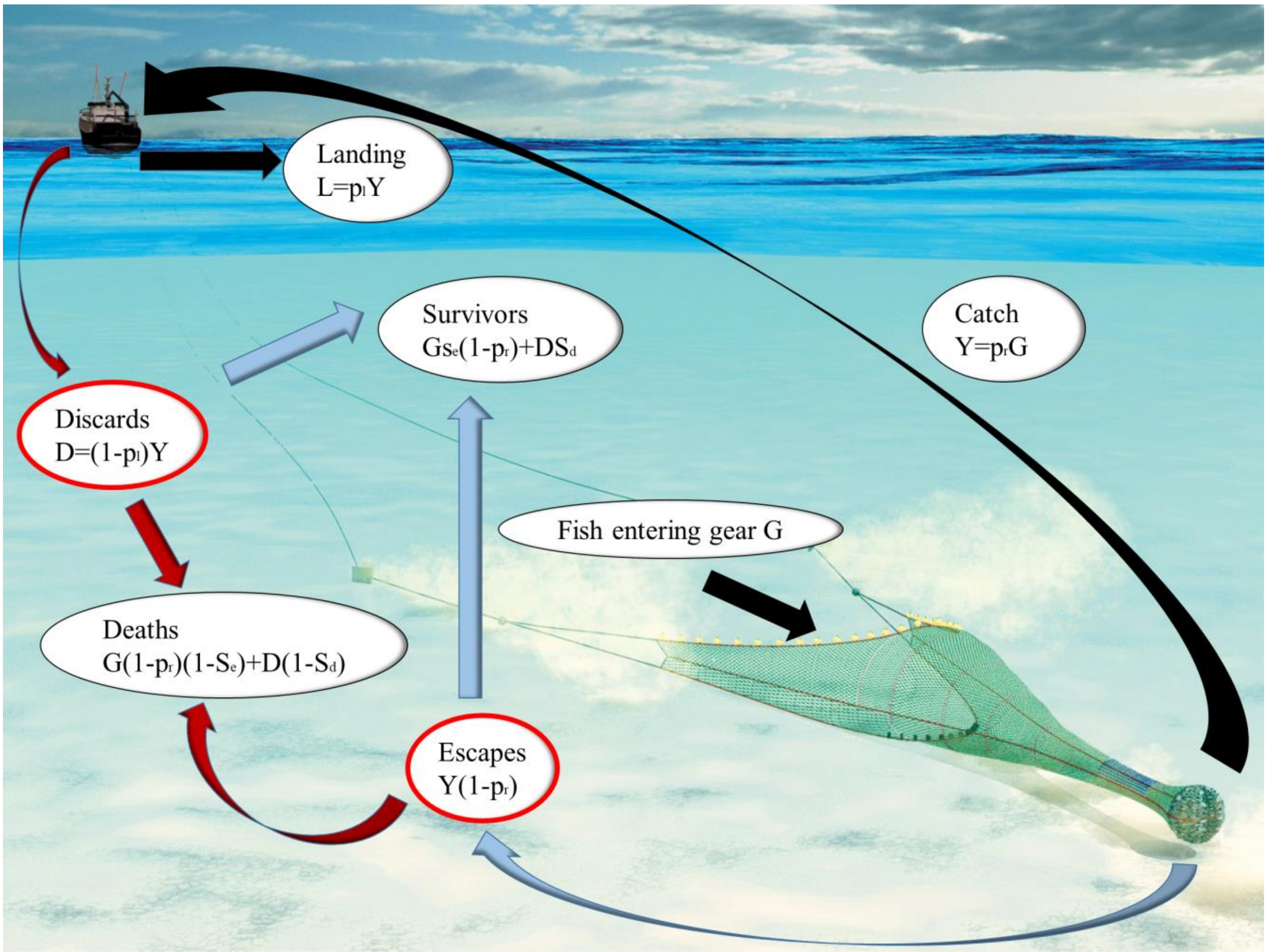

Figure 2 Schematic representation of the unaccounted fish mortality during the bottom trawl fishing activity

Traditional stock assessments assume that all fish escaping from fishing gear or are rejected at the sea after the capture survive (Breen and Cook, 2002; Tenningen et al., 2021). However, considering that a fraction of fish that escape from fishing gear or that are rejected at the sea probably does not survive (unaccounted mortality), it is a major concern for sustainable fisheries management, as unaccounted mortality may lead to biased stock assessment since they will tend to underestimate fishing mortality and overestimate stock size (Figure 4) (Crowder and Murawski, 1998; Gilman et al., 2013).

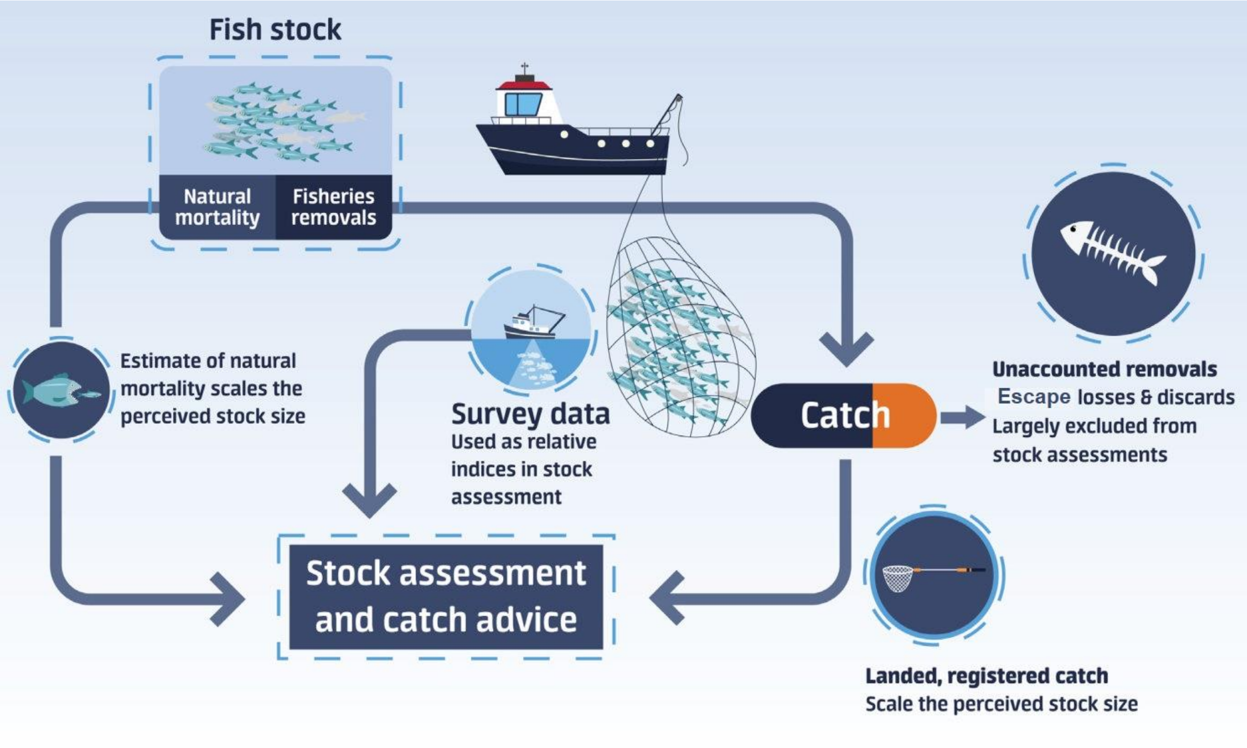

Figure 3 Conceptual representation of the stock assessment process and the role unaccounted fishing mortality such as escape losses and discards play in the estimation of perceived stock size (source Tenningen et al., 2021).

Therefore, unaccounted fishing mortality represents a significant share of global fisheries production and undermines the United Nations' Sustainable Development Goals to efficiently use marine resources and secure food supply (Zeller et al., 2018; Costello et al., 2020).

1.3.1 Discard mortality

Globally, it is estimated that around 10% of the fish that are caught are discarded (Perez-Roda et al., 2019). Discarding fish back to the sea that are caught during commercial fishing is often considered to be wasteful as many species are returned dead or dying (Madsen et al., 2022). On 1st January 2014, the latest reform of the EU Common Fisheries Policy (CFP) (1380/2013) came into force, and with it a discard ban or landing obligation for regulated species. The discard ban is being phased in and will cover all quota stocks in EU waters by January 2019. The principle of the new CFP is to incentivize fishers to avoid catching unwanted fish. Research has shown that some discards survive and that in some cases, the proportion of discarded fish that survive can be substantial, at least for elasmobranchs and crustaceans (Enever et al., 2009; Saygu et al., 2014; Catanese et al., 2018; Tsagarakis et al., 2018). As such, the new policy includes the possibility of exemptions for'… *species for which scientific evidence demonstrates high survival rates, taking into account the characteristics of the gear, of the fishing practices, and of the ecosystem* …'. In these cases, it may be beneficial to return a proportion of the catch to the sea to support the stock biomass and the profitability of the fishing industry. Some survival data on discarded fish has been published but the results are highly variable and available for only a few selected species and fisheries (Catanese et al., 2018; Runde et al., 2019; García-De-Vinuesa et al., 2020). Many factors, including biological attributes, season, and technical elements of the capture process, have been identified as affecting the survival rate of discarded species (Benoit et al., 2010; García-De-Vinuesa et al., 2020).

1.3.2 Escape mortality

Few studies have considered the management implications of mortality to target fish stocks caused by non-retention in commercial harvest gear (escape mortality). The escape survival of the fisheries resources was tested mainly in Atlantic waters (Soldal et al., 1991; Sangster et al., 1996; Pálsson et al., 2003; Breen et al., 2002; Ingólfsson, 2002) whereas in the Mediterranean Sea very few studies were carried out (Metin et al., 2004; Düzbastilar et al., 2010a,b,c; Düzbastilar et al., 2016; Düzbastilar et al., 2017). It is worth to highlight that, in Norway no mortality of one-year-old cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*), excluded from a shrimp trawl by a diagonal metal grid placed in front of the cod-end (the Nordmøre grid), was found (Soldal and Engås, 1997). Although estimates of escape mortality are very variable even for the same species, for example, haddock estimates vary from 3.5% to 52% mortality (Sangster et al, 1996; Lowry et al, 1996; Wileman et al, 1999). Moreover, these experiments indicate that this mortality may be dependent upon the size, age, and physical condition of the fish. As for the Mediterranean concerns, the survival rate of red mullet (*Mullus barbatus* Linnaeus 1758) after escaping from a commercial bottom-trawl codend (40 mm) was investigated in Turkish water (Metin et al., 2004). The authors found on average 93% of the red mullet survived during the observation period. More recently, Düzbastilar et al. (2017) found a seasonal effect on the survival of *M. barbatus* with mean escape mortality significantly higher ($p<0.0001$) in winter (33.2%±6.51) than that in summer (26.5%±6.19). Furthermore, mortality was also highest among the smallest fish, particularly during winter.

1.4. Objective of the thesis

First of all, to improve the exploitation pattern of the bottom trawl fishery which is the most important activity at least in the Strait of Sicily during my Ph.D. project the effect of some BRDs, such as artificial lights, sorting grids, and T90 codend, were tested. Lastly, given that there is an immediate demand for scientific evidence on fishery discard and escape survival rates, an estimation of unaccounted mortality for species exploited by fisheries and regulated through a MCRS by the reg. EU 1967/2006 and 1241/2019 was provided as well. In particular, the selected species were *T. trachurus* and *M. barbatus*, respectively assessed for discard and escape mortality estimates. All these aspects are part of improving the efficiency of fisheries management and its relative sustainability at the ecological, social, and economic level. Furthermore, during the Ph.D. period I collaborated with many colleagues on other research projects and these activities resulted in other articles published in

ISI scientific journals which will not be presented here but will be included in the list of articles published by the undersigned.

References

Benoît, H. P., Hurlbut, T., & Chassé, J. (2010). Assessing the factors influencing discard mortality of demersal fishes using a semi-quantitative indicator of survival potential. Fisheries Research, 106(3), 436-447.

Breen, M., Sangster, G., O'Neill, B., Kynoch, R., Jones, E., and Soldal, A. V. (2002). Evidence of sampling induced biases in mortality estimates from experiments investigating mortality in fish escaping from towed fishing gears. ICES CM 2002/V: 25

Catanese G, Hinz H, Gil MdM, Palmer M, Breen M, Mira A, Pastor E, Grau A, Campos-Candela A, Koleva E, Grau AM, Morales-Nin B. (2018). Comparing the catch composition, profitability and discard survival from different trammel net designs targeting common spiny lobster (Palinurus elephas) in a Mediterranean fishery. PeerJ 6:e4707. https://doi.org/10.7717/peerj.4707

Crowder, L.B.; Murawski, S.A. Fisheries bycatch: Implications for management. Fisheries 1998, 23, 8–17 https://doi.org/10.1577/1548-8446(1998)023<0008:fbifm>2.0.co;2

Costello C., Cao L., Gelcich S., Cisneros-Mata M. A., Free C. M., Froehlich H. E., Golden C. D. et al. 2020. The future of food from the sea. Nature, 588: 95–100. https://doi.org/10.1038/s41586-020-2616-y

Di Lorenzo, M., Sinerchia, M., Colloca, F. (2018). The North sector of the Strait of Sicily: a priority area for conservation in the Mediterranean Sea. Hydrobiologia, 821, 235-253. https://doi.org/10.1007/s10750-017-3389-7

Düzbastılar F.O., Özgül A., Aydın İ., et al. 2010a. A preliminary study on the survival of brown comber, *Serranus hepatus* (Actinopterygii, Perciformes, Serranidae), escaping from the codend of a bottom trawl. Acta Ichthyol. Piscat. 40: 27-36. https://doi.org/10.3750/AIP2010.40.1.04

Düzbastılar F.O., Özbilgin H., Aydın C., et al. 2010b. Mortalities of fish escaping from square and diamond mesh codends in the Aegean Sea. Fish. Res. 106: 386-392. https://doi.org/10.1016/j.fishres.2010.09.008

Düzbastılar F.O., Aydın C., Metin G., et al. 2010c. Survival of fish after escape from a 40 mm streched diamond mesh trawl codend in the Aegean Sea. Sci. Mar. 74: 755-761. https://doi.org/10.3989/scimar.2010.74n4755

Düzbastilar F.O., Breen M., Aydin C., Özbilgin H., Özgül A., Ulaş A., Metin G., Gül B., Lök A. 2017. Seasonal variation in mortality of red mullet (*Mullus barbatus*) escaping from codends of three different sizes in the Aegean Sea. Sci. Mar. 81(3): 339-349. http://dx.doi.org/10.3989/scimar.04600.19A

Enever, R., Catchpole, T. L., Ellis, J. R., Grant, A. (2009). The survival of skates (Rajidae) caught by demersal trawlers fishing in UK waters. Fisheries Research, 97(1-2), 72-76.

Falsone, F., Fiorentino, F., Gancitano, V., Scannella, D., Colloca, F., Ben Abdellah, O., Ben Mariem, S., Jarboui, O., Di Maio, F., Gambin, M., Fezzani, S., Quattrocchi, F., Vitale, S., Ceriola, L., Arneri, E. & Cardinale, M. (2021). GFCM-WGSAD Scientific Advisory Committee on Fisheries (SAC) Working Group on Stock Assessment of Demersal Species (WGSAD), Online, 25–30 January 2021

Fiorentino F and Vitale S (2021) How Can We Reduce the Overexploitation of the Mediterranean Resources? Front. Mar. Sci. 8:674633. https://doi.org/10.3389/fmars.2021.674633

Food and Agriculture Organization (FAO). (2022). The State of Mediterranean and Black Sea Fisheries 2022. Rome: General Fisheries Commission for the Mediterranean. https://doi.org/10.4060/cc3370en

Gancitano, V., Scannella, D., Falsone, F., Ben Meriem, S., Ben Abdallah, O., Arneri, E., Ceriola, L., Jarboui, O., Gambin, M., Mifsud, J., Pisani, L., Vitale, S. & Fiorentino, F. (2021). GFCM-WGSAD Scientific Advisory Committee on Fisheries (SAC) Working Group on Stock Assessment of Demersal Species (WGSAD), Online, 25–30 January 2021

García-De-Vinuesa, A., Breen, M., Benoît, H. P., Maynou, F., & Demestre, M. (2020). Seasonal variation in the survival of discarded Nephrops norvegicus in a NW Mediterranean bottom-trawl fishery. Fisheries Research, 230, 105671.

Geraci, M.L., Colloca, F., Falsone, F., Fiorentino, F., Gancitano, V., Sardo, G., et al. (2021). How is artificial lighting affecting the catches in deep water rose shrimp trawl fishery of the Central Mediterranean Sea? Ocean & Coastal Management. 215: 105970. doi:10.1016/j.ocecoaman.2021.105970

GFCM, 2018. Working Group on Stock Assessment of Demersal Species (WGSAD). Scientific Advisory Committee on Fisheries (SAC), Final Report, 79 pp.

GFCM, 2009. Establishment of Geographical Sub-Areas in the GFCM Area Amending the Resolution GFCM/31/2007/2. GFCM Resolution RES-GFCM/33/2009/2, GFCM.

Gilman, E., Suuronen, P., Hall, M., Kennelly, S. (2013). Causes and methods to estimate cryptic sources of fishing mortalitya. Journal of Fish Biology, 83(4), 766-803. https://doi.org/10.1111/jfb.12148

Glass, C.W., Wardle, C.S., 1995. Studies on the use of visual stimuli to control fish escape from codends. II. The effect of a black tunnel on the reaction behaviour of fish in otter trawl codends. Fisheries Research, 23 (1), 165-174

Glass, C.W., Wardle, C.S., Gosden, S.J., Racey, D.N., 1995. Studies on the use of visual stimuli to control fish escape from codends. I. Laboratory studies on the effect of a black tunnel on mesh penetration. Fisheries Research, 23 (1), 157-164.

Jarboui, O., Ceriola, L., Fiorentino, F. (2022). Current fisheries management in the Strait of Sicily and progress towards an ecosystem approach. In Vasconcellos, M. and Ünal, V., eds. Transition towards an ecosystem approach to fisheries in the Mediterranean Sea – Lessons learned through selected case studies. FAO Fisheries and Aquaculture Technical Paper No. 681. Rome, FAO: 147-162.

Ingolfsson, O., Soldal, A. V., Huse, I. (2002). Mortality and injuries of haddock, cod and saithe escaping through codend meshes and sorting grids. ICES CM 2002/V:32

Lleonart, J., Maynou, F., 2003. Fish stock assessments in the Mediterranean: state of art. Scientia Marina, 67, 37-49

Lockwood, S., Pawson, M. & Eaton, D. (1983). The effect of crowding on mackerel (Scomber scombrus L.)—physical condition and mortality. Fisheries Research 2, 129–147. https://doi.org/10.1016/0165-7836(83)90114-5

Lowry, N., Sangster, G.I., Breen, M. (1996). Cod-end selectivity and fishing mortality. Final report of European Commission Study Contract No. 1994/005, September 1996.

Lucchetti, A., Piccinetti, C., Meconi, U., Frittelloni, C., Marchesan, M. et al., 2014. Transferable Fishing Concessions (TFC): A pilot study on the applicability in the Mediterranean Sea. Marine Policy, 44, 438-447

Madsen, N.; Ern, R.; Olsen Alstrup, A.K. Estimating Discard Mortality in Commercial Fisheries without Fish Dying: A 3R Challenge. Animals 2022, 12, 782. https://doi.org/10.3390/ani12060782

Maiorano, P.; Sabatella, R.F.; Marzocchi, B.M. Annuario sullo stato delle risorse e sulle strutture produttive dei mari italiani. Biol. Mar. Mediterr. 2019, 22 (Suppl. S1), 432. (In Italian)

Metin C., Tokaç A., Ulaş A., et al. 2004. Survival of red mullet (*Mullus barbatus* L., 1758) after escape from a trawl codend in the Aegean Sea. Fish. Res. 70: 49-53. https://doi.org/10.1016/j.fishres.2004.06.013

Milisenda, G., Vitale, S., Massi, D., Enea, M., Gancitano, V., Giusto, G.B., Badalucco, C., Gristina, M., Garofalo, G., Fiorentino, F., 2017. Discard composition associated with the deep water rose shrimp fisheries (Parapenaeus longirostris, Lucas 1846) in the south-central Mediterranean Sea. Mediterr. Mar. Sci. 18 (1), 53. https://doi.org/10.12681/mms.1787.

Misund, O., Beltestad, A. (1995). Survival of herring after simulated net bursts and conventional storage in net pens. Fisheries Research 22, 293–297. https://doi.org/10.1016/0165-7836(94)00326-r

Nolde Nielsen, K., Holm, P., Aschan, M., 2015. Results based management in fisheries: Delegating responsibility to resource users. Marine Policy, 51, 442-451.

Pálsson, Ó. K., Einarsson, H. A., Björnsson, H. (2003). Survival experiments of undersized cod in a hand-line fishery at Iceland. Fisheries Research, 61(1-3), 73-86.

Pérez Roda, M.A., Gilman, E., Huntington, T., Kennelly, S.J., Suuronen, P., Chaloupka, M., Medley, P., 2019. A Third Assessment of Global Marine Fisheries Discards. FAO Fisheries and Aquaculture Technical Paper No. 633. FAO, Rome.

Runde, B. J., Rudershausen, P. J., Sauls, B., Mikles, C. S., Buckel, J. A. (2019). Low discard survival of gray triggerfish in the southeastern US hook-and-line fishery. Fisheries Research, 219, 105313.

Sangster, G.I., Lehmann, K., Breen, M. (1996). Commercial fishing experiments to assess the survival of haddock and whiting after escape from four sizes of diamond mesh cod-ends. Fisheries Research 25(1996) 323-345.

Saygu, İ., Deval, M. C. (2014). The post-release survival of two skate species discarded by bottom trawl fisheries in Antalya Bay, Eastern Mediterranean. Turkish Journal of Fisheries and Aquatic Sciences, 14(4), 947-953.

Soldal, A.V., Isaksen, B., Marteinsson, J.E., Engås, A., 1991. Scale damage and survival of cod and haddock escaping from a demersal trawl. ICES CM 1991/B:44, 9 pp

Soldal, A.V.; Engås, A. Survival of young gadoids excluded from a shrimp trawl by a rigid deflecting grid. ICES J. Mar. Sci. 1997, 54, 117–124

Stratoudakis, Y., Marcalo, A. (2002). Sardine slipping during purse-seining off northern Portugal. ICES Journal of Marine Science 59, 1256–1262. https://doi.org/10.1006/jmsc.2002.1314

Suuronen, P., Erickson, D., Orrensalo, A. (1996). Mortality of herring escaping from pelagic trawl cod-ends. Fisheries Research 25, 305–321

Tenningen, M., Zimmermann, F., Enberg, K. (2021). Pre-catch and discard mortality in Northeast Atlantic herring and mackerel fisheries: consequences for stock estimates and advice. ICES Journal of Marine Science, 78(7), 2603-2614. https://doi.org/10.1093/icesjms/fsab135

Tsagarakis, K., Carbonell, A., Brčić, J., Bellido, J.M., Carbonara, P. et al., 2017. Old info for a new Fisheries Policy: Discard ratios and lengths at discarding in EU Mediterranean bottom trawl fisheries. Frontiers in Marine Science, 4 (99)

Tsagarakis, K, Nikolioudakis, N, Papandroulakis, N, Vassilopoulou, V, Machias, A. Preliminary assessment of discards survival in a multi-species Mediterranean bottom trawl fishery. J Appl Ichthyol. 2018; 34: 842– 849. https://doi.org/10.1111/jai.13691

Vasconcellos, M. and Ünal, V., eds. 2022. Transition towards an ecosystem approach to fisheries in the Mediterranean Sea – Lessons learned through selected case studies. FAO Fisheries and Aquaculture Technical Paper No. 681. Rome, FAO. https://doi.org/10.4060/cb8268en

Wileman, D.A., Sangster, G.I., Breen, M., Ulmestrand, M., Soldal, A.V., Harris, R.R., (1999). Roundfish and *Nephrops* survival after escape from commercial fishing gear. EC Contract FAIR-CT95-0753

Zeller D., Cashion T., Palomares M., Pauly D. (2018). Global marine fisheries discards: a synthesis of reconstructed data. Fish and Fisheries, 19: 30–39. https://doi.org/10.1111/faf.12233

Paper 1: Testing the catchability of the crustacean trawl fisheries

How is artificial lighting affecting the catches in deep water rose shrimp trawl fishery of the Central Mediterranean Sea?

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Abstract

The effect of artificial lights mounted on the headrope trawl net on the catch of deep water rose shrimp (*Parapenaeus longirostris*), European hake (*Merluccius merluccius*), and Atlantic horse mackerel (*Trachurus trachurus*) was tested in a survey carried out on-board a commercial trawler off the SW Sicilian coast. A total of 18 repeated nocturnal hauls, alternating without (control) and with (test) LED lights (10 green and 10 white) according to the fishers' setup, were conducted. Overall, the test net catch rates were not significantly higher than those of the control net (Kruskal-Wallis test, $p > 0.05$), except for *P. longirostris* ($p < 0.05$). Conversely, the two-tailed Kolmogorov–Smirnov test revealed statistical differences in the size structure of *P. longirostris*, *M. merluccius*, and *T. trachurus* between the test and control nets ($p < 0.05$). Using generalised linear mixed models, the test net was found to yield higher catches of undersized individuals of the three species and adults of *P. longirostris* than the control net. Our study results are discussed in the context of the exploitation and management of Mediterranean trawl fisheries.

Key-words: LED lights, gear selectivity, fisheries management, undersized catch, catch comparison

1. Introduction

Evidence of the use of light for fishing purposes is very ancient and can be traced back to the book "*De historia animalium*" written by Claudius Aelianus, a Roman philosopher that lived between the second and third centuries after Christ. Traditionally, light is used to attract and aggregate commercial fisheries species, such as pelagic fish and cephalopods, near fishing boats (e.g., Arakawa *et al.*, 1998, Parrish 1999, Kim & Wardle 2003, Arimoto *et al.*, 2010, Okpala *et al.*, 2017). In recent years, lights directly mounted on different types of active and passive fishing gear have been increasingly used to improve their catchability and/or reduce by-catch (e.g., Nguyen & Winger, 2019). Essentially, the main difference between underwater and surface lights is the inability of surface lights to affect different components of the marine community as surface lights cannot reach the depths of underwater lights mounted directly on the fishing gear.

The increasing use of underwater lights in recent years is linked with the rapid development of new lighting technology. In fact, very low amounts of energy are required, and they have a longer lifespan than the previous lighting technology (Matsushita *et al.*, 2012; ICES, 2012, 2013; Nguyen & Winger, 2019).

There is a growing scientific interest in understanding the effect of artificial light on animal catches (e.g., Bielli *et al.*, 2020; Cuende *et al.*, 2019, 2020; Field *et al.*, 2020; Lomeli & Wakefield, 2020; Southworth *et al.*, 2020; Lomeli *et al.*, 2021; Karlsen *et al.*, 2021). Experimental surveys carried out in oceanic waters have revealed that the effect of artificial lights on trawl catch depends on several factors, including technical (e.g., placement of lights, light intensity, light spectrum) or external (e.g., water turbidity, depth, moon phase) factors (Melli *et al.*, 2018, O'Neill & Summerbell 2019; Cuende *et al.*, 2019; Southworth *et al.*, 2020). Based on evidence gathered during trawl surveys, the effect of light on fish is species-specific (e.g., Lomeli & Wakefield 2012, Grimaldo *et al.*, 2018) and size-dependent (e.g., Lomeli *et al.*, 2018a; Melli *et al.*, 2018).

Knowledge on the reactions of crustaceans and cephalopods to artificial lights during trawling remains limited and highlights a weak or nil attractive effect (e.g., Lomeli *et al.*, 2018b, Sbrana *et al.*, 2018, Lomeli *et al.*, 2020).

In the Mediterranean Sea, artificial fixed lights mounted on boats are traditionally used by purse seiners to attract anchovies and sardines during the night (Vidoris *et al.*, 2001; Tsagarakis *et al.*, 2012; Kraljević *et al.*, 2014). Artificial lights are also used in hand line fishing for deep-water squids in southern Italy, where fishers use a hand-jig line (called "totanara") consisting of a crown of hooks mounted on a stainless-steel cylinder, baited in its centre, and enhanced by the addition of a small blinking light (Battaglia *et al.*, 2010). In trawl fisheries, the use of artificial lights is recent and mostly limited to vessels exploiting deep-water crustaceans, such as *P. longirostris*. A recent study based on a scientific survey revealed no significant difference in *P. longirostris* catch rates (Sbrana *et al.*, 2018) whereas another study based on interviews with fishermen reported higher *P. longirostris* catch rates during night hauls (Pinello *et al.,* 2018).

In the Strait of Sicily, where the largest Mediterranean bottom trawl fleet targeting *P. longirostris* and the giant red shrimp, *Aristaeomorpha foliacea*, is found (the Mazara del Vallo harbour) (Vitale *et al.,* 2014; Milisenda *et al.*, 2017), artificial lights mounted on the trawl head rope are increasingly used to enhance the catch per unit effort (CPUE) of these species during night hauls (Geraci *et al.*, in press; Pinello *et al.,* 2018). Accordingly, in the Strait of Sicily, Geraci *et al.* (in press) during an unplanned and preliminary trial recorded an overall increase in gross catch, including *P. longirostris* and *M. merluccius*.

Given the importance of the crustacean trawl fishery in the Strait of Sicily (Levi *et al.,* 1995, Fiorentino *et al.,* 2013; Di Lorenzo *et al.*, 2018), it is important to better understand the impact of such new technological improvements on demersal resources and fisheries ecological sustainability. These aspects are particularly important as the use of artificial light in commercial fisheries carried out in EU Mediterranean waters is not regulated by specific measures. Therefore, it is necessary to accelerate discussions and adopt specific strategies and regulations on the use of underwater light at local, national, and international scales to avoid any possible negative effects of their use on the exploited stocks (Nguyen et al. 2019).

In this study, the artificial lights used by Mazara del Vallo trawlers were tested for the first time during an *ad-hoc* trawl survey in the GSA16 (Geographical Subarea 16), South of Sicily, according to the General Fisheries Commission for the Mediterranean classification. The main aim of this study was to determine the effects of light on both catch composition and catch rate of the deep-water rose shrimp, *P. longirostris,* the European hake, *M. merluccius,* and Atlantic horse mackerel, *T. trachurus*. *P. longirostris* is the main target species of the fishery, while *M. merluccius* and *T. trachurus* are the main commercial bycatch and the main unwanted by-catch, *sensu* ICES (2020), respectively (Milisenda *et al.,* 2017). The results of this study have important implications for the long-term sustainability of trawl fisheries discussed in the context of the management goals of the EU Common Fisheries Policy, CFP (reg. EC 1380/2013).

2. Material and Methods

2.1 Study area and experimental setup

The study area is located off the southwestern coast of Sicily within GSA16 (Fig. 1).

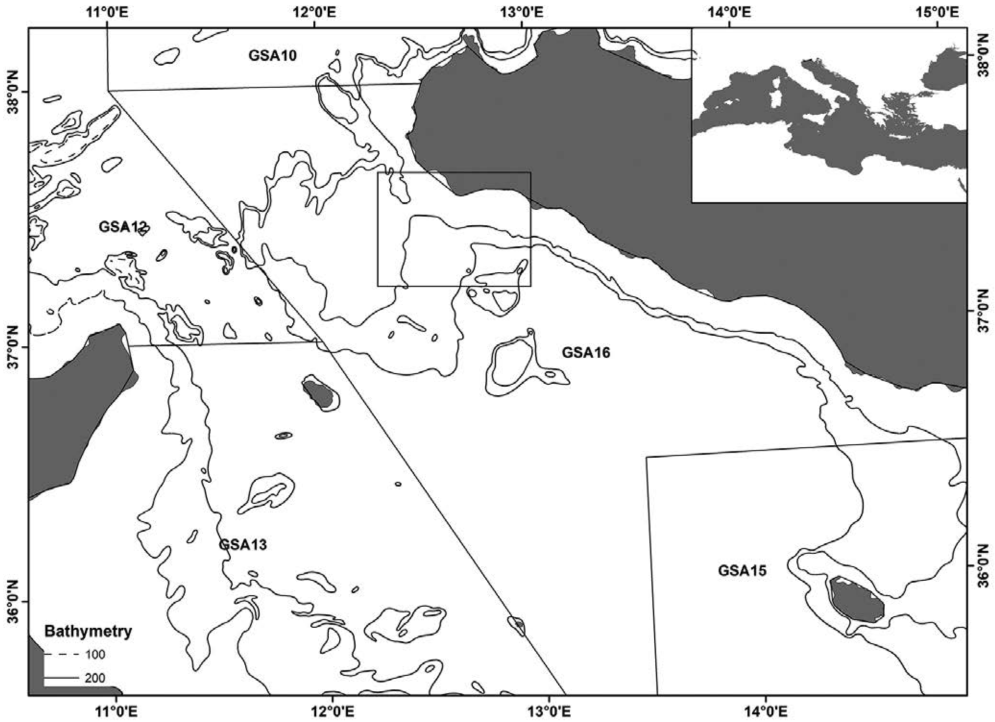

Fig. 1: The study area highlighted using a black square box (from Vitale *et al.*, 2018a, b).

In December 2018, a three-day survey was conducted by a commercial bottom trawler (20.95 m length overall and 294 kW engine power) of the Mazara del Vallo fleet. The trawler was equipped with a polyamide “volantina” trawl net, with a nominal mesh cod-end size of 40 mm square mesh. A total of 18 nightly hauls lasting one hour each (six repeated in each of the three nights) were carried out at speeds ranging from 2.6 and 2.8 knots, alternating the trawl net with (hereinafter referred to as test) and without light (hereinafter referred to as control) (Table 1).

Table 1. Main characteristics of the repeated hauls carried out at night throughout the 3-day experiment.

Haul	Time (start)	Time (end)	Lat. (start)	Long. (start)	Mean depth (m)
1	19: 00	20:00	37.560° N	12.403° E	134
2	21:00	22:00	37.506° N	12.421° E	142
3	23:00	24:00	37.483° N	12.456° E	143
4	01:00	02:00	37.503° N	12.425° E	136
5	03:00	04:00	37.537° N	12.395° E	128
6	05:00	06:00	37.519° N	12.406° E	131

The head rope of the net was equipped with a total of 20 LED underwater lights, 10 green and 10 white (Acquasport Sud ® S.A.S. Di Garzia Giovanni & C.) (Fig. 2).

Fig. 2: LED lights mounted on the headrope of the trawl net used during the survey

The choice to simultaneously use green and white LED lights is based on local ecological knowledge (fishers have declared this custom), on-board personal observations, and the monitoring activity of the landings in the context of the EU Data Collection Framework (DCF). In the same area, Geraci et al. (in press) carried out an unplanned preliminary trial using exactly the same configuration, colour of lights, and brand adopted by local fishers. In particular, the green and white LEDs were placed alternately and symmetrically along the head rope, with green and white LEDs alternating at a distance of approximately 50 cm from each other. The green and white LEDs peaked at wavelengths of 520 and 460 nm, respectively, with an intensity of 3.5 cd (data from manufacturer).

Environmental data that may affect the catch rate were collected for each haul, including sea state, sea water temperature, and moon phase. The moon phase was obtained from the tides4fishing.com website; obviously, this phase did not markedly differ during the survey. However, the third day was very cloudy, and the moon was completely covered; therefore, its effect was included in the analyses as moon presence/absence. Temperature data along the water column were recorded using a CTD probe (STAR-ODDI https://www.star-oddi.com/) mounted on a trawl (Appendix A).

On-board scientific observers were involved throughout the survey to monitor all fishing operations, collect biological samples, and collect data on fishing operations (e.g., speed, coordinates, depth). The catch of each haul was sorted on board in commercial and non-commercial fractions, according to local fishers' habits. All biological samples were transported to the National Research Council (CNR) laboratory, weighed (0.1-gram accuracy), and measured (to the nearest 5 mm Total Length – TL and 1 mm Carapace Length – CL) individually, while the benthic organisms were identified, numbered, and weighed as total by species (Appendix B).

2.3 Statistical analysis

2.3.1 Catch Per Unit Effort (CPUE)

The CPUE expressed as kg/h was used to compare the control and test nets for the following categories: (i) ALL, (ii) *P. longirostris*, (iii) *M. merluccius*, and (iv) *T. trachurus* specimens. The first category included all species pooled by haul, except for benthic organisms which were excluded from the data analysis; this is because these organisms were assumed to be caught passively and therefore, independent of the use of artificial light. Local fishers, Pinello *et al.* (2018) and Geraci *et al.* (in press), previously reported an increase in catch rates. This background information allowed us to hypothesise that the use of artificial lights determines an increase in CPUE; therefore, a one-tailed Kruskal-Wallis H test ($\chi 2$) was applied to test the differences between the test and control nets.

Size structures analyses

The size structures were expressed in terms of the number of specimens for each length class (i.e., length frequency distributions (LFDs)). The general differences in the LFDs for *P. longirostris, M. merluccius*, and *T. trachurus* between the control and test nets were assessed using a two-sample Kolmogorov-Smirnov test (KS test).

As two fishing vessels could not be hired and a paired haul design could not be adopted, we assumed the same catch probability for control and test net hauls carried out at the same time of day, depth, and geographical position. The probability of retaining a fish at length in the test net related to the total catch in the control net was assessed according to the method proposed by Fryer *et al.* (2003). The comparison was made between nine hauls (i.e., nine in the test and nine in the control nets) and the length classes were set at 2 mm CL, 20 mm, and 10 mm TL for *P. longirostris, M. merluccius*, and *T. trachurus*. Undersized specimens were identified as fish whose length was below the minimum conservation reference size (MCRS) established by the EC Reg. 1967/2006 and Reg. 1380/2013 (20 mm CL for *P. longirostris*, 200 mm TL for *M. merluccius*, and 150 mm TL for *T. trachurus*).

The experimental average catch comparison for each length class (CC_l) is given by the following expression:

$$CC_l = \frac{\sum_{i=1}^{9} nt_{li}}{\sum_{i=1}^{9} nc_{li} + \sum_{i=1}^{9} nt_{li}} \tag{1}$$

where n_c and n_t are the number of fish caught in each length class *l* in the control and test nets, respectively (e.g., Sola & Maynou, 2018; Vitale *et al.*, 2018a). A value of 0.5 for CC_l indicates that the probability in capturing a fish of length *l* is the same between the test and control. Instead, a value above 0.5 indicates a higher probability of catching a fish of length *l* in the test than the control, and *vice versa* for a value below 0.5.

The observed CC_l values of the test and control net of each selected species were modelled using generalised linear mixed models (GLMMs) with binomial distribution, where hauls were included as random effects to remove the variance linked to the expected change in abundance/catchability of the three species during the days and timeframes (Holst & Revill, 2009). The models were fitted with splines with different degrees of freedom. The selection of the best model was based on choosing the model with the lowest Bayesian information criterion (BIC) using the BICtab function (Brooks *et al.*, 2020).

The initial probability model was defined as follows:

$$P\ [logit(test/test + ctrl)] = \alpha + f(size\ class) + \beta_1 moon\ presence/absence + \beta_2 day + \beta_3 timeframe + Uhaul + \varepsilon_i$$

where α is the model intercept, *f* is the spline function, *β* is the regression coefficient, *U* is the random factor, and ε is the error term in the model.

Temperature and sea state were not included in the model as they did not vary during the survey. Variables were first checked for collinearity with a scatterplot of each pair of variables and Pearson's correlation matrix plots. In addition, the homoscedasticity assumption was assessed purely based on a scatter plot of the residuals (Zuur *et al.*, 2009). To directly quantify the relative effect of using the test *versus* control net on the length-dependent gear catch efficiency, the so-called catch ratio was estimated (e.g., Sistiaga *et al.*, 2015; Melli *et al.*, 2020; Lomeli *et al.*, 2021). The ratio between the catch efficiency of the control and test trawl nets of a given length, *l*, was computed using the following expression for the experimental data:

$$CR_l = \frac{\sum_{i=1}^{9} nt_{li}}{\sum_{i=1}^{9} nc_{li}} \qquad (2)$$

Simple mathematical manipulation yields the following general relationship between catch ratio and catch comparison:

$$CR_l = \frac{\sum_{i=1}^{9} CC_l}{\sum_{i=1}^{9} 1 - CC_l} \qquad (3)$$

CC_l is the predicted value of the catch comparison model (based on Eq. 1). A value of 1.0 for CR_l indicates no difference in catch efficiency between the test and control groups. On the other hand, a value of 0.60 or 1.45 indicates that the probability of fish caught for a given length, with the test net is 40% less or 45% more than that sampled with the control net. In addition, to provide an overall idea for the effect of mounting LED lights on the trawl net, the mean CR_l was provided. A double bootstrap approach with 1000 repetitions was applied to estimate the 95% confidence limits (Efron 1982; Millar, 1993). We removed the random effect of haul from the most parsimonious model before bootstrapping as it already accounted for variation/uncertainty through resampling, among hauls (i.e., among the nine haul pairs, with replacement) and within-haul (i.e., on the size structures, with replacement) (Brooks *et al.*, 2020).

Lastly, the probability of the test *versus* control net to catch undersized specimens (P_u) was calculated for *P. longirostris, M. merluccius,* and *T. trachurus,* as follows:

$$P_u = \frac{\sum_{i=1}^{9} nt_u}{\sum_{i=1}^{9} nc_u + \sum_{i=1}^{9} nt_u} \qquad (4)$$

where nc_u and nt_u represent the number of specimens in each length class up to the MCRS, respectively, in the control and test nets. To provide an overall idea of the light effect on juveniles, P_u was provided as the mean value. All analyses were carried out with R version 3.6.3 using the package, *selfisher* (Brooks, 2019).

3. Results

3.1 Catch Per Unit Effort (CPUE)

The main descriptive statistics of *P. longirostris, M. merluccius,* and *T. trachurus* specimens are shown in Table 2. In terms of absolute numbers, the test net caught more *P. longirostris, M. merluccius,* and *T. trachurus* specimens than the control net. For *M. merluccius* and *T. trachurus*, the number and percentage of undersized specimens were higher in the test than in the control, whereas the percentage of undersized specimens was higher in the control (Table 2).

Table 2. Main descriptive statistics of *Parapenaeus longirostris, Merluccius merluccius*, and *Trachurus trachurus* caught during the survey.

Net	Species	Total number	Range (mm)	Mean (mm) ± sd	Nr. Undersized	%Undersized
TEST	*P. longirostris*	10519	9-33	19±3	6975	66
	M. merluccius	320	75-595	178±84	219	68
	T. trachurus	572	75-245	135±20	463	81
CONTROL	*P. longirostris*	7253	8-31	18±3	5475	75
	M. merluccius	243	60-595	196±89	137	56
	T. trachurus	243	90-235	144±31	159	65

Comparisons of CPUE between the test and control nets are shown in Fig. 3. In particular, the median CPUE was slightly higher for the test in all categories, except for *M. merluccius*. However, the Kruskal-Wallis test did not highlight significant CPUE differences between the test and control net for ALL ($\chi 2 = 1.335$, $p = 0.124$), *M. merluccius* ($\chi 2 = 0.276$, $p = 0.300$), and *T. trachurus* ($\chi 2 = 1.335$, $p = 0.124$), whereas for *P. longirostris*, a significant increase in the test net was found ($\chi 2 = 2.823$, $p = 0.043$).

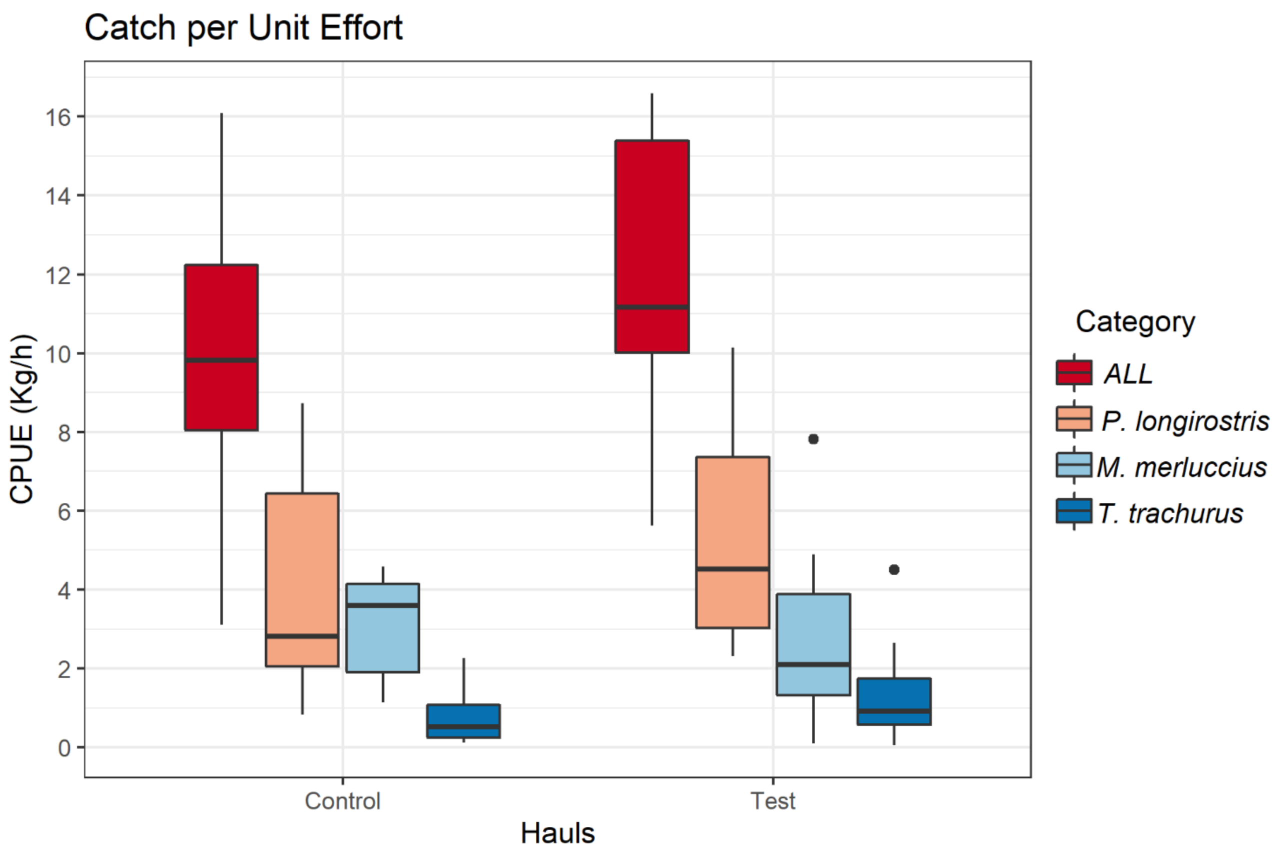

Fig. 3: Catch per Unit Effort (CPUE) expressed as kg/h for: ALL (all catch pooled by haul), *Parapenaeus longirostris*, *Merluccius merluccius*, and *Trachurus trachurus*

3.2 Size structure analyses

Overall, LFDs expressed as absolute frequency for *P. longirostris*, *M. merluccius*, and *T. trachurus* revealed that the main component of the catch was composed of undersized specimens according to Reg. EU 1967/2006 in both test and control net configurations (Fig. 4). In particular, the modal class lengths for *P. longirostris* were 18 mm CL for both the test and control nets, whereas those for *M. merluccius* were 140 mm and 200 mm TL, respectively. The modal class length for *T. trachurus* was 135 mm TL in the test and 145 mm TL in the control net (Fig. 4). The KS test highlighted significant differences in the shape of the LFDs for the three species, namely *P. longirostris* ($D = 0.114$, $p < 2.2^{-16}$), *M. merluccius* ($D = 0.156$, $p = 0.002$), and *T. trachurus* ($D = 0.167$, $p < 0.0001$).

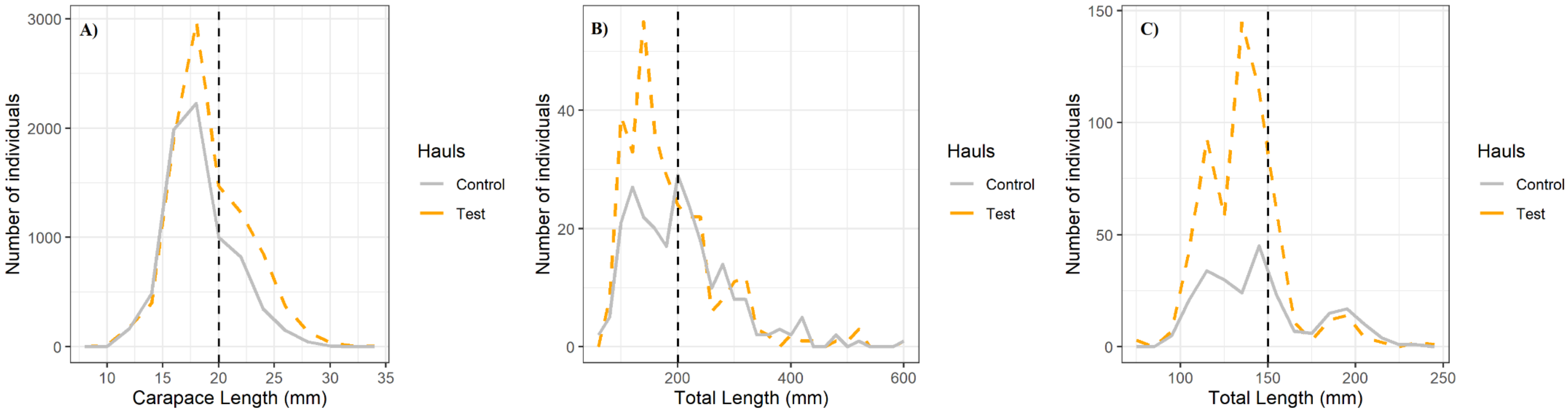

Fig. 4: Absolute length frequency distribution of A) *Parapenaeus longirostris*, B) *Merluccius merluccius*, and C) *Trachurus trachurus*. Black dashed lines indicate the minimum conservation reference size (MCRS).

The final GLMMs by species are presented in Table 3.

Table 3. Selected GLMM models with parameters and fit for the catch comparison curves (test vs control net) of *Parapenaeus longirostris*, *Merluccius merluccius*, and *Trachurus trachurus*. In bold, significant terms.

Stock	Model				
	~ *f*(size class, df = 3)*moon presence/absence + *U*(Haul)	Estimate	Std. Error	z value	p-value
	(Intercept)	-0.116	0.442	-0.263	0.793
	***f*(size class, df = 3)1**	**-1.700**	**0.814**	**-2.089**	**0.037**
	***f*(size class, df = 3)2**	**2.297**	**0.361**	**6.357**	$\mathbf{2.06^{-10}}$
P. longirostris	*f*(size class, df = 3)3	0.927	0.766	1.211	0.226
	moon presence/absence	-0.192	0.612	-0.311	0.756
	***f*(size class, df = 3)1:moonpresence**	**4.210**	**1.214**	**3.468**	$\mathbf{5.2^{-04}}$
	***f*(size class, df = 3)2:moonpresence**	**-2.624**	**0.599**	**-4.378**	$\mathbf{1.20^{-05}}$
	f(size class, df = 3)3:moonpresence	1.042	1.227	0.850	0.396
	~ *f*(size class, df = 5) + *U*(Haul)	Estimate	Std. Error	z value	p-value
	(Intercept)	-0.710	0.474	-1.496	0.134
	***f*(size class, df = 5)1**	**2.569**	**0.783**	**3.281**	**0.001**
M. merluccius	*f*(size class, df = 5)2	-0.659	0.517	-1.276	0.202
	f(size class, df = 5)3	1.350	0.831	1.625	0.104
	f(size class, df = 5)4	0.480	0.678	0.708	0.479
	f(size class, df = 5)5	0.796	0.648	1.227	0.220
T. trachurus	~ *f*(size class, df = 3) + *U*(Haul)	Estimate	Std. Error	z value	p-value
	(Intercept)	0.410	0.643	0.638	0.524

***f*(size class, df = 3)1**	**2.541**	**1.244**	**2.043**	**0.041**
***f*(size class, df = 3)2**	**-3.104**	**0.765**	**-4.059**	**4.93^{-05}**
f(size class, df = 3)3	-0.236	0.796	-0.296	0.767

Among the selected predictive variables, only the size class significantly affected the catch rates of all species, whereas the moon light affected significantly per size class only the *P. longirostris* ones.

The CC_l and CR_l values for *P. longirostris* were lower than the no-level effect up to 14 mm CL ($CC_l = 0.48$, $CR_l = 0.92$). Thereafter, the trend increased constantly up to 32 mm CL ($CC_l = 0.76$, $CR_l = 3.21$) and slightly decreased up to 34 mm CL ($CC_l = 0.75$, $CR_l = 3.11$), showing that the test had a higher catch probability than the control (Fig. 5A, B).

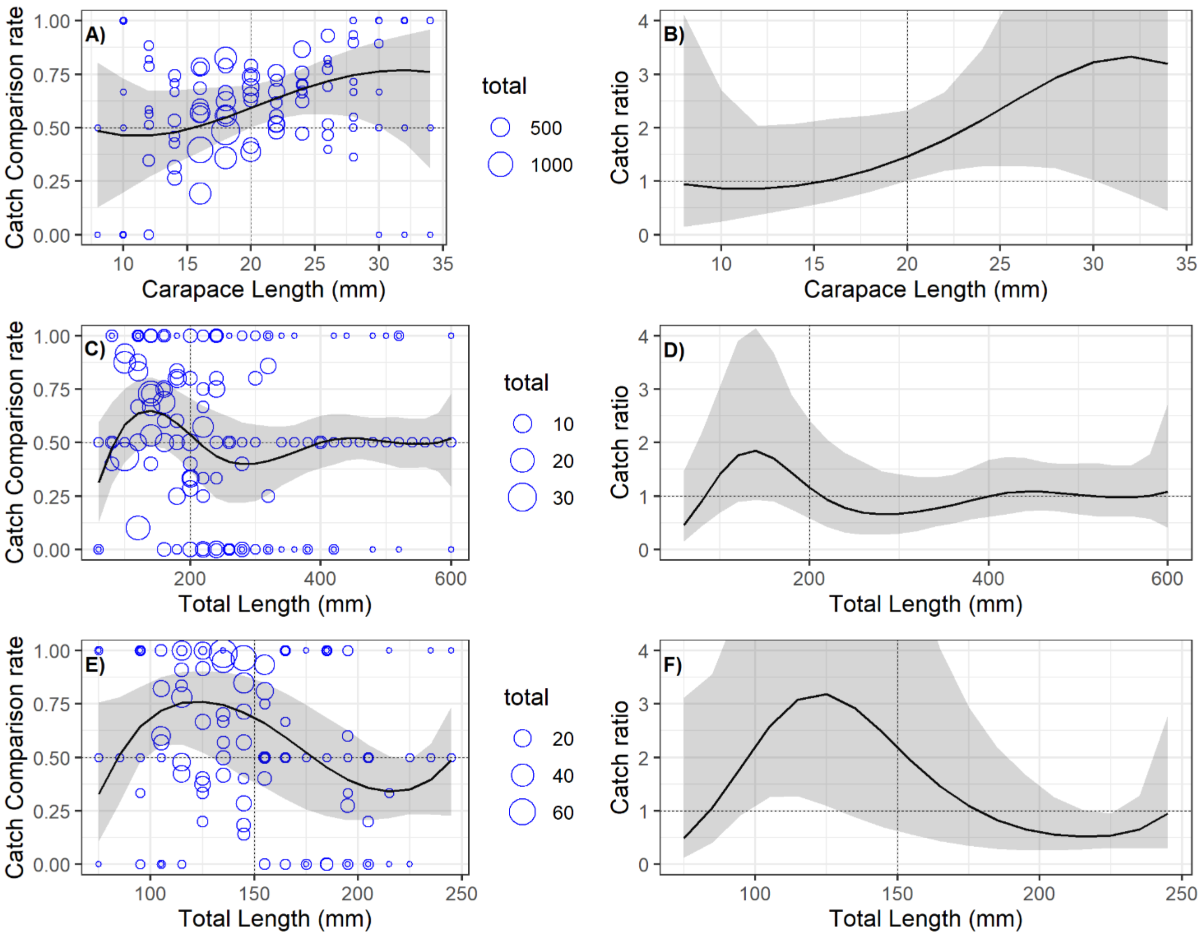

Fig. 5: Catch comparison curves (left) and Catch Ratio curves (right) for (A, B) *Parapenaeus longirostris*, (C, D) *Merluccius merluccius*, and (E, F) *Trachurus trachurus*. (Left) blue circles are observed proportions, black dashed lines represent the model prediction, the grey band indicates the 95% confidence limit. The level of no effect (CCl = 0.5) is depicted by horizontal black dashed lines while the MCRS is indicated by black vertical dashed lines. (Right) solid black lines represent mean CR_l, the grey band indicates the 95% confidence limit. The level of no effect (CR_l = 1.0) is depicted by horizontal black dashed lines.

The mean CR_l across all size classes highlighted as the catch by test net was approximately 86% more than that of the control (Fig. 6).

The CC_l and CR_l values for *M. merluccius* showed a higher efficiency of the test net in catching specimens from 100 to 200 mm TL (CC_l = 0.61; CR_l = 1.56; CC_l = 0.56; CR_l = 1.26). In contrast, for specimens between 220 mm and 380 mm TL (CC_l = 0.49, CR_l = 0.97; CC_l = 0.48, CR_l = 0.94), a slight decrease in the efficiency of the test was estimated. For the largest specimens, the CC_l and CR_l remained slightly above or equal to the level of no effect. For example, at 600 mm TL, CC_l = 0.52 and CR_l = 1.10 (Fig. 5 C, D). The mean CR_l across all size classes highlighted as the test catch was more or less equal to the control (8% more) (Fig. 6). The CC_l and CR_l of *T. trachurus* indicated a greater efficiency of the test up to 175 mm TL (CC_l = 0.52; CR_l = 1.07), except for 85 mm TL (CC_l

= 0.36; CR_l = 0.57). Conversely, for larger specimens, from 185 (CC_l = 0.45; CR_l = 0.82) to 235 mm TL (CC_l = 0.41 and CR_l = 0.70), the test was less efficient (Fig. 5 E, F). The mean CR_l across all size classes was more for the test catch than the control (50%) (Fig. 6).

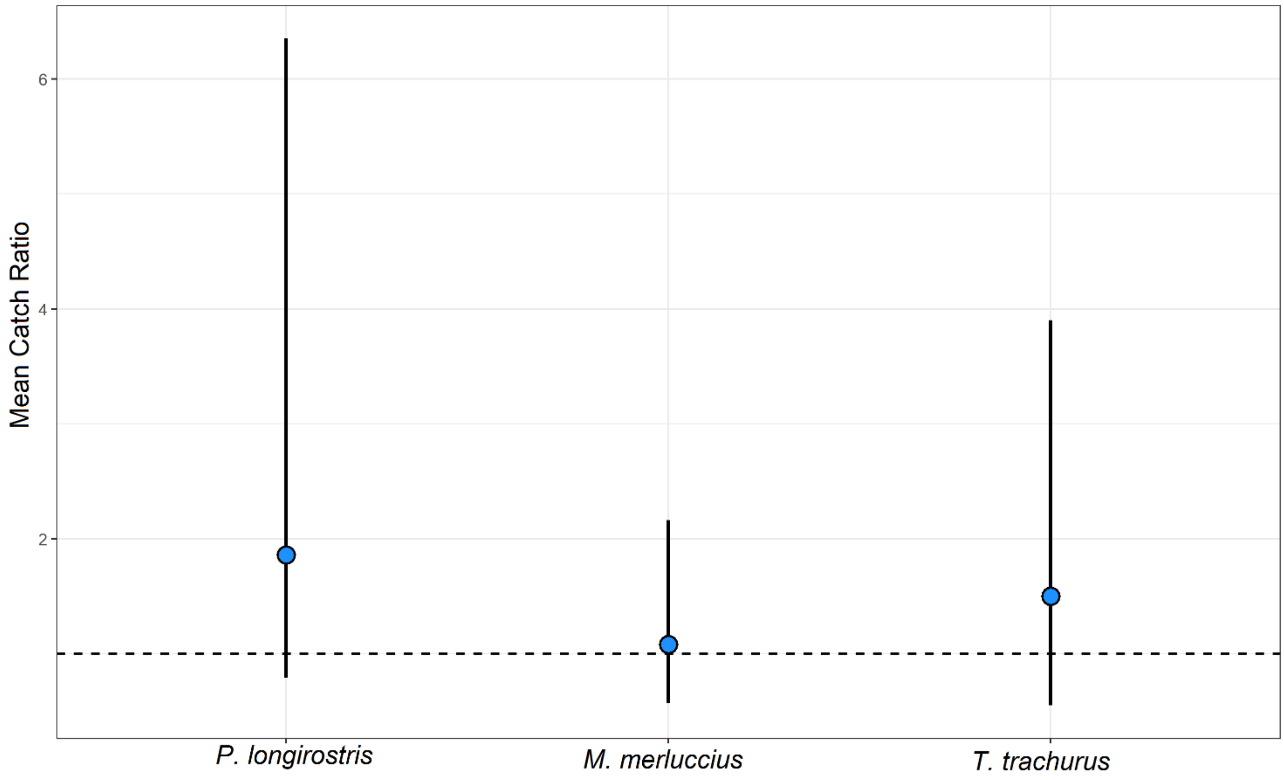

Fig. 6: Mean Catch Ratio for *Parapenaeus longirostris*, *Merluccius merluccius*, and *Trachurus trachurus* between test and control nets is depicted by blue dots; bars indicate the 95% confidence limit. The level of no effect (mean CRl = 1.0) is depicted by the horizontal black dashed lines.

The mean probability to catch undersized specimens (P_u± sd) was higher for all species in the test than the control net, despite the similarity of P_u for *P. longirostris* between both configurations (i.e.: *P. longirostris*: 0.56 ± 0.20; *M. merluccius*: 0.62 ± 0.20; *T. trachurus*: 0.74 ± 0.15).

4. Discussion

The results of the present study indicate that bottom trawl nets equipped with 20 (10 green and 10 white) LED lights increase the overall catch rates during the night, even if they only significantly affected *P. longirostris*. In particular, catches of this species increased across almost all size classes. Importantly, the efficiency of the artificial illumination increased for *P. longirostris* specimens ranging from 20 to 30 mm CL, which is above the MCRS according to Reg. EC 1967/2006. This finding could be reflected in a higher profit for fishers owing to the larger size of the *P. longirostris* specimens caught using light. Conversely, for *M. merluccius* and *T. trachurus*, the test net caught more undersized species than the control, which might undermine the goal of the CFP to minimise unwanted catch (Reg. EC 1380/2013).

Although light is increasingly used in many Mediterranean fisheries, their impact on catch is still poorly understood, and the results of the few studies carried out are controversial (see Table 4).

Table 4. Synopsis of the studies conducted to test the effect of artificial lights during trawling. Target/bycatch is here intended to as for fisheries.

Area	Trawl type	Species	Target/by-catch	Light type	Colour/wavelength	Power/ Flux/intensity	Number of lights	Placement	Effect on size	Catch rates	Author
Bay of Biscay/Madeira	Midwater	Cephalopods	E	Electric (filament)	NA	70 W	1/2	Top bar	NA	+	Clarke & Pascoe, 1985
		Fish							NA	+	
		Crustaceans							NA	-	
Plymouth	Bottom	*Trachurus trachurus*	E	Electric (filament)	NA	70 W	2	3 m from each other from the headline centre	NA	+	Clarke et al., 1986
		Merlangius merlangus							NA		
		Trisopterus minutus							NA		
		Eutrigla gurnardus							NA		
		Micromesitius potassou							NA		
		Merluccius merluccius							NA		
		Limanda limanda							NA		
		Other 13 fish							NA	+/-	
Bay of Biscay	Midwater	Deep-Sea fish (12 species)	E	Electric (filament)	NA	70 W	1/2	Top bar	Y*	+	Swinney et al., 1986
		Gonostoma elongatum							N	-	
		Deep-Sea fish (20 species)							N	+/-	
Bering Sea	Bottom	*Theragra chalcogramma*	E	Electric (quartz halogen)	NA	50 W	1	Footrope 3 m starboard of centre	N	+/-	Weinberg & Munro, 1999
		Atheresthes stomias							N	+/-	
		Pleuronectes asper							N	+/-	
		Lepidopsetta bilineata							N	+/-	
		Gadus macrocephalus							N	+/-	
		Hippoglossoides elassodon							N	-	
Rockal Trough	Bottom	*Alocephalus bairdii*	E	Electric (filament)	NA	70 W	2	3 m from each other from the headline centre	Y	+	Gordon et al., 2002
		Centroscymnus coelolepis							Y	+	

		Centroscymnus crepidater							Y	+	
		Coelorinchus labiatus							Y	-	
		Coryphaenoides rupestris							Y	+	
		Halargyreus johnsonni							Y	+	
		Notacanthus bonapartei							Y	+	
		Xenodermichthys copei							Y	+	
		Other fish							N	+/-	
Gulf of Mexico**	Bottom	Shrimp	T	Light sticks	NA	NA	8	35 cm downstream of a BRD	N	+/-	Parsons et al., 2012
		Lutjanus campechanus	B						Y	-	
		Other fish	B						N	+/-	
U.S. Pacific coast**	Midwater	*Merluccius productus*	T	LED	White	2600 lm+850 lm (from camera)	2	Top panel of an escape window (BRD)	NA	+/-	Lomeli & Wakefield, 2012
		Oncorhynchus tshawytscha	B							-	
		Sebastes entomelas	B							+/-	
U.S. Pacific coast**	Midwater	*Merluccius productus*	T	LED	White	2600 lm+850 lm (from camera)	2	Top panel of an escape window (BRD)	NA	+/-	Lomeli & Wakefield, 2014
		Oncorhynchus tshawytscha	B							+	
		Sebastes entomelas	B							+/-	
Newport, Oregon**	Bottom	*Pandalus jordani*	T	LED	Green (540 nm); Blue (460 nm)	≥0.5-2.0 lx	1[#],3[#], 4[#], 10[##]	Near a sorting grids[#], centre of the footrope (1.2 m each other)[##]	NA[#]	+/-[#], +/-[##]	Hannah et al., 2015
		Thaleichthys pacificus	B						N[#]	+[#], -[##]	
		Lyopsetta exilis	B						NA[#]	+[#],	
		Sebastes crameri	B						NA[#]	+/-[#], -[##]	
		Sebastes spp	B						NA[#]	+/-[#], -[##]	
Barents Sea**	Bottom	*Pandalus borealis*	T	LED	Green (540 nm)	≥0.5-2.0 lx	5	Around the escape exit of a sorting grids	Y	+/-	Larsen et al., 2017
		Sebastes spp.	B						N	+	
		Melanogrammus aeglefinus	B						Y	+	
		Gadus morhua	B						Y	+	
		Hippoglossoides platessoides	B						N	+	

Finnmark, Barents Sea***	Bottom	*Melanogrammus aeglefinus*	T	LED	Green (540 nm)	≥0.5-2.0 lx	8	In the centre of a square mesh panel by means floats	Y	+	Grimaldo et al., 2018
		Gadus morhua	T						Y	+/-	
Barents Sea**	Bottom	*Pandalus borealis*	T	LED	Green (540 nm)	≥0.5-2.0 lx	4	lower part of a Nordmøre grid	N	+/-	Larsen et al., 2018
		Hippoglossoides platessoides	B						N	+/-	
		Gadus morhua	B						N	+/-	
		Melanogrammus aeglefinus	B						N	+/-	
		Sebastes spp	B						N	+/-	
Newport, Oregon***	Bottom	*Hippoglossus stenolepis*	T	LED	Green (540 nm)	≥0.5-2.0 lx	87	Headrope (clusters of three ~1.3 m apart starting from the headrope centre)	N	-	Lomeli et al., 2018a
		Parophrys vetulus	T						N	+	
		Glyptocephalus zachirus	T						N	-	
		Atheresthes stomias	T						N	-	
		Microstomus pacificus	T						Y	-	
		Eopsetta jordani	T						N	+	
		Sebastes crameri	B						N	+	
		Sebastes elongatus	B						N	+	
		Sebastes pinniger	B						N	+	
		Other rockfishes	B						N	+	
		Anoplopoma fimbria	B						Y	-	
		Ophiodon elongatus	B						N	-	
U.S. Pacific coast**	Bottom	*Pandalus jordani*	T	LED	Green (519 nm)	≥0.5-2.0 lx	5[#], 10[#], 20[###]	Footrope (5[#], 10[#] lights 1.2 m apart from the centre; 20[###] lights 0.6 m apart from the centre)	Y[#], Y[##], Y[###]	+/-[#], +/-[##], +/-[###]	Lomeli et al., 2018b
		Thaleichthys pacificus	B						Y[#], Y[##], Y[###]	-[#], -[##], -[###]	
		Allosmerus elongatus	B						Y[#], Y[##], Y[###]	-[#], -[##], -[###]	
		Merluccius productus	B						Y[#], Y[##], Y[###]	+/-[#], +[##], +/-[###]	
		Rockfish	B						Y[#], Y[##], Y[###]	-[#], -[##], -[###]	

		Citharichthys sordidus	B						Y[#], Y[##], Y[###]	-[#], -[##], -[###]	
		Glyptocephalus zachirus	B						Y[#], Y[##], Y[###]	-[#], -[##], -[###]	
		Lyopsetta exilis	B						Y[#], Y[##], Y[###]	-[#], -[##], -[###]	
Skagerrak, Denmark**	Bottom (horizontally separated)	*Nephrops norvegicus*	T	LED	Green (540 nm)	≥0.5-2.0 lx	10	Before lower netting panel[#], before upper netting panel[##]	Y[#], Y[##]	+[#]	Melli et al., 2018
		Gadus morhua	B						Y[#], N[##]	NA	
		Melanogrammus aeglefinus	B						N[#], Y[##]	NA	
		Merlangius merlangus	B						N[#], Y[##]	NA	
		Pleuronectes platessa	B						Y[#], N[##]	NA	
		Microstomus kitt	B						N[#], Y[##]	NA	
Tyrrhenian Sea, Italy****	Bottom	*Parapenaeus longirostris*	T	LED	NA	NA	NA	Headrope	NA	+/-	Sbrana et al., 2018
		Merluccius merluccius	T						Y	NA	
Bay of Biscay***	Bottom	*Merluccius merluccius*	T	LED	Blue	NA	10	Close to a square mesh panel just before the codend	N	+/-	Cuende et al., 2019
		Trachurus trachurus	B						N	+/-	
		Micromesistius poutassou	T						Y	+	
Oregon, N Pacific**	Midwater	*Oncorhynchus tshawytscha*	B	LED	Blue (464 nm)+ white light from video camera	≥0.5-2.0 lx + 700 lm	28 (in cluster of two)[#] 24 (in cluster of two)[##]	About 61 cm apart over the distance of two escape windows	NA[#], N[##]	-[#], -[##]	Lomeli & Wakefield, 2019
		Other rockfishes	B						NA[##]	+/-	
Orkney Islands, Scotland*****	Bottom (horizontally separated)	*Limanda limanda*	B	LED (fibre optic cable)	Green (530 nm)	NA	1 (30 m long but doubled up on itself)	Footrope#, leading edge of the separator panel##	Y[#] and [##]	+	O'Neill & Summerbell, 2019
		Melanogrammus aeglefinus	B						N	-	
		Merlangius merlangus	B						Y[#] and [##]	-	

		Pleuronectes platessa	B						N	-	
		Eutrigla gurnardus	B						Y[#] and [##]	-	
		Chelidonichthys cuculus	B						N	-	
		Microstomus kitt	B						Y[#] and [##]	NA	
Bay of Biscay**	Bottom	*Merluccius merluccius*	T	LED	White	NA	10	Upper part of the extension piece, over a square mesh panel#	N[#], N[##]	+/-[#], +/-[##]	Cuende et al., 2020
		Micromesistius poutassou	T					Lower part of the extension piece, in front a square mesh panel##	N[#], N[##]	+/-[#], +/-[##]	
Oregon, N Pacific**	Midwater	*Merluccius productus*	T	LED	Blue (464 nm)	≥0.5-2.0 lx	16[#], 32[#]	Along the escape area of a BRD 1.25 m apart each other	N	-	Lomeli & Wakefield, 2020
		Oncorhynchus tshawytscha	B						N	-	
Oregon, N Pacific**	Bottom	*Pandalus jordani*	T	LED	Green (519 nm)	≥0.5-2.0 lx	5	Headrope centre, about 1 m apart each other	N	+/-	Lomeli et al., 2020
		Thaleichthys pacificus	B						Y	-	
		Sebastes flavidus	B						Y	-	
		Sebastes saxicola	B						Y	+	
		Other rockfishes	B						Y	+	
		Atheresthes stomias	B						N	+	
		Lyopsetta exilis	B						Y	+	
		Other flatfishes	B						Y	+	
Irish Sea**	Bottom	*Aequipecten opercularis*	T	LED	White	33 cd	6	Over a square mesh panel inserted 1.8 m aft of the centre of the headrope	NA	+/-	Southworth et al., 2020
		Merlangius merlangus	B						N	-	
		Melanogrammus aeglefinus	B						N	-	
		Gadus morhua	B						NA	+/-	
		flatfish	B						N	-	
Skagerrak, Denmark*******	Bottom (horizontally)	*Nephrops norvegicus*	T	Luminous net	Green (520 nm)	NA	A v-shape ascending	Just before the codend	N	NA	Karlsen et al., 2021
		Gadus morhua	B						Y	NA	

	separated)	*Melanogrammus aeglefinus* *Merlangius merlangus*	B				stripe of net		Y	NA	
		flatfishes	B						Y	NA	
			B						N	NA	
Oregon, N Pacific**	Bottom	*Hippoglossus stenolepis*	B	LED	Green (519 nm)	18 (attached in clusters of three)	≥0.5-2.0 lx	Upper bridles and wing tips	Y	-	Lomeli et al., 2021
		Microstomus pacificus	T						Y	-	
		Eopsetta jordani	T						Y	-	
		Anoplopoma fimbria	T						Y	-	
		Ophiodon elongatus	T						N	-	
Strait of Sicily, Italy****	Bottom	*Parapenaeus longirostris*	T	LED	Green (520 nm), white (460 nm)	20 (10 green + ten white)	3.5 cd	Headrope, 50 cm apart each other	Y	+	Geraci et al., in press
		Merluccius merluccius	B						N	+	
		All groundfishes combined	B						NA	+	
Strait of Sicily, Italy****	Bottom	*Parapenaeus longirostris*	T	LED	Green (520 nm), white (460 nm)	20 (10 green + ten white)	3.5 cd	Headrope, 50 cm apart each other	Y	+	Present study
		Merluccius merluccius	B						Y	+/-	
		Trachurus trachurus	B						Y	+/-	
		All groundfishes combined	B						NA	+/-	

E: explorative; **T:** target; **B:** bycatch; **NA:** not available; **+:** increase, **-:** decrease, **+/-:** unaffected; **Y:** Yes, **N:** No; **Lampanyctus crocodilus*, *Sagamichthys schnakenbecki*; **the aim of the study was to reduce the catch of the bycatch species (intended as undersized individuals); ***the aim of the study was to reduce the catch of undersized target and bycatch species; ****the aim of the study was to assess the effect of lights (increase/decrease of catch rates) on both target and bycatch species (intended as accessory commercial catch) and discard (i.e. undersized individuals); ****** the aim of the study was to alter the height at which fish enter a trawl gear and reduce bycatch species (intended as undersized individuals); ******* the aim of the study was to increase the fish capture in the upper compartment; #: configuration of light

Previously, in the Strait of Sicily, an unplanned and preliminary trial suggested a general attractive effect of artificial lights. In fact, a significant increase was recorded for the catch rates in weight during night in hauls with light for *P. longirostris*, *M. merluccius*, and gross catch (Geraci *et al.*, in press). Conversely, in the northern Tyrrhenian Sea, the use of light did not affect the catch rates in weight of *P. longirostris*, but caused a decrease in *M. merluccius* specimens below the MCRS (Sbrana *et al.*, 2018). On the other hand, Sardo *et al.* (2020) recently found that *T. trachurus* juveniles were repelled by white light in a laboratory study. In oceanic water, artificial lights have been evaluated as a potential tool to reduce the bycatch of fish in several fisheries, such as bottom trawls targeting shrimp and *Nephrops norvegicus* (Hannah *et al.*, 2015; Larsen *et al.*, 2017, 2018; Melli *et al.*, 2018; Lomeli *et al.*, 2018a, b, 2020; Karlsen *et al*., 2021); midwater trawl for Pacific hake *(Merluccius productus*) (Lomeli & Wakefield, 2012; 2014; 2019; 2020); mixed bottom trawl fishery (Cuende *et al.*, 2019; 2020; Lomeli *et al.*, 2021); and trawl fishery for Queen scallops (*Aequipecten opercularis*) (Southworth *et al.*, 2020). These studies have revealed that the effects of artificial light on catch are highly variable, as they are dependent on many factors. Larsen *et al.* (2018), who worked with a rigid Nordmøre grid mounted on a shrimp trawl net targeting *Pandalus jordani*, noted that the addition of green LEDs around the escape exit was ineffective at reducing juvenile fish bycatch. Previously, in Pacific waters, Hannah *et al.* (2015) demonstrated that the CPUE of *P. jordani* did not change using blue-green lights in different portions of the trawl net; however, the bycatch amount was variable and dependent on the proper placement/location of lights within the fishing gear. Specifically, adding artificial light around a sorting grid caused an increase in bycatch, which was reduced when lights were mounted on the fishing line (Hannah *et al.*, 2015). Lomeli *et al.* (2018b) compared the CPUE obtained with a trawl net equipped with different configurations of 5, 10, and 20 LED lamps with those of an unilluminated trawl net; however, these researchers did not find any differences in *P. jordani* catch rates. On the contrary, they found a significant reduction in the bycatch for most of the species, except for *M. productus* using a ten LED-configuration. In Basque mixed bottom trawl fisheries, Cuende *et al.* (2019) tested a square mesh panel (SMP) together with different types of stimulators (i.e., ropes, floats, blue LED lights), and reported that blue LED light did not enhance the escape probability of *M. merluccius* and *T. trachurus*. More recently, no significant improvement in the release efficiency for either *M. merluccius* or *Micromesisitius poutassou* was confirmed in the same area by testing white LED lights with an SMP (Cuende *et al.,* 2020). The bulk of global discards from fisheries is derived from trawling (Perez-Roda *et al.,* 2019) and the recent implementation of the EC Reg. 1241/2019 aims to minimise the impact of fishing on marine ecosystems. The application of artificial light in trawl fisheries to reduce unwanted by-catch could be very fruitful, but needs to be further assessed (ICES, 2020). For this purpose, a shared protocol or "paper guidelines", summarising all information from scientific surveys, personal experience, and other disciplines (e.g., physics, physiology, ethology), could be very useful for both fishery biologists and fishers.

Our results confirmed the general positive effects of artificial lights on *P. longirostris* catch rates during the night reported by local fishers, who are increasingly using green and white (simultaneously) artificial lights on the headrope of trawl nets. Moreover, the use of 20 LED lights mounted symmetrically to the centre of the head rope in the crustacean trawl net might have an important effect on the size selectivity of the trawl, particularly for legal-sized *P. longirostris* and undersized individuals of *M. merluccius* and *T. trachurus*. As the estimated annual costs of approximately 500 € are associated with the use/maintenance of light (Pinello *et al.*, 2018) as well as the work for managing these lights on board, it is reasonable to suppose that the cost-benefit ratio should be positive. Traditionally, crustacean trawl fisheries are mainly carried out during the day owing to the higher catchability of the gear than the night. Indeed, during the daytime, *P. longirostris* stays on or relatively close to the bottom to avoid predators (Aguzzi *et al.,* 2009); however, at night, they migrate from the seafloor to prey on water columns (Rodríguez-Climent *et al.*, 2016). In the last few years, the use of artificial lights has enabled shrimp fishing activity during the night, abandoning the traditional alternation between deep-water trawling during the day, targeted to shrimp, and shallow water trawling during the night, targeted to fish and cephalopods. Owing to such recent widespread use of artificial light in deep-water crustacean fisheries, a further evaluation of its impact on the catch is needed to avoid the fact that an increase in CPUE can lead to a depletion of the exploited stocks. Fishing fleets using artificial lights should be carefully considered because of their expected effect in improving the catchability of target and non-target species. In the well-known situation of high overexploitation of stocks in the Mediterranean (e.g., Colloca *et al.*, 2017), including *P. longirostris* and *M. merluccius* in the Strait of Sicily (GFCM, 2019), lights and other technological tools may be increasingly used by fishing vessels to “buffer” the reduction in catch rate of traditional fishing gear. An expected consequence of the use of light in trawling could be an increase in fishing mortality that eliminates the reduction of the fishing effort implemented by the European CFP and contributing to a deterioration of the stocks status. Although more quantitative data should be gathered to generalise the results obtained, this study shows clear trade-offs between gains due to higher CPUE of commercial *P. longirostris* specimens and risks linked to higher unwanted by-catch of juveniles below the MCRS of *M. merluccius* and *T. trachurus*.

5. Conclusions

The present study indicates that the use of underwater lights in Mediterranean trawl fisheries should be carefully regulated through ad hoc measures that are currently lacking. The meta-synthesis of the effect of artificial lights during trawling highlights that, similar to the next years, scientists will face a new challenge in enhancing knowledge on the impact of artificial lighting on marine ecosystems during fishing activities, which are only now beginning to be examined in detail, at least in the Mediterranean. In the absence of sound scientific understanding, precautionary management measures should be taken to minimise the potential impacts of artificial light on some already overexploited stocks, where possible. Thus, more studies are needed to explore trade-offs in mixed trawl fisheries using different experimental artificial light settings (number location, intensity, and wavelengths) on different fishing grounds and species assemblages. Lastly, the different behaviour of species when approaching the gear should be considered. The aim would be to establish rules for the use of underwater lights in trawl fisheries, and to identify more suitable settings to improve fishery selectivity, thereby avoiding unwanted increases in both fishing mortality and unwanted by-catch. The construction of a solid baseline of knowledge on the impacts of artificial lighting in fishing practices will enable the potential design of realistic and effective management strategies that can benefit both marine ecology and society.

Declaration of competing interest

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

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Data availability statement

The dataset analysed during the current study is available from the corresponding author upon reasonable request.

References

Aguzzi, J., Costa, C., Antonucci, F., Company, J. B., Menesatti, P., Sarda, F., 2009. Influence of diel behaviour in the morphology of decapod natantia. *Biological Journal of the Linnean Society,* 96(3), 517─532. https://doi.org/10.1111/j.1095-8312.2008.01162.x

Arakawa, H., Choi, S., Arimoto, T., Nakamura, Y., 1998. Relationship Between Underwater Irradiance and Distribution of Japanese Common Squid Under Fishing Lights of a Squid Jigging Boat. *Fisheries science*, 64(4), 553–557. https://doi.org/10.2331/fishsci.64.553

Arimoto, T., Glass, C.W., Zhang, X., 2010. Fish vision and its role in fish capture, in: Pingguo, H. (Eds.), Behavior of Marine Fishes: Capture Processes and Conservation Challenges. Blackwell Publishing, Ames, Iowa, USA, pp. 25–44.

Battaglia, P., Romeo, T., Consoli, P., Scotti, G., Andaloro, F., 2010. Characterization of the artisanal fishery and its socio-economic aspects in the central Mediterranean Sea (Aeolian Islands, Italy). *Fisheries Research*, 102, 87–97. http://dx.doi.org/10.1016/j.fishres.2009.10.013

Bielli, A., Shigueto, J.A., Doherty, P.D., Godley, B.J., Ortiz, C., Pasara, A., Wang, J.H., Mangel, J.C., 2020. An illuminating idea to reduce bycatch in the Peruvian small-scale gillnet fishery. *Biological Conservation*, 241: 108277. https://doi.org/10.1016%2Fj.biocon.2019.108277

Brooks, M.E., 2019. selfisher: Selectivity of Fisheries Gear, Modeled using Template Model Builder. R package version 1.0.0. https://github.com/mebrooks/selfisher

Brooks, M.E., Melli, V., Savina, E., Santos, J., Millar, R., O'Neill, F.G., Veiga-Malta, T., Krag, L.A., Feekings, J. P., 2020. Introducing selfisher: open source software for statistical analyses of fishing gear selectivity. bioRxiv.

Colloca, F., Scarcella, G., Libralato, S., 2017. Recent Trends and Impacts of Fisheries Exploitation on Mediterranean Stocks and Ecosystems. *Frontiers in Marine Science,* 4, 244. http://dx.doi.org/10.3389/fmars.2017.00244

Cuende, E., Arregi, L., Herrmann, B., Sistiaga, M., Onandia, I., 2020a. Stimulating release of undersized fish through a square mesh panel in the Basque otter trawl fishery. *Fisheries Research,* 224, 105431. http://dx.doi.org/doi:10.1016/j.fishres.2019.105431.

Cuende, E., Arregi, L., Herrmann, B., Sistiaga, M., Basterretxea, M., 2020b. Release efficiency and selectivity of four different square mesh panel configurations in the Basque mixed bottom trawl fishery. *Scientia Marina*, 84(1), 39. http://dx.doi.org/10.3989/scimar.04975.17a.

Di Lorenzo, M., Sinerchia, M., Colloca, F., 2018. The North sector of the Strait of Sicily: a priority area for conservation in the Mediterranean Sea. *Hydrobiologia*, 821, 235–253. http://dx.doi.org/10.1007/s10750-017-3389-7.

Efron, B. 1982., The jackknife, the bootstrap and other resampling plans. Society for Industrial and Applied Mathematics, CBMSNSF Regional Conference Series in Applied Mathematics Monograph 38, Philadelphia. 85 pp

Field, R., Crawford, R., Enever, R., Linkowski, T., Martin, G., Morkūnas, J., Morkūnė, R., Rouxel, Y., Oppel, S., 2019. High contrast panels and lights do not reduce bird bycatch in Baltic Sea gillnet fisheries. *Global Ecology and Conservation,* 18, e00602. https://doi.org/10.1016%2Fj.gecco.2019.e00602

Fiorentino, F., Patti, B., Colloca, F., Bonanno, A., Basilone, G., Gancitano, V., Garofalo, G., Goncharov, S., Gristina, M., Sinacori, G., Mazzola, S., 2013. A comparison between acoustic and bottom trawl estimates to reconstruct the biomass trends of sardine and anchovy in the Strait of Sicily (Central Mediterranean). *Fisheries Research,* 147, 290–295. https://doi.org/10.1016/j.fishres.2013.06.001

Fryer, R.J., Zuur, A.F., Graham, N., 2003. Using mixed models to combine smooth size selection and catch-comparison curves over hauls. *Canadian Journal of Fisheries and Aquatic Sciences*, 60: 448–459. https://doi.org/10.1139/f03-029

Geraci, M.L., Scannella, D., Falsone, F., Sardo, G., Gancitano, V., Colloca, F., Fiorentino, F., Vitale, S. An unplanned trial with artificial light revealed a yield increase in crustacean trawl fisheries. In: Symposium on the Light session and the Topic Group Lights: ICES-FAO Working Group on Fishing Technology and Fish Behaviour, Bergen (Norway), 19–23 April 2021. In press.

G.F.C.M., 2019. Working Group on Stock Assessment of Demersal Species (WGSAD). FAO headquarters, Rome, Italy, 9–14 December 2019

Grimaldo, E., Sistiaga, M., Herrmann, B., Larsen, R.B., Brinkhof, J., Tatone, I., 2018. Improving release efficiency of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Barents Sea demersal trawl fishery by stimulating escape behaviour. *Canadian Journal of Fisheries and Aquatic Sciences*, 75 (3), 402–416. http://dx.doi.org/10.1139/cjfas-2017-0002

Hannah, R.W., Lomeli, M.J.M., Jones, S.A., 2015. Tests of artificial light for bycatch reduction in an ocean shrimp (*Pandalus jordani*) trawl: Strong but opposite effects at the footrope and near the bycatch reduction device. *Fisheries Research*, 170, 60–67. http://dx.doi.org/10.1016/j.fishres.2015.05.010

Holst, R., Revill, A.S., 2009. A simple statistical method for catch comparison studies. *Fisheries Research*, 95, 254–259. https://doi.org/10.1016/j.fishres.2008.09.027

ICES. 2012. Topic Group on the Use of Artificial Light in Fishing. In the Report of the ICES-FAO Working Group on Fishing Technology and Fish Behaviour (WGFTFB), 23-27 April 2012, Lorient, France. ICES CM 2012/SSGESST:07. 206 pp.

ICES. 2013. Topic Group on the Use of Artificial Light in Fishing. In the Report of the ICES-FAO Working Group on Fish Technology and Fish Behaviour (WGFTFB), 6-10 May 2013, Bangkok, Thailand. ICES CM 2013/SSGESST:11. 116 pp.

ICES. 2020. ICES Workshop on Innovative Fishing Gear (WKING). ICES Scientific Reports. 2, 96. http://doi.org/10.17895/ices.pub.7528

Karlsen, J.D., Melli, V., Krag, L.A., 2021. Exploring new netting material for fishing: the low light level of a luminous netting negatively influences species separation in trawls. *ICES Journal of Marine Science*, 0: 1–12. https://doi.org/10.1093/icesjms/fsab160

Kim, Y.H., Wardle, C.S., 2003. Optomotor response and erratic response: quantitative analysis of fish reaction to towed fishing gears. *Fisheries Research*, 60 (2-3), 455–470. http://dx.doi.org/10.1016/s0165-7836(02)00114-5

Kraljević, V., Čikeš Keč, V., Zorica, B., 2014. Analysis of purse-seine catches in the Adriatic Sea. *Croatian Journal of Fisheries*, 72, 142–149. http://dx.doi.org/10.14798/72.4.764

Larsen, R.B., Herrmann, B., Sistiaga, M., Brinkhof, J., Tatone, I., Langård, L., 2017. Performance of the Nordmøre grid in shrimp trawling and potential effects of guiding funnel length and light stimulation. *Marine and Coastal Fisheries,* 9(1), 479–492. http://dx.doi.org/10.1080/19425120.2017.1360421

Larsen, R.B., Herrmann, B., Sistiaga, M., Brčić, J., Brinkhof, J., Tatone, I. 2018. Could green artificial light reduce bycatch during Barents Sea deep-water shrimp trawling? *Fisheries Research*, 204, 441–447. http://dx.doi.org/10.1016/j.fishres.2018.03.023

Levi, D., Andreoli, M.G., Giusto, G.B., 1995. First assessment of the rose shrimp, *Parapenaeus longirostris* (Lucas, 1846) in the central Mediterranean. *Fisheries Research*, 21 (3-4): 375–393. http://dx.doi.org/10.1016/0165-7836(94)00298-b

Lomeli, M.J.M., Wakefield, W.W., 2012. Efforts to reduce Chinook salmon (*Oncorhyncus tshawytscha*) and rockfish (*Sebastes* spp.) bycatch in the U.S. west coast Pacific hake (*Merluccius productus*) fishery. *Fisheries Research*, 119–120, 128–132. http://dx.doi.org/10.1016/j.fishres.2011.11.003

Lomeli, M.J.M., Wakefield, W.W., 2014. Examining the potential use of artificial illumination to enhance Chinook salmon escapement out a bycatch reduction device in a Pacific hake midwater trawl. National Marine Fisheries Service, Northwest Fisheries Science Center Report, Seattle, WA, pp. 15

Lomeli, M.J.M., Wakefield W.W., Herrmann B., 2018a. Illuminating the Headrope of a Selective Flatfish Trawl: Effect on Catches of Groundfishes, Including Pacific Halibut. *Marine and Coastal Fisheries*, 10 (2), 118–131. http://dx.doi.org/10.1002/mcf2.10003

Lomeli, M.J.M., Groth, S.D., Blume, M.T.O., Herrmann, B., Wakefield, W.W., 2018b. Effects on the bycatch of eulachon and juvenile groundfish by altering the level of artificial illumination along an ocean shrimp trawl fishing line. *ICES Journal of Marine Science*, 75 (6), 2224–2234. http://dx.doi.org/10.1093/icesjms/fsy105

Lomeli, M.J.M., Wakefield, W.W., 2019. The effect of artificial illumination on Chinook salmon behavior and their escapement out of a midwater trawl bycatch reduction device. *Fisheries Research,* 218, 112–119. https://doi.org/10.1016/j.fishres.2019.04.013

Lomeli, M.J.M., Groth, S.D., Blume, M.T.O., Herrmann, B., Wakefield, W.W., 2020. The Efficacy of Illumination to Reduce Bycatch of Eulachon and Groundfishes Before Trawl Capture in the Eastern North Pacific Ocean Shrimp Fishery. *Canadian Journal of Fisheries and Aquatic Sciences*, 77(1), 44–54. https://doi.org/10.1139/cjfas-2018-0497

Lomeli, M.J.M., Wakefield, W.W., 2020. Altering the level of illumination on a bycatch reduction device and its effect on the catch rates of Pacific hake and Chinook salmon. Pacific States Marine Fisheries Commission Report, 27 pp.

Lomeli, M.J.M, Wakefield, W.W., Herrmann, B., Dykstra, C.L., Simeon, A., Rudy, D. M., Planas, J. V., 2021. Use of artificial illumination to reduce Pacific halibut bycatch in a US West Coast groundfish Bottom trawl. *Fisheries Research*, 233, 105737. https://doi.org/10.1016/j.fishres.2020.105737

Matsushita, Y., Azuno, T., Yamashita, Y., 2012. Fuel reduction in coastal squid jigging boats equipped with various combinations of conventional metal halide lamps and low-energy LED panels. *Fisheries Research*, 125, 14–19. https://doi:10.1016/j.fishres.2012.02.004

Melli, V., Krag, L.A., Herrmann, B., Karlsen, J.D., 2018. Investigating fish behavioural responses to LED lights in trawls and potential applications for bycatch reduction in the Nephrops-directed fishery. *ICES Journal of Marine Science*, 75 (5), 1682–1692. https://doi.org/10.1093/icesjms/fsy048

Melli, V., Krag, L. A., Herrmann, B., Karlsen, J. D., Feekings, J. P., 2020. Does the efficiency of a counter-herding device depend on seabed contact? *Fisheries Research*, 230, 105686. https://doi.org/10.1016/j.fishres.2020.105686

Milisenda, G., Vitale, S., Massi, D., Enea, M., Gancitano, V., Giusto, G.B., Badalucco, C., Gristina, M., Garofalo, G., Fiorentino, F., 2017. Discard composition associated with the deep water rose shrimp fisheries (*Parapenaeus longirostris*, Lucas 1846) in the south-central Mediterranean Sea. *Mediterranean Marine Science*, 18 (1), 53. https://doi.org/10.12681/mms.1787

Millar, R.B., 1993. Incorporation of between-haul variation using bootstrapping and nonparametric estimation of selection curves. *Fishery Bulletin*, 91, 564-572.

Nguyen, K.Q., Winger, P.D., 2019. Artificial Light in Commercial Industrialized Fishing Applications: A Review. *Reviews in Fisheries Science & Aquaculture*, 27(1), 106–126. https://doi.org/10.1080/23308249.2018.1496065

Okpala, C.O.R., Sardo, G., Vitale, S., 2017. Lighting Methods Employed in Harvest of Fishery Products: A Narrative Review. *Natural Resources and Conservation*, 5(4), 57–74. https://doi.org/10.13189/nrc.2017.050401

O'Neill, F.G., Summerbell, K., 2019. The influence of continuous lines of light on the height at which fish enter demersal trawls. *Fisheries Research*, 215, 131–142. https://doi.org/10.1016/j.fishres.2019.03.010

Parrish, J.K., 1999. Using behavior and ecology to exploit schooling fishes. *Environmental Biology of Fishes*, 55 (1-2), 157–181. https://doi.org/10.1023/a:1007472602017

Pérez Roda, M.A., Gilman, E., Huntington, T., Kennelly, S.J., Suuronen, P., Chaloupka, M., Medley, P., 2019. A Third Assessment of Global Marine Fisheries Discards. FAO Fisheries and Aquaculture Technical Paper No. 633. FAO, Rome.

Pinello, D., Gee, J., Accadia, P., Sabatella, E.C., Vitale, S., Polymeros, K., Fiorentino, F., 2018. Efficiency of shallow- and deep-water trawling in the Mediterranean and its implications for discard reduction. *Scientia Marina*, 82 (S1), 97–106. https://doi.org/10.3989/scimar.04749.22a

R Core Team., (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rodríguez-Climent, S., Sonderblohm, C.P., Fonseca, P., Erzini, K., Campos, A., 2016. Diel variation in the deep-water rose shrimp *Parapenaeus longirostris* (Lucas, 1846) catches off the Portuguese south coast. In: Front. Mar. Sci. Conference Abstract: XIX Iberian Symposium on Marine Biology Studies. https://doi.org/10.3389/conf. FMARS (Vol. 73).

Sardo, G., Okpala, C.O.R., Geraci, M.L., Vitale, S. 2020. The effects of different artificial light wavelengths on some behavioural features of juvenile pelagic Atlantic horse mackerel, *Trachurus trachurus* (Actinopterygii: Perciformes: Carangidae). *Acta Ichthyologica Et Piscatoria*, 50 (1), 85–92. https://doi.org/10.3750/AIEP/02709

Sbrana, M., De Carlo, F., Viva, C., Massaro, A., 2018. Use of artificial lights in the bottom trawl fishery in the northern Tyrrhenian sea. 49° Congresso della Società Italiana di Biologia Marina, 4–8 June 2018, Cesenatico (FC), Italy.

Sistiaga, M., Herrmann, B., Grimaldo, E., Larsen, R.B., 2015. Effect of lifting the sweeps on bottom trawling catch efficiency: A study based on the Northeast arctic cod (*Gadus morhua*) trawl fishery. *Fisheries Research*, 167, 164–173. https://doi.org/10.1016/j.fishres.2015.01.015

Sola, I., Maynou F., 2018. Assessment of the relative catch performance of hake, red mullet and striped red mullet in a modified trawl extension with T90 netting. *Scientia Marina*, 82S1, 19–26. https://doi.org/10.3989/scimar.04711.04A

Southworth, L.K., Ratcliffe, F.C., Bloor, I.S.M., Emmerson, J., Watson, D., Beard, D., Kaiser, M.J., 2020. Artificial light improves escapement of fish from a trawl net. *Journal of the Marine Biological Association of the United Kingdom*, 100(2), 267–275. https://doi.org/10.1017/s0025315420000028.

Tsagarakis, K., Vassilopoulou, V., Kallianiotis, A., Machias, A., 2012. Discards of the purse seine fishery targeting small pelagic fish in the eastern Mediterranean Sea. *Scientia Marina*, 76(3), 561–572. https://doi.org/10.3989/scimar.03452.02b

Vidoris, P., Argyrokastritis, A., Kallianiotis, A., 2001. Purse seine catches composition in Kavala fishing port. Proceedings of the Working Group on Small Pelagic species, Sub-committee for Stock assessment, Scientific Advisory Committee, General Fisheries Commission for the Mediterranean, Kavala, 27-30 March.

Vitale, S., Ragonese, S., Cannizzaro, L., Fiorentino, F., Mazzola, S., 2014. Evidence of trawling impact on *Hoplostethus mediterraneus* in the central–eastern Mediterranean Sea. *Journal of the Marine Biological Association of the United Kingdom,* 94(3), 631–640. https://doi:10.1017/S0025315413001884

Vitale, S., Milisenda, G., Gristina, M., Baiata, P., Bonanomi, S., Colloca, F., Gancitano, V., Scannella, D., Fiorentino, F., Sala, A. 2018a. Towards more selective Mediterranean trawl fisheries: are juveniles and trash excluder devices effective tools for reducing undersized catches? *Scientia Marina*, 82 (S1), 215–223. https://doi.org/10.3989/scimar.04751.28a

Vitale, S., Enea, M., Milisenda, G., Gancitano, V., Geraci, M.L., Falsone, F., Bono, G., Fiorentino, F., Colloca, F. 2018b. Modelling the effects of more selective trawl nets on the productivity of European hake (*Merluccius merluccius*) and deep-water rose shrimp (*Parapenaeus longirostris*) stocks in the Strait of Sicily. *Scientia Marina*, 82 (S1), 199–208. https://doi.org/10.3989/scimar.04752.03a

Wood, S.N. 2006. Generalized additive models: an introduction with R. Chapman and Hall, Boca Raton, Florida, U.S.A. https://doi.org/10.1201/9781420010404

Zuur, A.F., Ieno, E.N., Walker, N., Saveliev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology with R. Statistics for Biology and Health, XXII. Springer-Verlag, New York, NY, USA. http://link.springer.com/10.1007/ 978-0-387-87458-6

Appendix A.

Supplementary data

Figure

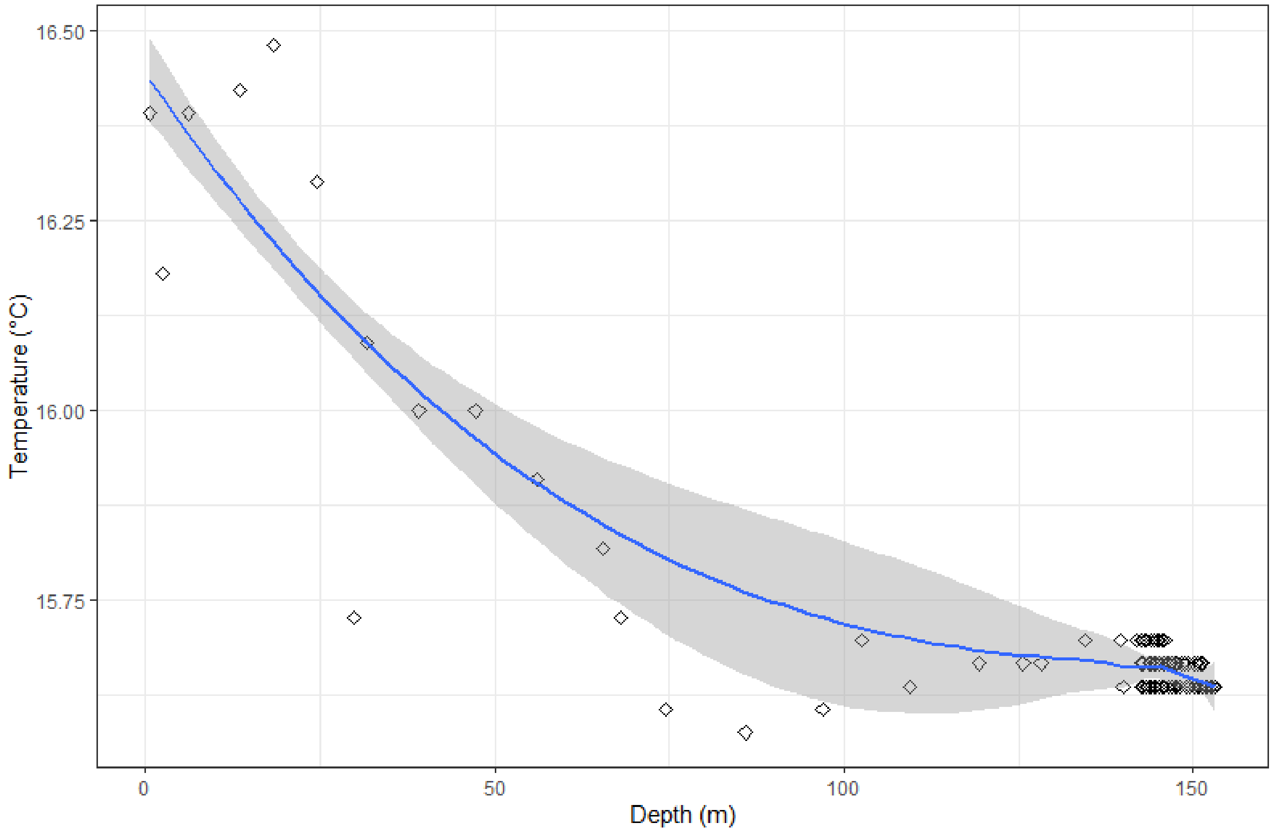

Fig. S1: Mean temperature recorded at various depth by STAR-ODDI probe during the three days' survey. Grey band gives the 95% confidence limit; the smooth curve of the LOESS regression is depicted in blue.

Appendix B

Table

Table S1. List of the species caught during survey. Control and test net expressed in total weight (grams) and total number, Δ is the difference between test and control.

Species	Total weight (g)		Total number		Δ	
	control	test	control	test	weight	number
Acanthocardia echinata (Linnaeus, 1758)	22	0	2	0	-22	-2
Acanthocardia paucicostata (G. B. Sowerby II, 1834)	1	0	1	0	-1	-1
Acanthocardia tuberculata (Linnaeus, 1758)	0	3	0	1	3	1
Adamsia palliata (Fabricius, 1779)	114	139	0	0	25	0
Alcyonium palmatum Pallas, 1766	49	17	7	3	-32	-4
Alloteuthis media (Linnaeus, 1758)	0	13	0	1	13	1
Alpheus glaber (Olivi, 1792)	1	2	1	2	1	1
Anadara gibbosa (Reeve, 1844)	97	66	10	6	-31	-4
Annelida (Lamarck, 1802)	372	243	17	9	-129	-8
Aphrodita aculeata Linnaeus, 1758	72	0	2	0	-72	-2
Arca noae Linnaeus, 1758	0	9	0	0	9	0
Arca tetragona Poli, 1795	7	0	1	0	-7	-1
Argentina sphyraena Linnaeus, 1758	106	124	9	16	18	7
Armina tigrina Rafinesque, 1814	0	2	0	1	2	1
Arnoglossus laterna (Walbaum, 1792)	507	613	98	110	106	12
Astropecten aranciacus (Linnaeus, 1758)	24	0	1	0	-24	-1
Astropecten irregularis pentacanthus (Delle Chiaje, 1827)	11	0	4	0	-11	-4
Astrospartus mediterraneus (Risso, 1826)	39	0	1	0	-39	-1
Bolinus brandaris (Linnaeus, 1758)	50	0	2	0	-50	-2
Bolma rugosa (Linnaeus, 1767)	81	37	31	29	-44	-2
Euthria cornea (Linnaeus, 1758)	6	41	1	7	35	6
Buccinum humphreysianum Bennett, 1824	2	0	1	0	-2	-1
Calappa granulata (Linnaeus, 1758)	2353	3265	24	39	912	15
Calappa tuerkayana Pastore, 1995	34	0	2	0	-34	-2
Calliactis parasitica (Couch, 1842)	595	493	105	102	-102	-3
Callionymus maculatus Rafinesque, 1810	0	4	0	1	4	1
Calliostoma granulatum (Born, 1778)	34	19	17	14	-15	-3
Capros aper (Linnaeus, 1758)	12	5	3	2	-7	-1
Capulus ungaricus (Linnaeus, 1758)	0	3	0	1	3	1
Carapus acus (Brünnich, 1768)	0	6	0	2	6	2
Galeodea echinophora (Linnaeus, 1758)	438	229	30	19	-209	-11
Cepola macrophtalma (Linnaeus, 1758)	7	0	1	0	-7	-1
Chelidonichthys lucerna (Linnaeus, 1758)	120	376	3	3	256	0
Chelidonichthys obscurus (Walbaum, 1792)	104	25	4	1	-79	-3
Aequipecten opercularis (Linnaeus, 1758)	5	5	1	2	0	1
Mimachlamys varia (Linnaeus, 1758)	2	0	0	0	-2	0
Chlorotocus crassicornis (A. Costa, 1871)	34	99	32	87	65	55
Citharus linguatula (Linnaeus, 1758)	586	122	22	14	-464	-8
Codium bursa (Olivi) C.Agardh, 1817	12	0	1	0	-12	-1
Conger conger (Linnaeus, 1758)	270	892	3	8	622	5
Hirtomurex squamosus (Bivona e Bernardi, 1838)	9	0	3	0	-9	-3
Cuspidaria rostrata (Spengler, 1793)	1	0	1	0	-1	-1
Monoplex corrugatus (Lamarck, 1816)	18	0	1	0	-18	-1
Cymodocea nodosa (Ucria) Ascherson, 1870	0	15	0	0	15	0

Dardanus arrosor (Herbst, 1796)	1489	839	82	48	-650	-34
Deltentosteus collonianus (Risso, 1820)	0	14	0	2	14	2
Gracilechinus acutus (Lamarck, 1816)	13	0	2	0	-13	-2
Eledone cirrhosa (Lamarck, 1798)	0	0	0	0	0	0
Eledone moschata (Lamarck, 1798)	225	392	5	3	167	-2
Engraulis encrasicolus (Linnaeus, 1758)	19	54	3	3	35	0
Parastichopus regalis (Cuvier, 1817)	1064	736	14	11	-328	-3
Gadiculus argenteus Guichenot, 1850	97	102	27	23	5	-4
Gibbula magus (Linnaeus, 1758)	9	0	5	0	-9	-5
Glossus humanus (Linnaeus, 1758)	3	0	1	0	-3	-1
Glycymeris glycymeris (Linnaeus, 1758)	190	0	7	0	-190	-7
Gnathophis mystax (Delaroche, 1809)	76	0	1	0	-76	-1
Hadriania craticulata Bucquoy and Dautzenberg, 1882	0	1	0	1	1	1
Halecium halecinum (Linnaeus, 1758)	11	2	0	0	-9	0
Helicolenus dactylopterus (Delaroche, 1809)	143	0	1	0	-143	-1
Laetmonice hystrix (Savigny in Lamarck, 1818)	32	0	1	0	-32	-1
Hinea lineata (da Costa, 1778)	0	3	0	5	3	5
Holothuria (Panningothuria) forskali Delle Chiaje, 1823	208	159	2	3	-49	1
Hyalinoecia tubicola (O.F. Müller, 1776)	0	1	0	0	1	0
Illex coindetii (Vérany, 1839)	6	24	1	1	18	0
Glossus humanus (Linnaeus, 1758)	12	14	0	0	2	0
Janthina pallida W. T*T. trachurus*pson, 1840	1	1	1	1	0	0
Laevicardium oblongum (Gmelin, 1791)	0	18	0	2	18	2
Laminaria rodriguezii Bornet, 1888	658	920	0	0	262	0
Latreillia elegans P. Roux, 1830 [in P. Roux, 1828-1830]	1	2	3	3	1	0
Lepidopus caudatus (Euphrasen, 1788)	0	0	0	0	0	0
LepidorT. trachurusbus boscii (Risso, 1810)	0	0	0	0	0	0
Lepidotrigla cavillone (Lacepède, 1801)	22	103	4	17	81	13
Leptogorgia sarmentosa (Esper, 1789)	25	8	0	0	-17	0
Lesueurigobius suerii (Risso, 1810)	0	1	0	1	1	1
Liocarcinus depurator (Linnaeus, 1758)	41	99	3	10	58	7
Lophius budegassa Spinola, 1807	1692	211	9	3	-1481	-6
Euspira fusca (Blainville, 1825)	34	38	18	32	4	14
Lytocarpia myriophyllum (Linnaeus, 1758)	47	73	0	0	26	0
Macropipus tuberculatus (P. Roux, 1830 [in P. Roux, 1828-1830])	0	2	0	1	2	1
Macropodia tenuirostris (Leach, 1814 [in Leach, 1813-1815])	17	13	14	14	-4	0
Macroramphosus scolopax (Linnaeus, 1758)	0	10	0	2	10	2
Neomaja goltziana (d'Oliveira, 1889)	88	494	1	7	406	6
Maja squinado (Herbst, 1788)	0	62	0	1	62	1
Medorippe lanata (Linnaeus, 1767)	79	92	15	15	13	0
Merluccius merluccius (Linnaeus, 1758)	23525	25605	243	320	2080	77
Microchirus variegatus (Donovan, 1808)	0	35	0	2	35	2
Mullus barbatus Linnaeus, 1758	542	479	20	29	-63	9
Munida iris A. Milne Edwards, 1880	796	794	741	769	-2	28
Naticarius hebraeus (Martyn, 1786)	4	1	7	1	-3	-6
Naticarius stercusmuscarum (Gmelin, 1791)	529	436	269	207	-93	-62
Nemertesia antennina (Linnaeus, 1758)	5	0	2	0	-5	-2
Nemertesia ramosa (Lamarck, 1816)	2	7	0	0	5	0
Octopus vulgaris Cuvier, 1797	0	200	0	1	200	1
Ophiura ophiura (Linnaeus, 1758)	0	2	0	1	2	1
Pagellus bogaraveo (Brünnich, 1768)	141	24	3	1	-117	-2

Pagurus prideaux Leach, 1815 [in Leach, 1815-1875]	1385	1429	506	389	44	-117
Parapenaeus longirostris (H. Lucas, 1846)	28702	46135	7253	10519	17433	3266
Parasquilla ferussaci (Roux, 1828)	15	0	1	0	-15	-1
Spinolambrus macrochelos (Herbst, 1790 [in Herbst, 1782-1790])	26	11	2	1	-15	-1
Pecten jacobaeus (Linnaeus, 1758)	0	29	0	4	29	4
Pennatula rubra (Ellis, 1761)	4	6	1	1	2	0
Phycis blennoides (Brünnich, 1768)	569	248	30	3	-321	-27
Phycis phycis (Linnaeus, 1766)	250	386	3	5	136	2
Plesionika heterocarpus (A. Costa, 1871)	59	191	53	135	132	82
Aegaeon cataphractus (Olivi, 1792)	1	1	1	1	0	0
Pontocaris spp.	1	23	1	18	22	17
Porifera Grant, 1836	35	24	1	2	-11	1
Posidonia oceanica (Linnaeus) Delile, 1813	8054	7945	0	0	-109	0
Pseudamussium clavatum (Poli, 1795)	1	0	1	0	-1	-1
Pteria hirundo (Linnaeus, 1758)	6	10	0	0	4	0
Pteroeides griseum (Bohadsch, 1761)	63	2	3	1	-61	-2
Neopycnodonte cochlear (Poli, 1795)	374	467	0	0	93	0
Raja miraletus Linnaeus, 1758	0	81	0	1	81	1
Ranella olearium (Linnaeus, 1758)	60	0	1	0	-60	-1
Sargassum muticum (Yendo) Fensholt, 1955	6	0	0	0	-6	0
Scaeurgus unicirrhus (Delle Chiaje [in Férussac and d'Orbigny], 1841)	193	317	3	6	124	3
Scalpellum scalpellum (Linnaeus, 1767)	0	1	0	0	1	0
Scorpaena elongata Cadenat, 1943	32	0	1	0	-32	-1
Scorpaena porcus Linnaeus, 1758	8	0	1	0	-8	-1
Scorpaena scrofa Linnaeus, 1758	269	0	2	0	-269	-2
Scyliorhinus canicula (Linnaeus, 1758)	393	201	2	2	-192	0
Semicassis saburon (Bruguière, 1792)	60	0	4	0	-60	-4
Semicassis undulata (Gmelin, 1791)	552	437	32	24	-115	-8
Sepia elegans Blainville, 1827	30	288	7	35	258	28
Sepia officinalis Linnaeus, 1758	500	2109	3	9	1609	6
Sepietta oweniana (d'Orbigny, 1841)	31	16	8	4	-15	-4
Sertularella Gray, 1848	1	0	1	0	-1	-1
Serranus hepatus (Linnaeus, 1758)	16	31	2	4	15	2
Reteporella beaniana (King, 1846)	2	0	1	0	-2	-1
Sertularella spp.	1	0	1	0	-1	-1
Solenocera membranacea (Risso, 1816)	197	250	120	131	53	11
Spicara maena (Linnaeus, 1758)	35	359	2	14	324	12
Spicara smaris (Linnaeus, 1758)	0	0	2	0	0	-2
Squilla mantis (Linnaeus, 1758)	3358	3648	69	84	290	15
Stylocidaris affinis (Philippi, 1845)	61	19	11	6	-42	-5
Suberites domuncula (Olivi, 1792)	4	0	1	0	-4	-1
Symphurus nigrescens Rafinesque, 1810	14	18	2	2	4	0
Synchiropus phaeton (Günther, 1861)	7	11	2	3	4	1
Tethyaster subinermis (Philippi, 1837)	0	14	0	2	14	2
Tonna galea (Linnaeus, 1758)	148	25	5	3	-123	-2
Torpedo marmorata Risso, 1810	903	1541	12	14	638	2
Torpedo torpedo (Linnaeus, 1758)	0	58	0	1	58	1
Trachurus trachurus (Linnaeus, 1758)	6464	11951	243	572	5487	329
Trisopterus capelanus (Lacepède, 1800)	6	323	1	2	317	1
Uranoscopus scaber Linnaeus, 1758	370	0	2	0	-370	-2
Venus verrucosa Linnaeus, 1758	173	49	14	12	-124	-2
Osmundaria volubilis (Linnaeus) R.E.Norris, 1991	1	0	1	0	-1	-1

Paper 2: Testing the catchability of the crustacean trawl fisheries

Exploring the feasibility of technological transfers of two bycatch reduction devices (BRDs) in the crustacean bottom trawling of the central Mediterranean

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Abstract

Introduction: Most Mediterranean fish stocks are overexploited owing to high fishing efforts and poor exploitation patterns. Demersal trawl fisheries are considered the most impactful fishery type because of the high quantities of unwanted catch that is then routinely discarded at sea.

Methods: In the present study, two types of by-catch reduction devices (BRDs), that is a sorting grid (Grid-T45 40 mm) and a T90 50 mm codend, were compared to a typical commercial bottom trawl net (control) in terms of size structures and catch per unit effort to assess the effect of gear modification on the selectivity of crustacean fisheries in the central Mediterranean Sea. In particular, three randomly selected trawlers were involved in a paired hauls experiment fishing at the same time in the same fishing ground. Each trawler carried out four hauls per day during a 3-day campaign for a total of 36 hauls. The target species of the fishery is *Parapenaeus longirostris* (herein DPS), and the main commercial by-catch is *Merluccius merluccius* (herein HKE).

Results: The results showed that the landing per unit effort (LPUE) of DPS was higher for Grid-T45 40 mm net, although it did not differ significantly from that of the control net. Conversely, the discard per unit effort (DPUE) of the control net was significantly higher than of both BRD configurations.

For HKE, a slightly higher LPUE was recorded using the T90 50 mm codend compared to that of the control, but this result was not statistically significant. The lowest DPUE was found for the T90 50 mm codend, with significant differences compared to that of the control and Grid-T45 40 mm net. The catch comparison of the size structures analysed through generalised linear mixed models highlighted that the Grid-T45 40 mm net was more effective in catching adult DPS, whereas the T90 50 mm codend was more selective for adult HKE.

Discussion: In conclusion, although further studies should be carried out in future to test the performance of the BRDs in different areas and seasons, the investigated gear seems to be promising for reducing the catch of undersized individuals and contributing to mitigating the current overfishing of DPS and HKE.

1. Introduction

The Mediterranean Basin is affected by a very high level of human pressure (Micheli et al., 2013). Among these pressures, fisheries are considered one of the main sources of impact on marine ecosystems, with most of the exploited stocks being overfished (Colloca et al., 2013; Vasilakopoulos et al., 2014; Colloca et al., 2017). Despite efforts to establish an effective legal framework and ensure the implementation and compliance of the fishery sector, 75% of the assessed stocks in the Mediterranean are still considered to be threatened by overfishing (FAO, 2020). Furthermore, the increasing level of fishing effort applied in the last three decades has led to profound modification of the marine ecosystem in terms of loss of biodiversity (Coll and Libralato, 2012; Piroddi et al., 2017).

Among the different fisheries, bottom trawling is considered one of the most impactful techniques in the Mediterranean, due to high quantities of unwanted catch, including the incidental catch of non-target species and juveniles of both target and non-target species, which are either discarded because of their low economic value or because of legal restrictions (Pravin et al., 2011; Gorelli et al., 2016; Tsagarakis et al., 2017; GFCM, 2018; Sardo et al., 2020a).

In the Strait of Sicily, one of the most productive areas for demersal resources in the Mediterranean Sea, a large trawler fleet is present, where 785 trawlers from Italy, Malta, and Tunisia exploit shared resources in international waters (Colloca et al., 2017). Among the different species targeted by bottom trawling, the deep-water rose shrimp Parapenaeus longirostris Lucas, 1846 (herein DPS) is one of the most important in terms of landings and revenue (Di Maio et al., 2022). However, in the DPS trawl fisheries of the Strait of Sicily, a discarded fraction of 25-40% of the total catch has been reported (Milisenda et al. 2017). Therefore, the General Fisheries Commission for the Mediterranean (GFCM) adopted the Recommendation GFCM/44/2021/12 on a multiannual management plan for bottom trawl fisheries exploiting demersal stocks in the Strait of Sicily, which aims to ensure the sustainable use of marine living resources through measures to prevent overfishing, including selectivity to minimise discard. In addition, according to Reg. UE 1241/2019, fishermen must use square mesh codends (terminal end of the net) with a minimum mesh size of 40 mm or, only upon approval of a request, a 50 mm diamond mesh. These legal codend mesh sizes allow the catching adults of small to medium sized species, such as shrimps, red mullet, and cephalopods, but do not prevent the catching of undersized specimens of medium to large sized species, such as European hake (Merluccius merluccius, herein HKE), monkfish, and horse mackerel (Vitale et al., 2018a,b; Lucchetti et al., 2021). Because adopting a larger mesh size in the codend implies a strong reduction in the valuable fraction of catch, different technical solutions are being tested to modify the mesh shape to reduce the unwanted by-catch from trawling in the Mediterranean Sea. Considering the selectivity of the T90 (i.e., a diamond mesh turned 90°) codend, this solution was tested in the Adriatic Sea (Petetta et al., 2020) and the Aegean Sea (Dereli and Aydin, 2016; Deval et al., 2016; Genç et al., 2018), but not in the Strait of Sicily. The T90 codend, compared to other meshes currently used by trawlers, should remain more open during fishing operations, allowing undersized fishes and shrimps to escape. Given that the T90 codend is a very simple modification that does not involve any technical handling problems or any safety risk, it could be more easily accepted by fishing communities of the Strait of Sicily. Other promising by-catch reduction devices (BRDs) are the sorting grids, which are placed in the extension section of the trawl net. In the Mediterranean, the adoption of sorting grids in bottom trawling fisheries was tested to avoid catching undersized specimens of the target species, such as DPS and HKE (e.g., Sardà et al., 2004; Sardà et al., 2005; Bahamon et al., 2007; Aydın and Tosunoglu, 2012; Vitale et al., 2018a,b), as well as to reduce the unwanted by-catch of sharks (Brcic et al., 2015) and sea turtles (Lucchetti et al., 2016; Lucchetti et al., 2019). The grid tested in the present study was similar to that tested by Vitale et al. (2018a,b), but the novelty was that, for the first time, to our knowledge, it was installed in a commercial, rather than an experimental, trawl net. In particular, it was constructed with a steel frame and a stretched 40 mm square mesh in the selective area. The fishes and shrimps were conveyed toward the selective area of the grid through a funnel, allowing them to pass through this area, thus by-catch could be released, while the individuals that did not pass through the grid meshes were pushed down and retained by the codend mesh. Although the previous finding of all relevant studies point to a generally positive impact of sorting grids on the size at capture of commercial species as well as reducing the amount of unwanted by-catch, their adoption in Mediterranean trawl fisheries remains very low. The lack of sorting grid implementation could be linked to several causes, including fishers' resistance to changing their behaviour and, consequently, their unwillingness to modify their fishing gear (Vitale et al., 2018a). Other possible causes are linked to the lack of efficient technology transfer from researchers to fishers (e.g., Morrissey and Almonacid, 2005) as well as the overall weakness of fishing management in the Mediterranean region (Colloca et al., 2017).

To reduce the catch of undersized DPS and of HKE (unwanted by-catch according to the definition provided by ICES, 2020), the present study explored options to facilitate the transfer of BRDs to DPS trawl fisheries, showing important implications for their long-term sustainability, in-line with the management goals of the EU Common Fisheries Policy, CFP (reg. EC 1380/2013).

2. Material and Methods

2.1. Study area

The study area, located in the northern part of the Strait of Sicily, belongs to Geographical Sub-Area 16 (GSA16 - South of Sicily), according to the GFCM classification (GFCM, 2007; Figure 1). GSA16 is characterised by a wide continental shelf with an intense hydrographic circulation pattern, a stable upwelling system, and high biodiversity (Di Lorenzo et al., 2018). These abiotic and biotic features lead to high productivity of fish resources, which are exploited by a multinational fleet in national and international waters (Di Maio et al., 2022; Falsone et al., 2022; Jarboui et al., 2022).

2.2. Sampling design

In December 2020, a 3-day selectivity campaign was conducted with three trawlers based at the Mazara del Vallo harbour. The fishing vessels operated simultaneously and in parallel according to a paired hauls design (Wileman et al., 1996) in a DPS fishing ground where the main commercial by-catch, according to the definition of ICES (2020), is HKE (Figure 1).

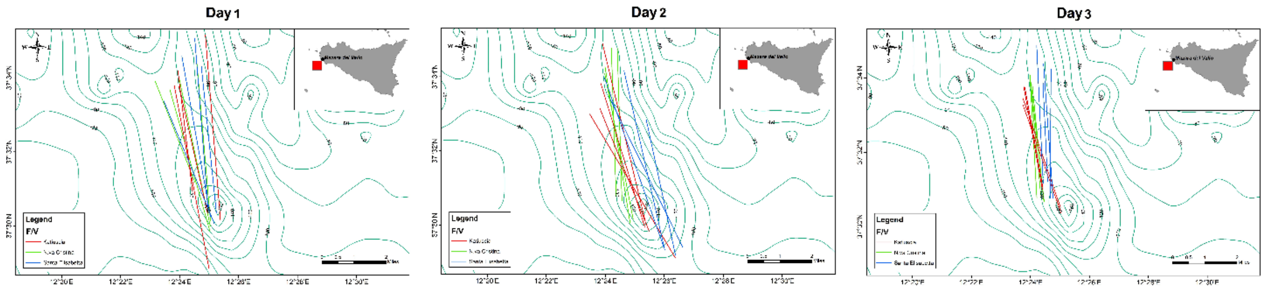

Figure 1 Maps of the hauls carried out with the control (Blue line), T90 50 mm codend (Green line), and Grid-T45 40 mm (Red line) nets over 3 days of the survey. The study area is highlighted with a red square box.

Given that the involved trawlers were not exactly the same in terms of overall length, to assess the potential variability among them, the swept area (A) of each haul to which the catch was estimated according to the formula proposed by Sparre and Venema (1998):

$$\boldsymbol{A = D * Hr * X}, \qquad \textbf{(1)}$$

where D is the distance covered during the haul, Hr is the length of the head-rope, and X is a fraction of Hr. Multiplying X * Hr gives the width of the path swept by the trawl, the so-called wing ‘spread’. According to Pauly (1980), a value of X of 0.5 is the best compromise for a demersal otter trawl. Finally, for each haul, the higher swept area recorded by a vessel was compared to the other areas as a percentage difference (Δ%) (Table S1).

On a daily basis, each vessel carried out four hauls of 90 min (usually in the commercial fishery, the haul duration ranged between 120 and 150 min) for a total of 12 hauls per day per vessel and 36 hauls over the campaign. In particular, one vessel used a control net; namely, a typical trawl net used by the Italian fleet in the Strait of Sicily with a 40 mm square mesh codend, whereas the other two vessels rigged the nets (test) with a sorting grid (i.e., Grid-T45 40 mm; see section 2.3 and Vitale et al. 2018a, for details) in the extension section (just in front of the codend) and a T90 50 mm codend, respectively. Due to the SARS-CoV-2 pandemic, scientific observers were unable to follow fishing operations on board. To overcome this problem, a video camera was installed on the stern of each vessel to register all fishing operations. The fishers were trained on the aims of the project and the sampling procedures of the commercial and discarded fractions of DPS and HKE. In particular, for the purpose of the study, for each haul the on-board activity included: i) recording of the geographical coordinates, depth, and fishing time (start and end); ii) sorting the catch and sampling the commercial fraction of DPS and HKE selected according to the fishers’ habits; iii) recording the weight (in kg) of the commercial catch of DPS and HKE by counting the box number (a box of DPS corresponded to 2 kg, while a box of HKE corresponded to 6 kg), iv) sampling the discarded marine organism fraction (including undersized specimens of DPS and HKE); and v) recording the total amount of marine organisms rejected and returned to the sea, the so-called discard. Each fishing trip was monitored remotely using an AIS tracking system. The sorting of the catch on-board and how fishers sub-sampled discard were assessed through visual inspection of the frame recorded by the video camera. The recordings of discard sampling were compared to the fishers' self-reported data. In addition, given that the number of hauls carried out on each fishing day was known (i.e., four), the number of boxes of both species was counted at the landing port, which was compared with the fishers' self-reported data by summing the number of boxes reported in each haul. Representative samples of DPS and HKE commercial (one box per category) and discarded (5–10 kg, min–max, of discard) fractions by haul were brought to the National Research Council (CNR) laboratory, weighed (0.1-gram accuracy), and measured (to the nearest 5 mm total length [TL] for HKE and to the nearest 1 mm for carapace length [CL] of DPS) individually.

2.3. Gears description

During the campaign, the vessels used very similar trawl nets, except for the BRDs (Figure S1, S2, and S3).

2.3.1 Control trawl with a T45 40 mm codend

The control trawl was built with a nominal 50 mm diamond mesh and polyamide nylon netting in the main body and extension sections of the net whereas the codend had a 40 mm square mesh. The control trawl had an overall length of 54.75 m, a 57 m-long headrope (diameter, hereinafter Ø, 24 mm, polyamide–stainless-steel combined material), a 64.90 m-long footrope (Ø 36 mm, polyamide–stainless-steel combined material) with steel chain, and 800 and 900 meshes of circumference in the upper and lower part of the net, respectively (Figure S1). It was rigged with two bottom trawl doors high yield type (150×95 cm, 200 kg each).

2.3.2 Test trawl mounting Grid-T45 40 mm

The design of the test trawl, which mounted the grid system in the extension section, was equivalent to that of the control trawl. Therefore, the only major difference between the two trawls was the presence of the grid in the test one. The sorting grid was similar to that tested by Vitale et al. (2018a), including a funnel panel (opening 20 mm, square mesh) of approximately 3 m, adapting its size to the local trawl nets (Figure 2).

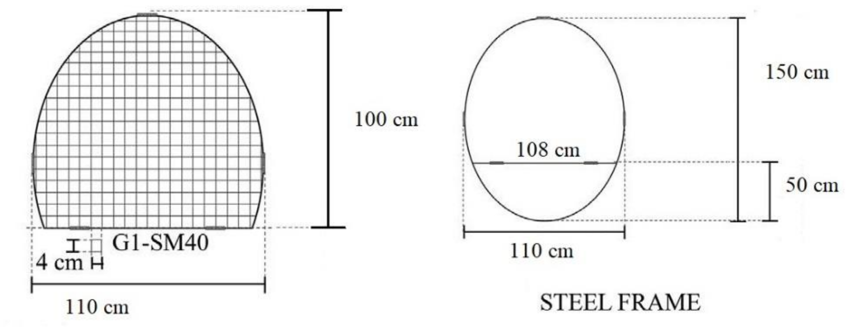

Figure 2 The sorting grid used during the bottom trawl campaign and its size features (modified from Vitale et al. 2018a,b).

Specifically, the grid was built with a stretched net of 40 mm square mesh (selective area of the grid) directly sewn to a steel frame (150 × 110 cm) and placed in the extension part of the trawl net. Other slight differences to the control trawl were their overall length (54.75 m control vs 56 m Grid-T45 40 mm), the headrope length (57 m control vs 60 m Grid-T45 40 mm), and the footrope length (64.90 m control vs 68 m Grid-T45 40 mm) (Figure S2). It was rigged with two bottom trawl doors high yield type (158 × 97 cm, 230 kg each).

2.3.3 Test trawl mounting T90 50 mm codend

The design and dimensions of this test gear were similar to those used in the DPS fishery, except for the T90 50 mm codend. The trawl slightly differed from the control one for the overall length (54.75 m control vs 55.15 m T90 50 mm codend), the headrope length (57 m control vs 58 m T90 50 mm codend), and the footrope length (64.90 m control vs 66 m T90 50 mm codend) (Figure S3). The trawl was spread using the same trawl doors as the Grid-T45 40 mm.

Notably, the extension pieces of the three trawl nets were cylindrical, with a total length of 10 m and 500 meshes in circumference, whereas the codend was 6 m long, with a twine Ø of 3 mm and 350 meshes in circumference. The sweeps of the three trawls were approximately 652 m long (slightly changing according to the depth of the fishing ground) and had a Ø of 14 mm, while warps were approximately 250 m long and had a Ø of 30 mm.

The mesh openings of the extension pieces and the codends of the three types of gears were measured 30 times each in wet conditions with a digital Vernier calliper, with a 4 kg weight tied vertically to the stationary jaw (Càrdenas et al., 1997; Aydın and Tosunoglu, 2012). The meshes in the extension section of the three nets were equal to 48.95 ± 2.10 mm (control; mean±standard error), 49.10 ± 1.56 mm (Grid-T45 40 mm), and 50.21 ± 1.34 mm (T90 50 mm codend). The meshes in the codends were 39.45 ± 1.13 mm (control), 38.95 ± 1.56 mm (Grid-T45 40 mm), and 49.65 ± 1.45 mm (T90 50 mm codend).

2.4. Catch comparison analysis

2.4.1. Landing per unit effort and discard per unit effort

The commercial and discarded DPS and HKE fractions classified according to the fishers' habits had two different subsampling ratios (where the subsampling ratio was calculated as sample in kg / total catch in kg). To ensure that the global subsampling was correctly calculated, the methodology proposed by Cosgrove et al. (2019) was applied. The required sub-sampling ratio q_l for the combined discarded (q_d) and commercial (q_c) fractions solves the following equation:

$$\frac{nd_{li}}{qd_l} + \frac{nc_{li}}{qc_l} = \frac{n_{cli}+n_{dli}}{q_l}, \qquad \textbf{(2)}$$

where $\frac{nd_{li}}{q_{dl}}$ is the raised count of the discard and $\frac{nc_{li}}{q_{cl}}$ is the raised count of the commercial fraction. Re-arranging (2) gives the following equation:

$$q_l = \frac{q_{dl}q_{cl}(nd_{li}+nc_{li})}{q_{cl}nd_{li}+qd_l n_{dli}}, \qquad \textbf{(3)}$$

This demonstrates that the combined sub-sampling ratio of the combined fractions was length-dependent. This ensures that the raised counts for the total (right-hand side of Equation 2) were equal to the sum of the separately raised counts (left-hand side of Equation 2). After being raised, the DPS and HKE individuals were re-classified into commercial and discarded fractions according to the minimum conservation reference size (MCRS) defined by Reg. EU 1241/2019, that is, above (commercial) and below (discarded) 20 mm CL and 200 mm TL, respectively. Then, their total weight in kg was standardized to 1 h to obtain the catch per unit effort (CPUE) expressed as kg/h by species. In particular, the catch rates of the commercial fraction were herein named landing per unit effort (LPUE) while the catch rates of the discard fraction were herein named discard per unit effort (DPUE). Linear mixed models (LMMs) were applied by species to evaluate whether the control and test nets differed significantly, without any assumption regarding the direction (i.e., two-tailed). The catch rates were contrasted against gear on a logarithmic scale, including the hauls as a random intercept, i.e., assuming that an intercept was different for each level of the variable 'gear'. To check the significance of the variable 'gear' in the model, a likelihood ratio test was applied. In the case of significant differences, *post-hoc* Tukey HSD tests were performed to compare the gear to one another. To directly interpret the coefficient estimates of the LMMs and Tukey HSD tests, they were transformed as antilogs. The LMMs were run through the 'lme4' package (Bates et al., 2015) whereas the Tukey HSD test used the 'multicomp' package (Hothorn et al., 2008). All analyses were carried out in R Studio version 3.6.3 (R Core Team, 2020).

2.4.2 Size structures

The probability of retaining a fish of a given length in the test net in relation to the total catch was assessed according to the method proposed by Fryer et al. (2003) and Holst and Revill (2009). A comparison was made between 12 hauls (i.e., 12 in the test and 12 in the control nets), and the length classes were set at 2 mm CL and 20 mm TL for DPS and HKE, respectively. The undersized specimens were identified as fish with lengths below the MCRS.

The observed average catch comparison for each length class (CC_l) was expressed as follows:

$$CC_l = \frac{\sum_{i=1}^{12} n_t}{\sum_{i=1}^{12} n_t + \sum_{i=1}^{12} n_c}, \tag{4}$$

where n_c and n_t are the number of fish caught in each length class l in the control and test nets, respectively (e.g., Vitale et al., 2018a; Geraci et al., 2021a). The observed proportion of catch caught in the test gear of each selected species was modelled to obtain a catch comparison curve using generalised linear mixed models (GLMMs) with a binomial distribution, where hauls were included as random intercept, using the Laplace approximation, to remove the variance linked to the expected change in abundance/catchability of the investigated species during the days and timeframes (Holst and Revill, 2009). A value of 0.5 for the catch comparison curves, $CC(l)$, indicates that there is the same probability of capturing a fish of length l in the test and control. A value above 0.5 indicates a higher probability of catching a fish of length l in the test compared to the control, and vice versa for a value below 0.5. The global sub-sampling ratio (q_l, see Section 2.4.1) in the test and control nets was also included as an offset in the model (Fryer et al., 2003; Holst and Revill, 2009). In addition, the models were fitted using splines with different degrees of freedom (df). The df in the model were assigned based on the fitting of predictions and observations. Subsequently, the model fit was checked by assessing the residuals.

To directly quantify the relative length-dependent gear catch efficiency of the test versus control net, the so-called 'catch ratio' (CR), that is, the ratio between the catch of the control and test trawl nets of a given length, l, was estimated (e.g., Melli et al., 2020; Lomeli et al., 2021; Geraci et al., 2021a). In particular, $CR(l)$ was computed as:

$$CR(l) = \frac{CC(l)}{1 - CC(l)}, \quad (5)$$

being CC(l) the predicted values of the catch comparison model (based on Equation 4). A value of 1.0 for CR(l) indicates no difference in catch efficiency between the test and the control. On the other hand, a value of 0.60 or 1.45 indicates that the probability of fish being caught for a given length with the test net is 40% less or 45% more, respectively, than that sampled with a control net. To provide a global idea of the effect of the tested BRDs, the CR(l) has been shown as the overall mean. The 95% confidence intervals of CC(l) and mean CR(l) were estimated from the model predictions and using the qt() function in R language to return the inverse probability cumulative density of the Student t-distribution. All size structure analyses were carried out with R version 3.6.3 using the package ‘glmmTMB’ (Brooks et al., 2017).

3. Results

3.1. Operational information and catches

The depth of the surveyed fishing grounds ranged between 89 and 170 m (i.e., the continental shelf). The commercial sub-sampled fraction for DPS ranged between 2 and 15 whereas no subsampling was required for the commercial fraction of HKE. The sub-sampling fraction of the discard for DPS ranged between 2 and 16, whereas that for HKE ranged between 2 and 6. The size ranges of the DPS specimens caught by the control and T90 50 mm codend (5/6–31 mm CL) were very similar, while specimens retained by the Grid-T45 40 mm net were slightly bigger (10–34 mm CL). The size ranges of HKE specimens were 55–700 mm TL for the control, 55–570 mm TL for Grid-T45 40 mm, and 75–635 mm TL for the T90 50 mm codend (Table 1).

Table 1. Description of the fishing operations by haul carried out during the survey.

Gear	Day	N haul	Start	Duration (minutes)	Depth range (m)	Species	G	N. measured samples-discard	q_d	N. measured samples-commercial	q_c	Length range (mm)
Control	1	1	06:45	90	139-139	DPS	22824	130	0.33	495	0.10	10-28
						HKE	6186	5	0.50	124	//	95-425
Grid-T45 40 mm	1	1	06:40	90	141-145	DPS	25933	38	//	459	0.10	11-32
						HKE	13027	10	//	160	//	90-520
T90 50 mm codend	1	1	06:45	90	140-143	DPS	2282	4	0.17	354	//	13-31
						HKE	10585	//	//	42	//	80-520
Control	1	2	08:40	90	145-97	DPS	25145	64	0.17	560	0.10	5-29
						HKE	7705	2	//	117	//	90-530
Grid-T45 40 mm	1	2	08:45	90	147-100	DPS	28581	62	//	458	0.10	11-32
						HKE	8875	11	//	70	//	115-530
T90 50 mm codend	1	2	08:50	90	145-98	DPS	3186	4	0.33	563	//	12-28
						HKE	11584	//	//	40	//	215-445
Control	1	3	10:50	90	143-148	DPS	24077	54	0.12	522	0.10	9-28
						HKE	6460	5	0.17	35		55-575
Grid-T45 40 mm	1	3	10:50	90	146-152	DPS	28781	19	//	519	0.10	12-34
						HKE	6056	12	//	71	//	120-400
T90 50 mm codend	1	3	10:45	90	150-153	DPS	3070	11	0.50	548	//	13-28
						HKE	10427	3	0.50	49	//	125-590
Control	1	4	12:40	90	148-119	DPS	30034	114	0.17	548	0.08	9-29
						HKE	7054	3	//	27	//	60-530
Grid-T45 40 mm	1	4	12:35	90	145-117	DPS	35652	43	//	459	0.07	11-28
						HKE	4743	9	//	47	//	55-570
T90 50 mm codend	1	4	12:35	90	146-120	DPS	8817	//	//	360	0.25	13-31
						HKE	9745	//	//	32	//	135-605
Control	2	1	06:00	90	143-143	DPS	16292	199	0.17	584	0.20	10-31
						HKE	8583	5	0.33	126	//	65-400
Grid-T45 40 mm	2	1	06:00	90	145-147	DPS	16292	//	//	535	0.17	10-32
						HKE	2439	//	//	42	//	60-505
T90 50 mm codend	2	1	06:00	90	143-146	DPS	4289	//	//	450	0.50	6-28
						HKE	5276	//	//	15	//	210-505

Control	2	2	08:00	90	146-117	DPS	39615	33	0.06	555	0.07	10-28
						HKE	19663	3	0.20	143	//	75-700
Grid-T45 40 mm	2	2	08:05	90	145-120	DPS	44889	26	//	556	0.07	12-32
						HKE	5066	9	//	23	//	120-470
T90 50 mm codend	2	2	08:05	90	143-118	DPS	4424	16	0.50	711	//	13-30
						HKE	12255	//	//	31	//	215-495
Control	2	3	10:15	90	150-170	DPS	34733	65	0.17	486	0.07	10-29
						HKE	4759	5	0.50	20	//	75-460
Grid-T45 40 mm	2	3	10:20	90	145-168	DPS	40311	36	//	497	0.07	12-31
						HKE	2371	13	//	40	//	110-250
T90 50 mm codend	2	3	10:15	90	143-172	DPS	5867	//	//	543	0.50	11-29
						HKE	6063	//	//	27	//	220-485
Control	2	4	12:10	90	155-110	DPS	22909	113	0.33	579	0.12	10-27
						HKE	2002	3	0.25	99	//	100-165
Grid-T45 40 mm	2	4	12:10	90	152-113	DPS	25994	25	//	477	0.10	11-29
						HKE	3795	15	//	26	//	85-510
T90 50 mm codend	2	4	12:05	90	146-110	DPS	1447	77	0.33	122	//	13-27
						HKE	1208	//	//	4	//	295-385
Control	3	1	06:15	90	137-152	DPS	14233	94	0.33	595	0.20	8-29
						HKE	6293	4	//	27	//	85-640
Grid-T45 40 mm	3	1	06:15	90	139-150	DPS	14618	//	//	563	0.20	13-29
						HKE	5781	//	//	19	//	145-570
T90 50 mm codend	3	1	06:10	90	146-155	DPS	3205	45	0.50	638	//	12-26
						HKE	5112	//	//	18	//	75-550
Control	3	2	07:55	90	146-95	DPS	23932	155	0.25	496	0.10	10-28
						HKE	10720	//	//	71	//	125-505
Grid-T45 40 mm	3	2	08:00	90	144-89	DPS	24462	9	//	458	0.10	12-33
						HKE	1962	4	//	18	//	130-370
T90 50 mm codend	3	2	07:55	90	141-93	DPS	5335	//	//	487	0.50	13-29
						HKE	5066	//	//	15	//	295-445
Control	3	3	09:30	90	126-148	DPS	17335	351	0.25	599	0.20	9-28
						HKE	2287	//	//	8	//	265-420
Grid-T45 40 mm	3	3	09:35	90	127-150	DPS	17137	21	//	542	0.17	12-31
						HKE	1578	4	//	7	//	125-405
T90 50 mm codend	3	3	09:30	90	132-145	DPS	1106	//	//	254	//	11-25

						HKE	3005	//	//	7	//	270-535
Control	3	4	11:15	90	145-117	DPS	15961	133	0.25	544	0.17	10-30
						HKE	2500	//	//	26	//	70-345
Grid-T45 40 mm	3	4	11:10	90	144-118	DPS	15529	28	//	498	//	10-30
						HKE	1463	5	//	3	//	110-440
T90 50 mm codend	3	4	11:10	90	139-115	DPS	5089	10	0.50	460	0.50	14-27
						HKE	5243	//	//	8	//	280-635

q_d: subsampling fraction of the discard according to fishers' habits; q_c: subsampling fraction of the commercial catch according to fishers' habits; //: not available

3.2. Landing Per Unit Effort (LPUE) and Discard Per Unit Effort (DPUE)

The LPUEs of the DPS, were higher for the Grid-T45 40 mm configuration than for either the control or T90 50 mm codend, whereas the DPUEs were highest for the control gear. Conversely, the lowest catch rates were recorded for the T90 50 mm codend, for both LPUE and DPUE (Figure 3, Table 2).

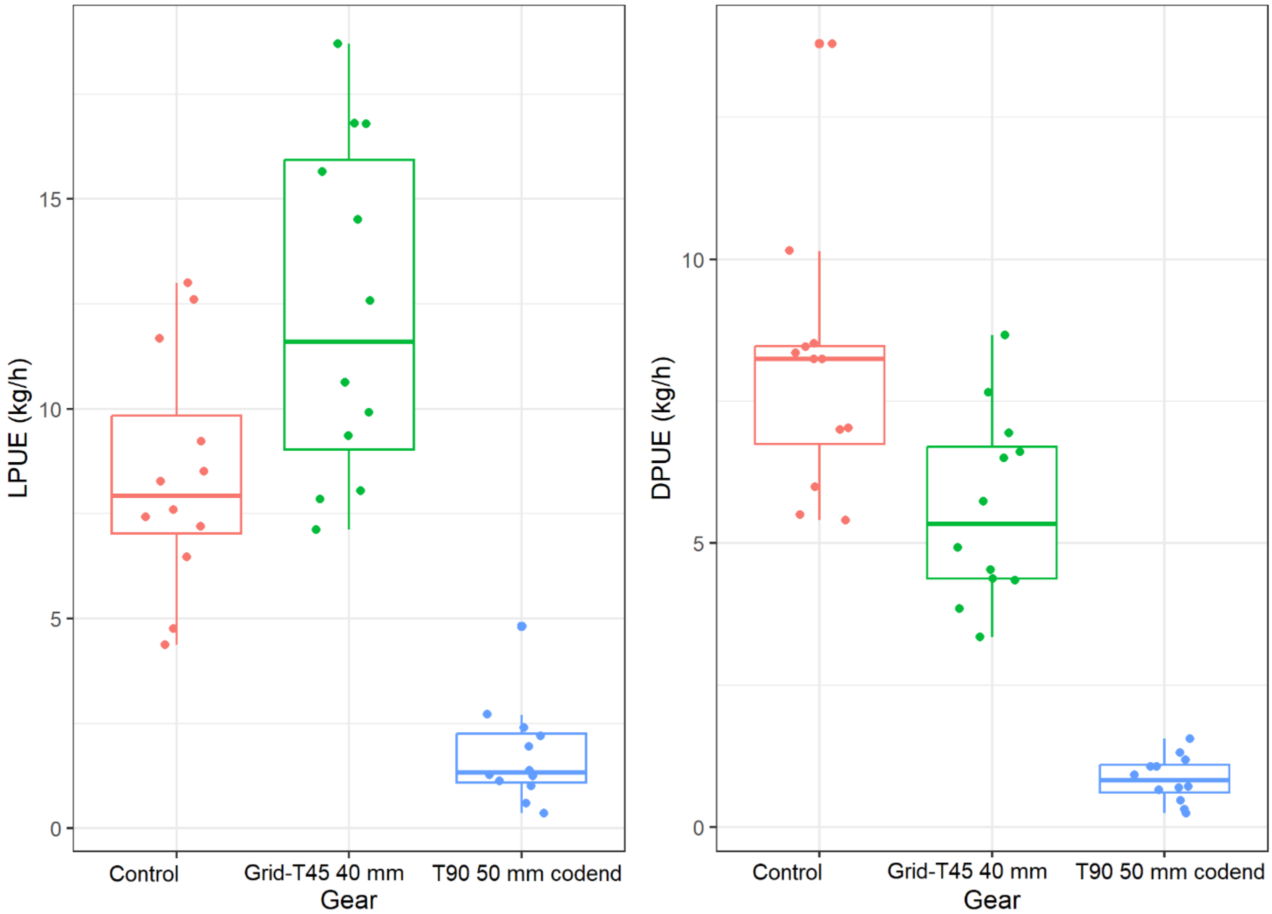

Figure 3 Boxplots of *Parapenaeus longirostris* (herein DPS) catch rates (kg/h) per gear caught during the campaign classified in landing per unit effort (LPUE; commercial) – left – and discard per unit effort (DPUE; discard) – right – according to the minimum conservation reference size (MCRS) established by the Reg. EU 1241/2019.

Table 2. Coefficient estimates for the catch rates of DPS and HKE modelled through linear mixed models in the catch fraction (commercial, LPUE and discard, DPUE).

Fraction		Gear	Estimate	s.e.	t value	*p*
LPUE	DPS	Intercept	7.995	1.152	14.691	4.045^{-13}
		Grid T45 40mm	1.465	1.204	2.060	
		T90 50 mm codend	0.179	1.204	-9.271	
	HKE	Intercept	3.611	1.224	6.362	0.025
		Grid T45 40mm	0.571	1.262	-2.407	
		T90 50 mm codend	1.033	1.269	0.137	
DPUE	DPS	Intercept	7.793	1.127	17.199	$< 2.2^{-16}$
		Grid T45 40mm	0.694	1.163	-2.415	
		T90 50 mm codend	0.096	1.163	-15.514	
	HKE	Intercept	0.529	1.485	-1.611	0.001
		Grid T45 40mm	0.746	1.728	-0.535	
		T90 50 mm codend	0.031	2.348	-4.058	

The LMMs considering LPUEs and DPUEs of DPS showed significant differences between the gear (LPUE, $p < 4.045^{-13}$; DPUE, $p < 2.2^{-16}$). In particular, for LPUEs the HSD Tukey *post-hoc* test revealed significant differences between the T90 50 mm codend and control net and between the two BRDs, whereas no significant difference between the Grid-T45 40 mm and control net was recognized. The DPUEs differed significantly for all gear (Table 3).

Table 3. Outcomes of the Tukey HSD post-hoc test of the catch rates of DPS and HKE, classified in catch fraction (commercial, LPUE and discard, LPUE), among different gear.

Fraction		Contrast	Estimate	s.e.	z value	*p*
LPUE	DPS	Grid-T45 40 mm – Control	1.465	1.203	2.060	0.098
		T90 50 mm codend – Control	**0.179**	**1.203**	**-9.271**	**<0.001**
		T90 50 mm codend – GRID-T45 40 MM	**0.122**	**1.203**	**-11.332**	**<0.001**
	HKE	**Grid T45 40mm – Control**	**0.571**	**1.262**	**-2.407**	**0.042**
		T90 50 mm codend – Control	1.034	1.269	0.137	0.9897
		T90 50 mm codend – Grid T45 40mm	**1.809**	**1.262**	**2.547**	**0.029**
DPUE	DPS	**Grid T45 40mm – Control**	**0.694**	**1.163**	**-2.415**	**0.042**
		T90 50 mm codend – Control	**0.096**	**1.163**	**-15.514**	**<0.001**
		T90 50 mm codend – Grid T45 40mm	**0.138**	**1.163**	**-13.099**	**<0.001**
	HKE	Grid T45 40mm – Control	0.746	1.728	-0.535	0.851
		T90 50 mm codend – Control	**0.031**	**2.347**	**-4.058**	**<0.001**
		T90 50 mm codend – Grid T45 40mm	**0.042**	**2.330**	**-3.749**	**<0.001**

In bold are significant differences.

For HKE, slightly higher median LPUEs were recorded using the T90 50 mm codend, followed by the control net, whereas the DPUEs were higher for the control gear and negligible for the T90 50 mm codend (Figure 4).

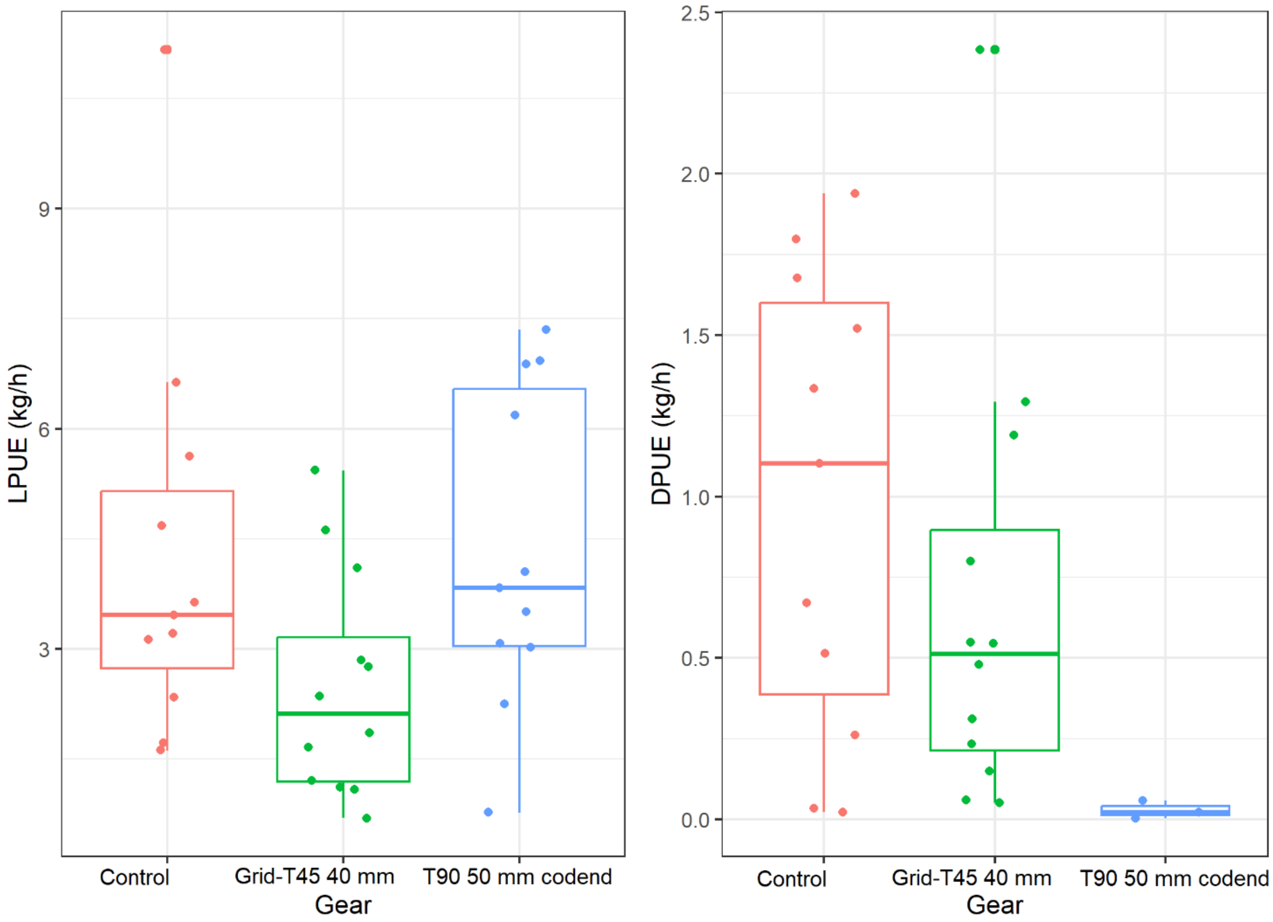

Figure 4 Boxplots of *Merluccius merluccius* (herein HKE) catch rates (kg/h) per gear caught during the campaign classified in landing per unit effort (LPUE; commercial) – left – and discard per unit effort (DPUE; discard) – right – according to the minimum conservation reference size (MCRS) established by the Reg. EU 1241/2019.

The LMMs for LPUEs and DPUEs of HKE showed significant differences among the gear (LPUE, $p = 0.025$; DPUE, $p = 0.001$). Specifically, for LPUEs, the Tukey HSD *post-hoc* test revealed significant differences between Grid-T45 40 mm and control net and between the two BRDs, whereas no significant difference between the T90 50 mm codend and control net was recognised. For DPUEs, significant differences between the pairwise comparison of Grid-T45 40 mm–T90 50 mm codend and T90 50 mm codend–control were detected (Table 3).

Table 3. Outcomes of the Tukey HSD post-hoc test of the catch rates of DPS and HKE, classified in catch fraction (commercial, LPUE and discard, LPUE), among different gear.

Fraction		Contrast	Estimate	s.e.	z value	*p*
LPUE	DPS	Grid-T45 40 mm – Control	1.465	1.203	2.060	0.098
		T90 50 mm codend – Control	**0.179**	**1.203**	**-9.271**	**<0.001**
		T90 50 mm codend – GRID-T45 40 MM	**0.122**	**1.203**	**-11.332**	**<0.001**
	HKE	**Grid T45 40mm – Control**	**0.571**	**1.262**	**-2.407**	**0.042**
		T90 50 mm codend – Control	1.034	1.269	0.137	0.9897
		T90 50 mm codend – Grid T45 40mm	**1.809**	**1.262**	**2.547**	**0.029**

		Grid T45 40mm – Control	**0.694**	**1.163**	**-2.415**	**0.042**
	DPS	**T90 50 mm codend – Control**	**0.096**	**1.163**	**-15.514**	**<0.001**
		T90 50 mm codend – Grid T45 40mm	**0.138**	**1.163**	**-13.099**	**<0.001**
		Grid T45 40mm – Control	0.746	1.728	-0.535	0.851
DPUE	HKE	**T90 50 mm codend – Control**	**0.031**	**2.347**	**-4.058**	**<0.001**
		T90 50 mm codend – Grid T45 40mm	**0.042**	**2.330**	**-3.749**	**<0.001**

In bold are significant differences.

3.2. Size structures analyses

The length-frequency distributions of DPS and HKE showed that the bulk of the catch of the control was mainly composed of undersized specimens, indicating a potentially poor selectivity of the gear with legal mesh size in the codend. As for the BRDs, the Grid-T45 40 mm caught more commercial DPS whereas the T90 50 mm codend was more effective in catching adult HKE (Figure 5C and 6C).

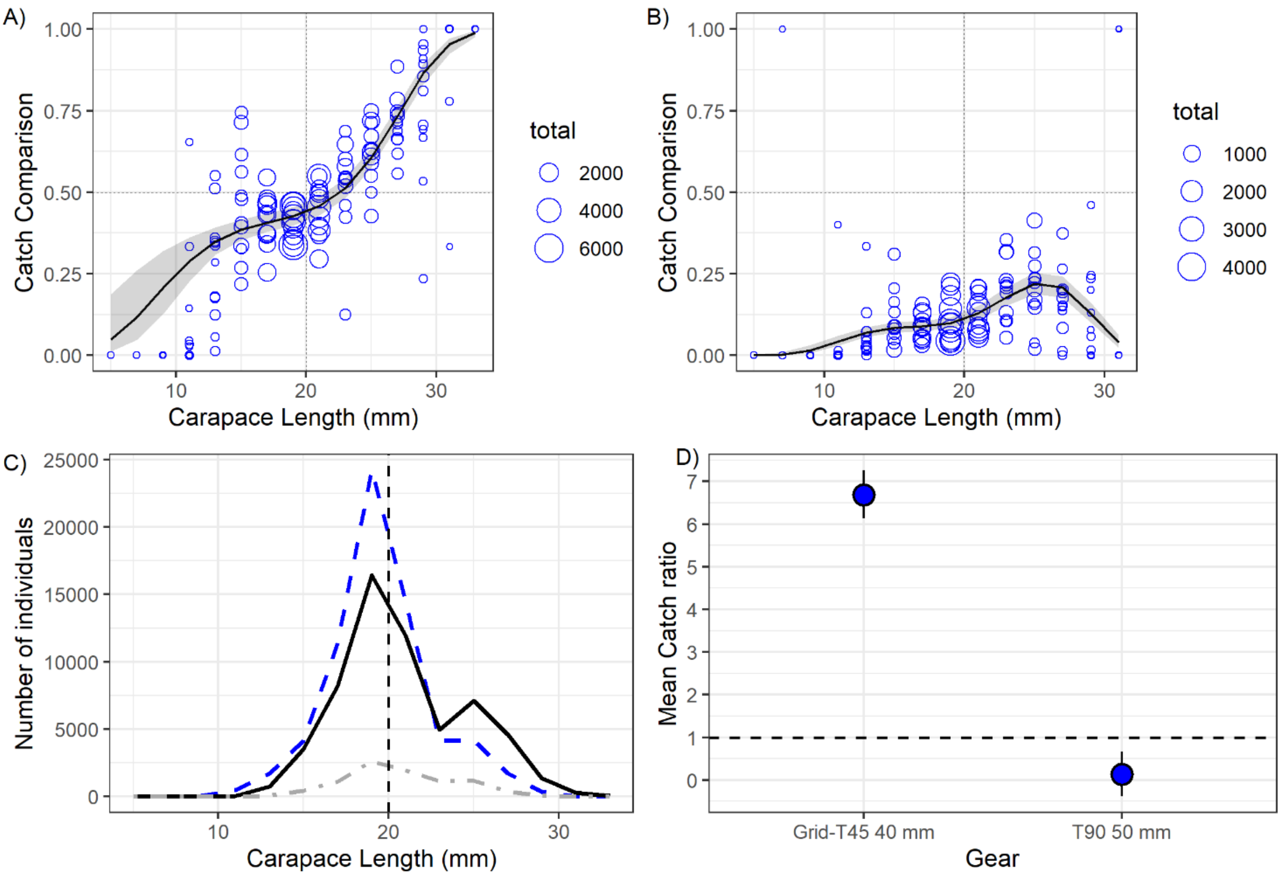

Figure 5 (A) Catch comparison curves for DPS caught with the Grid-T45 40 mm, and (B) with the T90 50 mm codend. Blue circles show observed proportions by haul, black dashed lines represent the model prediction, and the grey band indicates the 95% confidence limit. The level of no effect (CC(*l*) = 0.5) is shown by horizontal black dashed lines while the MCRS is shown by the black vertical dashed lines. (C) Length frequency distributions of DPS caught during the campaign. The blue dashed line represents the control, the continuous black line represents the Grid-T45 40 mm, and the dark grey line represents the T90 50 mm codend. Black vertical dashed lines depict the MCRS according to the Reg. EU

1241/2019. (D) The blue dots indicate the mean catch ratio (CR(l)), and horizontal bars indicate the 95% confidence limit. The level of no effect (CR(l) = 1.0) is depicted by horizontal black dashed lines.

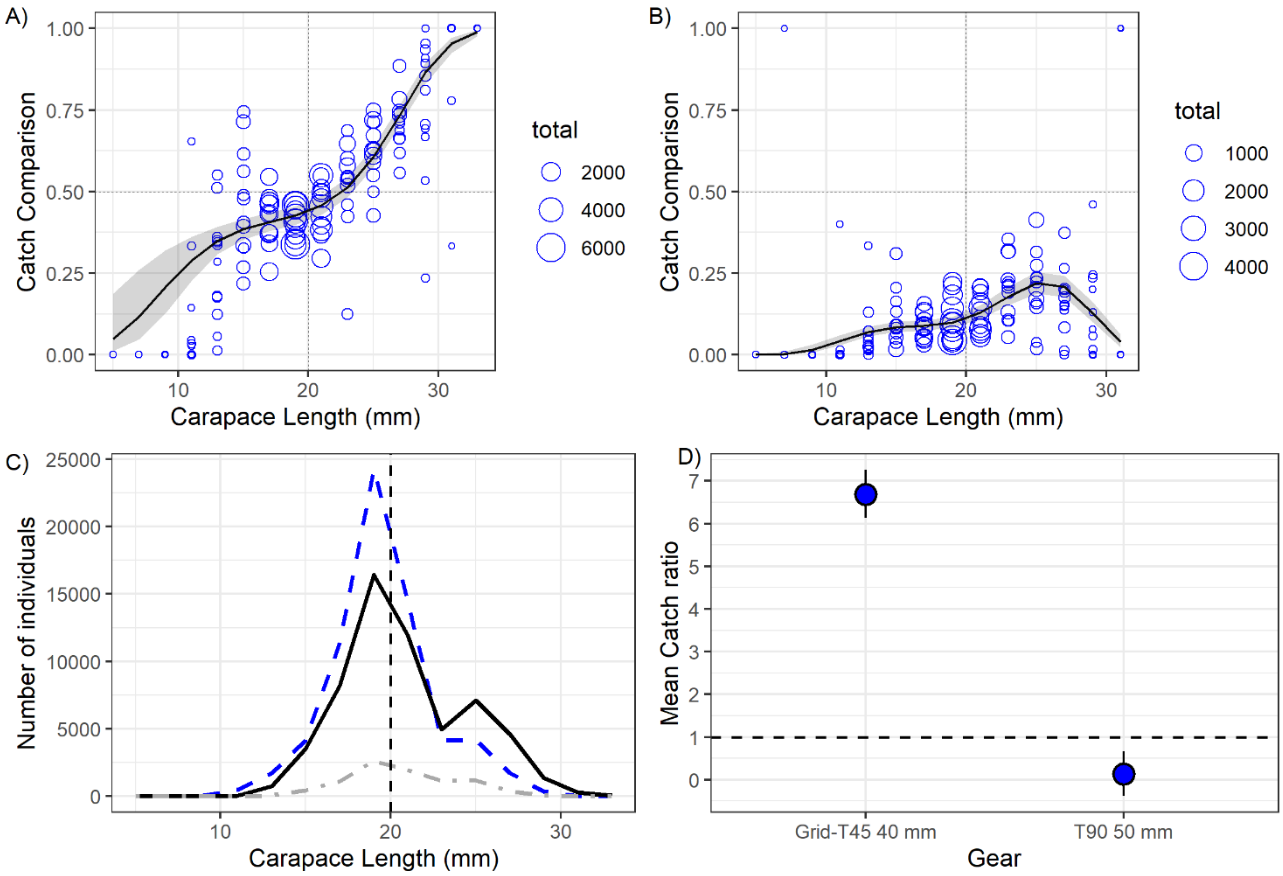

Figure 6 (A) Catch comparison curves for HKE caught with the Grid-T45 40 mm, and (B) with the T90 50 mm codend. Blue circles show observed proportions by haul, black dashed lines represent the model prediction, and the grey band indicates the 95% confidence limit. The level of no effect (CC(l) = 0.5) is shown by horizontal black dashed lines while the MCRS is shown by the black vertical dashed lines. (C) Length frequency distributions of DPS caught during the campaign. The blue dashed line represents the control, the continuous black line represents the Grid-T45 40 mm, and the dark grey line represents the T90 50 mm codend. Black vertical dashed lines depict the MCRS according to the Reg. EU 1241/2019. (D) The blue dots indicate the mean catch ratio (CR(l)), and horizontal bars indicate the 95% confidence limit. The level of no effect (CR(l) = 1.0) is depicted by horizontal black dashed lines.

The catch comparison, modelled through GLMMs for DPS, was run with 3 df when considering the Grid-T45 40 mm and control, whereas 4 df were set for the T90 50 mm codend vs. control. As for HKE concerns, 4 df (Grid-T45 40 mm vs Control) or 3 df (T90 50 mm codend vs Control) were used.

The final GLMMs by species, including their R codes, are presented in Table 4.

Table 4 Selected GLMM models with coefficients estimates for the catch comparison curves (test vs control net) of DPS (*Parapenaeus longirostris*), and HKE (*Merluccius merluccius*) and the used R code to run them.

Species	Model (R code)	*CC(l)*	Estimate	Std. Error	z value	*p*
DPS	glmmTMB(prop~(bs(size, df=3))+(1|Haul)+offset(log(q_Grid/q_ctrl)), family = binomial(link = "logit"), weights = total, data= DPS_Grid)	Grid *vs* Control	**(Intercept) 2.98**	**0.25**	**-11.77**	**$<2^{-16}$**
			1 5.21	**0.49**	**10.62**	**$<2^{-16}$**
			2 -0.56	**0.13**	**-4.21**	**2.53^{-05}**
			3 7.53	**0.37**	**20.43**	**$<2^{-16}$**
	glmmTMB(prop~(bs(size, df=4))+(1|Haul)+offset(log(q_T90/q_ctrl)), family = binomial(link = "logit"), weights = total, data= DPS_T90)	T90 *vs* Control	**(Intercept) -8.95**	**1.30**	**-6.88**	**5.91^{-12}**
			1 7.92	**1.51**	**5.26**	**1.45^{-07}**
			2 4.79	**1.17**	**4.08**	**4.47^{-05}**
			3 9.17	**1.37**	**6.69**	**2.19^{-11}**
			4 5.73	**1.23**	**4.64**	**3.48^{-06}**
HKE	glmmTMB(prop~(bs(size, df=4))+(1|Haul)+offset(log(q_Grid/q_ctrl)), family = binomial(link = "logit"), weights = total, data= HKE_Grid)	Grid *vs* Control	**(Intercept) -3.34**	**0.62**	**-5.38**	**7.50^{-08}**
			1 4.00	**0.81**	**4.93**	**8.28^{-07}**
			2 2.29	**0.65**	**3.55**	**3.80^{-04}**
			3 4.25	**1.47**	**2.89**	**3.83^{-03}**
			4 1.49	1.83	0.82	0.41
	glmmTMB(prop~(bs(size, df=3))+(1|Haul)+offset(log(q_T90/q_ctrl)), family = binomial(link = "logit"), weights = total, data= HKE_Grid)	T90 *vs* Control	**(Intercept) -7.94**	**0.96**	**-8.28**	**$<2^{-16}$**
			1 13.98	**2.29**	**6.10**	**1.05^{-09}**
			2 7.56	**1.11**	**6.75**	**1.46^{-11}**
			3 7.41	**1.80**	**4.12**	**3.70^{-05}**

prop, proportion; bs, b-spline; df, degree of freedom; q, subsampling fractions; *CC(l):* catch comparison curves; Std. Error: standard error. In bold, significant terms.

In particular, for DPS the Grid-T45 40 mm had a lower probability of catching undersized specimens compared to the control as the CC(*l*) values were always lower than the level of no effect, that is, the same probability of catching an individual at a given length for both types of gear, or numerically CC(*l*) = 0.5. In contrast, there was an increase in the CC(*l*) recorded for adults, showing that the Grid-T45 40 mm had a higher catch probability than the control, particularly for legal-sized specimens. An important increase in catch above the level of no effect was detected for individuals from 25 mm CL onward (Figure 5A). This trend is reflected in the mean CR(*l*), which is very high (6.68, confidence interval: 6.63–6.77) (Figure 5D). However, the probability of catching DPS was always lower for the T90 50 mm codend configuration than for the control net (Figure 5B and 5D).

For HKE, the Grid-T45 40 mm showed lower efficiency than the control in capturing undersized fish. Conversely, the probability of catching adults was equal to that of the control (Figure 6A). Importantly, the T90 50 mm codend showed a lower probability of catching undersized HKE specimens, whereas the CC(*l*) values generally exceeded the level of no effect for commercial-sized specimens, except for a few individuals caught in the latest size classes (Figure 6B). The mean CR(*l*) was below and above the level of no effect (CR(*l*) = 1.00) for Grid-T45 40 mm and T90 50 mm codend, respectively (Figure 6D).

4. Discussion

The adoption of both BRDs in DPS fisheries resulted in a reduction in the number of undersized DPS and HKE specimens in the catches, suggesting a potential overall enhancement in the exploitation pattern. In particular, the Grid-T45 40 mm seems to be a technological solution that could be capitalised on by commercial trawlers targeting DPS. In fact, the Grid-T45 40 mm provided a higher LPUE and a significant reduction in undersized DPS when compared to the other trawl net configurations. However, the T90 50 mm codend, tested in the Strait of Sicily for the first time, strongly reduced the catch of both legal and undersized DPS, thus, would not ensure the economic sustainability of the DPS fisheries. Regarding HKE, the most efficient gear was the T90 50 mm codend. It is worth noting that, although this device excluded almost all of the undersized HKE, higher catch rates were recorded for HKE due to an elevated number of legal-sized specimens. Given that the Tukey test did not detect significant differences between the LPUE of the T90 50 mm codend and the control, while overall the CC(l) highlighted a higher efficiency for the T90 50 mm codend in catching larger-sized HKE, an apparent inconsistency appeared. These differences were due to the different analyses applied; in particular, Tukey’s test compared the mean value of catch regardless the size structure while CC(l) described the variation of proportions in the catch of individuals by size, making it more informative in terms of selectivity aspects.

Considering the intrinsic relationship between the ecological purpose of the MCRS and mesh size, it seems clear that the common goal is to avoid catching juveniles until they are large enough to spawn (Beverton and Holt, 1957). From an economic standpoint, this means that juveniles are given time to grow to an economically valuable size before harvest. Indeed, according to Vasilakopoulos et al. (2014), overexploitation of HKE juveniles was particularly severe as they were being harvested during the first and second years of life before reaching sexual maturity. Despite the basic nature of this notion, the identification of an adequate legal mesh size could involve practical difficulties and management problems, mainly in fisheries where small-sized species, such as DPS, are caught together with fish that can reach a large size, such as HKE (Caddy, 1990; Fiorentino and Vitale, 2021). In other words, the adoption of a more selective mesh size for HKE would imply the loss of a large number of shrimp and other small-sized species, significantly reducing fishery profitability (Lucchetti et al., 2021).

For sorting grids, Vitale et al. (2018a) used an experimental trawl net with Grid-T45 40 mm in the same area and found a high sorting capability for DPS and HKE in the reduction of undersized specimens with a minor loss of the marketable fraction for DPS; however, similar to the present study, a low amount of legal-sized HKE was retained by the Grid-T45 40 mm (Table 5; Vitale et al., 2018a). Similarly, Vitale et al. (2018a) further reported a higher number of larger-sized DPS individuals caught with the Grid-T45 40 mm compared to the control. These confirmed results could be due to the slightly higher vertical aperture of the trawl equipped with the Grid-T45 40 mm allowing the catching of larger DPS individuals while remaining at a greater height from the bottom. To support this hypothesis, by studying the catch of the lower, middle, and upper compartments in the codend of the bottom trawl fisheries of the Barents Sea, Larsen et al. (2021) found that the majority of deep-water shrimps (*Pandalus borealis*) that entered the highest compartments of the trawl net were larger-sized individuals. Although further investigations through ad-hoc experiments are needed, the size-depth separation of the shrimps in the water column (vertical separation) can help improve the species/size selectivity of Mediterranean DPS bottom trawl fisheries, as suggested by oceanic studies (e.g. Engås et al., 1998; Ferro et al., 2007; Graham and Fryer, 2006; Karlsen et al., 2019).

In other Mediterranean demersal trawl fisheries, according to the present study, a substantial improvement in DPS and HKE selectivity was found through the incorporation of a sorting grid in the trawl net (Massutì et al., 2009; Aydın et al. 2011; Aydın and Tosunoğlu, 2012). Recently, in the

Adriatic Sea, an improvement in the catch pattern of HKE was found even if a loss of marketable DPS was at the same time detected (Table 5; Sbrana et al., 2022).

Similar to the present study, an improvement in the selectivity of HKE was found using a T90 50 mm codend in the Adriatic Sea, even if the nominal mesh size was inefficient at retaining specimens of commercial sizes of Mullus barbatus, Trachurus mediterraneus, Loligo vulgaris, and Merlangius merlangus (Petetta et al., 2020). Conversely, an increase in selectivity for mantis shrimp (Squilla mantis), allowing the escape of juvenile individuals often discarded by fishers, was reported. In the Aegean Sea, the T90 44 mm codend improved in the size of the first capture of HKE (Genç et al., 2018) whereas the T90 40 mm improved selectivity for *M. barbatus* and *T. trachurus* (Dereli and Aydin, 2016). Recently, on the eastern coast of Spain, modifying trawl extension with a T90 50 mm panel resulted in decreased fishing mortality for younger age classes of HKE and *M. barbatus* (Maynou et al., 2021), while in the Adriatic Sea (Petetta et al., 2022), and northern Tyrrhenian Sea (Sbrana et al., 2022) the application of a T90 40 mm panel in the extension piece did not significantly reduce the catch of juveniles of the target species (Table 5).

Table 5. Results of research in the Mediterranean Sea during which the sorting grid or T90 mesh was tested.

Area	BRD	Codend (mesh size/orientation)	Method	Target species	Result	Reference
Western Mediterranean (Balearic Islands)	Flexible sorting grids,15 and 20 mm bar spacing	T0 40 mm, T45 40 mm	Divided bottom trawl	DPS, HKE, *Mullus spp.*, *Zeus faber*, *Lophius spp.*, *Raja spp.*, *Nephrops norvegicus*, *Lepidorhombus boscii*, *Aristeus antennatus*	Increased L_{50} for DPS, HKE, and most commercial species whereas the unwanted by-catch species were decreased.	Massutì et al. 2009
Aegean Sea	Sorting grid with 20 mm bar spacing	T45 40 mm T0 44 mm	Covered codend	DPS	For DPS a loss of 23% and 25% was detected in the T0 44 mm and T45 40 mm codends, respectively; For HKE, it was found that a larger part was excluded in the T45 40-mm rather than in the T0 44-mm codends For all other species, separation values were generally high and similar for both codends	Aydin et al. 2011
Eastern Aegean Sea (Sıgacık Bay)	Sorting grid mounted at the end of a funnel, 10 and 15 mm bar spacing	T0 44 mm	Double codend	DPS	Separation ratios for HKE were between 96.3 and 100% in terms of weight. Separation ratios for DPS of 37.0% and 44.4% by weight in 10 and 15 mm grids, respectively.	Aydın and Tosunoğlu 2012
Aegean Sea (Mytilene and Chios Islands / Karaburun Peninsula and Kusadasi Bay)	T90 40 mm	T0 44 mm T0 50 mm T45 40 mm T90 40 mm	Covered codend	HKE, *Dentex maroccanus*, *Mullus barbatus*, *Trachurus trachurus*	T90 40 mm codends improved the selectivity of *M. barbatus* and *T. trachurus*.	Dereli and Aydin 2016
Aegean Sea (Kuşadası Bay)	T90 44-mm	T90 44 mm, 300 meshes on its circumference; T90 44 mm, 150 meshes	Alternate hauls	DPS, HKE,	For DPS no significant differences between L_{50} values of T90 40 mm and T90 44 mm were found	Genc et al. 2018

		on its circumference; T90 40 mm, 165 meshes on its circumference.		*T. trachurus*	For HKE the T90 40 mm and T90 44 mm codends improved the L_{50}	
Strait of Sicily	Grid G1-SM40 made with a net of 40-mm square mesh; Grid G2-ST20 and Grid G3-ST25 made from vertical steel bars spaced 20 and 25 mm apart, respectively	T45 40 mm	Alternate hauls	DPS, HKE	G1-SM40 showed a reduction of undersized individuals of about 60% and 44% for DPS and HKE, respectively. G2-ST20 showed a 34% catch decrease of HKE individuals smaller than 20 cm TL. G3-ST25 was efficient at reducing the catch of undersized specimens of both target species but showed the highest loss of marketable fractions.	Vitale et al. 2018a
North-western Adriatic Sea	T90 54 mm	T0 54 mm, T90 54 mm	Covered codend	HKE, *Merlangius merlangus, M. barbatus, Loligo vulgaris, Squilla mantis, T. mediterraneus*	T90 54 mm significantly excluded undersized specimens of HKE, whose average L_{50} was above the MCRS, and *Squilla mantis*. Both codends showed an excessive size selectivity, which involves a commercial loss, especially for *M. barbatus*, *T. mediterraneus*, *Loligo vulgaris*, and *M. merlangus*.	Petetta et al. 2020
Western Mediterranean (east coast of Spain)	Grid (G1-SM40) placed in the middle of the extension; T90 50 mm in the extension	T45 40 mm	Alternate hauls	DPS, HKE, *M. barbatus, M. surmuletus*	T90 50 mm extension panel allowed for a reduction of 35% of undersized specimens of HKE. Selective grid allowed for 95% and 100% of undersized specimens to escape for HKE and DPS, respectively	Maynou et al. 2021
North-western Adriatic Sea	T90 44 mm in the extension	T0 44 mm (standard extension piece); T0 44 mm, reduced number of meshes in circumference and reduced extension piece; T45 40 mm and 170 meshes in circumference	Paired hauls	HKE, *M. barbatus, Lophius spp.*	HKE and *Lophius spp.* showed no indication of improved selectivity or catch pattern compared to the standard extension piece of the trawl.	Petetta et al. 2022

Northern Tyrrhenian Sea	T90 44 mm, Grid (FLEXGRID) 20 mm bar spacing	T45 40 mm	Alternate hauls	DPS, HKE	No significant differences between the control and T90 44 mm Flexgrid showed a loss of marketable fractions for DPS, *M. barbatus*, and *Illex coindetii* but reduced the catch of undersized HKE	Sbrana et al. 2022

Given that demersal twin trawls are not present in the Strait of Sicily, the trawlers involved in this study were as similar as possible to those available to collaborate. Therefore, to verify whether the slight differences among vessels could introduce a potential bias in the sampling design, the swept areas were estimated and compared by haul. The results showed negligible differences between the swept areas amounting to no more than 5% (Table S1). The inevitable slight differences in the allocation of the hauls were implicitly accommodated considering the random effect (the hauls) within matrix D, which measures the variation in relative catch rate between paired hauls, which are assumed to occur at random and to average out over a series of paired hauls (Fryer et al., 2003; Holst and Revill, 2009). In addition, to corroborate the minimal effect of haul spatial allocation, the distance (at the beginning, intermediate, and final haul points) among vessels by haul was measured. Except for the fourth haul of the second day, during which distance reached a maximum of 2.3 nm during the intermediate and final haul points, the distances among vessels during the survey were negligible, ranging between 0.02 and 1.5 nm (Figure S4). Moreover, all fishing operations were conducted on the same biocenosis (Table 3) ensuring that the differences in catch rates were due to the different selectivity of the gear. The shorter haul duration in the present study (90 min) compared to the commercial hauls' duration (120–150 min) might be considered a potential weakness. This shorter time was due to the trade-off between the logistics needed to carry out all of the hauls in 1 day and having a haul that was long enough to collect a sufficient number of specimens.

Overall, the findings of the present study are consistent with those of previous studies obtained in other areas of the Mediterranean Sea, emphasising DPS and HKE a selectivity improvement through the adoption of the Grid-T45 40 mm and T90 50 mm codend mounted on commercial trawl nets. These findings confirmed that in a multi-specific fishery, such as Mediterranean otter trawling, it is unrealistic to secure a gear configuration that is ideally suited for all species (Fiorentino and Vitale, 2021; Lucchetti et al., 2021). This is because to the different shapes, sizes, swimming abilities, and behaviours of the various species caught during trawling activities. Therefore, it is important to explore technological solutions that are selective for the main target species of trawl fishery, such as DPS in the Strait of Sicily, with acceptable levels of losses of valuable by-catch, such as HKE, and mitigation of the impact on benthic habitat and communities (Maynou et al., 2021), considering the different behaviour and vertical distribution from the seabed of the species.

In addition, given that the success of the adoption of gear is affected by the acceptance of fishers, their viewpoints are of paramount importance. During the campaign, no negative feedback toward the use of sorting grids from the involved fishers was detected, and no handling issues were raised from them. As for concerns relating to the T90 50 mm, even though it was a very simple modification without any possible handling issues, some concerns were raised by the fishers owing to the important loss of marketable DPS.

Therefore, in the future, it will be of vital importance to take into account the trade-off between the socio-economic and ecological points of view and to engage with as many fishers as possible in developing and optimising more selective gear (e.g., Geraci et al., 2021b; Sardo et al., 2020b; Geraci et al., 2019) to be translated into the decision-making process of the management regulations.

However, before transferring the tested BRDs to fishing enterprises and improving the selectivity of bottom trawling, is desirable to carry out generously planned surveys using commercial vessels fishing in different conditions (time, season, and grounds) with a shared protocol, and with fishing gear that is comparable as much as possible. Once more robust data on the effect of BRDs are obtained, mitigation of the current poor exploitation pattern of DPS and HKE could be achieved by adopting a set of management measures. In particular, the Fisheries Restricted Areas where bottom trawling is prohibited, implemented by the GFCM to protect juveniles of HKE and DPS in the Strait of Sicily (Russo et al., 2019; Di Maio et al., 2022), could be coupled with the adoption of a boundary zone in which trawling is allowed only for vessels that mount a BRD that minimises the capture of undersized individuals. Another measure could be the introduction of a total allowable catch for DPS and the application of the T90 50 mm codend when the quota is reached. All these potential management rules should be carefully monitored to determine their effective application. In addition, as already shown by Vitale et al. (2018b), in the near future, to simulate the effect of mounting the tested BRDs or the adoption of the above-mentioned management rules, it would be worthwhile to incorporate the selectivity results in an ecosystem model (e.g., Ecopath With Ecosim) to assess the effects not only on commercial target species but also on the other components of the trophic web in the area (Agnetta et al., 2022).

In conclusion, although further studies should be carried out in the future to test different fishing arrangements, the investigated gear appears to be promising tools to contribute to reducing the overexploitation of DPS and HKE at the same time to ensure long-term socio-economic sustainability of the fishing process in-line with the goals of the EU Common Fisheries Policy (reg. EC 1380/2013).

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

SV, FF: conceptualization. MLG: formal analysis. MLG, FFA, DS, VG, GS: data curation. MLG, FFA, FDM, DS, VG, GS, PC, DM: data collection and figures. SV, FF: validation. MLG: writing – original draft. MLG, VG, FDM, FFA, DS, FF, GS, PC, DM, SV: writing – review & editing

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References

Agnetta, D., Badalamenti, F., Colloca, F., Cossarini, G., Fiorentino, F., Garofalo, G., et al. (2022). Interactive effects of fishing effort reduction and climate change in a central Mediterranean fishing area: Insights from bio-economic indices derived from a dynamic food-web model. Front. Mar. Sci., 9: 909164. Doi: 10.3389/fmars.2022.909164.

Aydın, C., Tokaç, A., Aydın, İ., Erdoğan, U., Maktay, B. (2011). Species selectivity in the Eastern Mediterranean demersal trawl fishery using grids to reduce non-target species. J. Appl. Ichthyol., 27(1): 61–66. Doi: 10.1111/j.1439-0426.2010.01605.x

Aydın, C., Tosunoğlu, Z.A.F.E.R. (2012). Evaluation of sorting grids for deepwater rose shrimp (Parapenaeus longirostris) in the Eastern Mediterranean demersal trawl fishery. J. Appl. Ichthyol., 28(1):102-106. Doi: 10.1111/j.1439-0426.2011.01897.x

Bahamon, N., Sardà, F., Suuronen, P. (2007). Selectivity of flexible size-sorting grid in Mediterranean multispecies trawl fishery. Fish. Sci., 73(6):1231-1240. Doi: 10.1111/j.1444-2906.2007.01460.x

Bates, D., Mächler, M., Bolker, B., Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. J. Stat. Softw., 67(1), 1–48. Doi: 10.18637/jss.v067.i01.

Benjamini, Y., Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. J. R. Stat. Soc. Ser. B., 57:289-300. http://www.jstor.org/stable/2346101.

Beverton, R.J.H., Holt, S.J. (1957). On the Dynamics of Exploited Fish Populations. Chapman and Hall, London, 39 pp.

Brčić, J., Herrmann, B., De Carlo, F., Sala, A. (2015). Selective characteristics of a shark-excluding grid device in a Mediterranean trawl. Fish. Res., 172:352-360. Doi: 10.1016/j.fishres.2015.07.035

Brooks, M.E., Kristensen, K., Benthem, K.J., Magnusson, A., Berg, C.W., Nielsen A., et al. (2017) glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. The R Journal. 9: 378–400.

Caddy, J. F. (1990). Options for the regulation of Mediterranean demersal fisheries. Nat. Resour. Model., 4(4):427-475. Doi: 10.1111/j.1939-7445.1990.tb00219.x

Cárdenas, E.D., Ávila de Melo, A., Iglesias, S., Saborido-Rey, F. (1997). Selectivity of 130 mm mesh size in deep sea bottom trawl fishery in NAFO Regulatory Area. NAFO Sci. Coun. Studies, 30: 21–25

Coll, M., Libralato, S. (2012). Contributions of food web modelling to the ecosystem approach to marine resource management in the Mediterranean Sea. Fish Fish (Oxf). 13(1), 60-88. Doi: 10.1111/j.1467-2979.2011.00420.x

Colloca, F., Cardinale, M., Maynou, F., Giannoulaki, M., Scarcella, G., Jenko, K., et al. (2013). Rebuilding Mediterranean fisheries: a new paradigm for ecological sustainability. Fish Fish. 14(1): 89–109. Doi:10.1111/j.1467-2979.2011.00453.x.

Colloca, F., Scarcella, G., Libralato, S. (2017). Recent Trends and Impacts of Fisheries Exploitation on Mediterranean Stocks and Ecosystems. Front. Mar. Sci. 4:244. Doi:10.3389/fmars.2017.00244.

Dereli, H., Aydin, C. (2016). Selectivity of commercial and alternative codends for four species in the Eastern Mediterranean demersal trawl fishery. Turk. J. Fish. Aquat. Sci., 16(4). Doi:10.4194/1303-2712-v16_4_25

Deval, M.C., Özgen, G., Özbilgin, H. (2016). Selectivity of 50 mm T0 and T90 codends for commercial shrimp species in the Turkish deepwater trawl fishery, Eastern Mediterranean. J. Appl. Ichthyol., 32 (6):1041-1057. Doi: 10.1111/jai.13128

Di Lorenzo, M., Sinerchia, M., Colloca, F. (2018). The North sector of the Strait of Sicily: a priority area for conservation in the Mediterranean Sea. Hydrobiologia, 821(1):235-253. Doi: 10.1007/s10750-017-3389-7

Di Maio, F., Geraci, M.L., Scannella, D., Russo, T., Fiorentino, F. (2022). Evaluation of the Economic Performance of Coastal Trawling off the Southern Coast of Sicily (Central Mediterranean Sea). Sustainability, 2022(14): 4743. Doi: 10.3390/su14084743

Efron, B. (1982). The Jackknife, the bootstrap and other resampling plans. Society for industrial and applied matemathics. Monograph no. 38. CBSM-NSF.

Engås, A., Jørgensen, T., West, C.W. (1998). A species-selective trawl for demersal gadoid fisheries. ICES J. Mar. Sci., 55(5): 835–845. Doi: 10.1006/jmsc.1998.0352

EU, 2013. Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. 2013. Available: http://data.europa.eu/eli/reg/2013/1380/oj.

EU, 2019. Regulation (EU) 2019/1241 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. Official Journal of the European Union, (198), 97.

Falsone, F., Gancitano, V., Geraci, M.L., Sardo, G., Scannella, D., Serena, F., Vitale, S., Fiorentino, F. (2022). Assessing the Stock Dynamics of Elasmobranchii off the Southern Coast of Sicily by Using Trawl Survey Data. Fishes, 7: 136. Doi: 10.3390/fishes7030136

Ferro, R.S.T., Jones, E.G., Kynoch, R.J., Fryer, R.J., Buckett, B.E. (2007). Separating species using a horizontal panel in the Scottish North Sea whitefish fishery. ICES J. Mar. Sci., 64(8): 1543–1550. Doi: 10.1093/icesjms/fsm099

Fiorentino, F., Vitale, S. (2021). How Can We Reduce the Overexploitation of the Mediterranean Resources? Front. Mar. Sci., 8:674633. Doi: 10.3389/fmars.2021.674633

Food and Agriculture Organization (FAO). (2020). The State of Mediterranean and Black Sea Fisheries 2020. Rome: General Fisheries Commission for the Mediterranean. Doi: 10.4060/cb2429en

Fryer, R.J., Zuur, A.F., Graham, N. (2003). Using mixed models to combine smooth size-selection and catch-comparison curves over hauls. Can. J. Fish. Aquat. Sci., 60(4):448-459. Doi: 10.1139/f03-029

GFCM. (2007). Recommendations and Resolutions on Mediterranean fisheries management - Resolution GFCM/31/2007/3 40 mm square mesh size in codend of trawl nets exploiting demersal resources. GFCM, 39 pp.

GFCM, 2018. Working Group on Stock Assessment of Demersal Species (WGSAD). Scientific Advisory Committee on Fisheries (SAC), Final Report, 79 pp.

Genç, T.Ş., Atamanalp, M., Aydın, C. (2018). Selectivity of turned meshes codends for Deepwater Rose Shrimp (Parapenaeus longirostris), Horse Mackerel, (Trachurus trachurus) and European Hake (Merluccius merluccius) in the Aegean Sea. Ege Journal of Fisheries and Aquatic Sciences, 35(2), 157-168. Doi: 10.12714/egejfas.2018.35.2.08

Geraci, M.L., Di Lorenzo, M., Falsone, F., Scannella, D., Di Maio, F., Colloca, F., et al. (2019). The occurrence of Norwegian skate, Dipturus nidarosiensis (Elasmobranchii: Rajiformes: Rajidae), in the Strait of Sicily, central Mediterranean. Acta Ichthyol. Piscat. 49:203–208. Doi:10.3750/aiep/02566.

Geraci, M.L., Colloca, F., Falsone, F., Fiorentino, F., Gancitano, V., Sardo, G., et al. (2021a). How is artificial lighting affecting the catches in deep water rose shrimp trawl fishery of the Central Mediterranean Sea? Ocean & Coastal Management. 215: 105970. Doi:10.1016/j.ocecoaman.2021.105970

Geraci, M.L., Ragonese, S., Scannella, D., Falsone, F., Gancitano, V., et al. (2021b). Batoid Abundances, Spatial Distribution and Life History Traits in the Strait of Sicily (Central Mediterranean Sea): Bridging a Knowledge Gap through Three Decades of Survey. Animals. 11: 2189. Doi: 10.3390/ani11082189.

Gorelli, G., Sardà, F., Company, J.B. (2016). Fishing effort increase and resource status of the deep-sea red shrimp Aristeus antennatus (Risso 1816) in the Northwest Mediterranean Sea since the 1950s. Rev. Fish. Sci. Aquac., 24(2):192-202. Doi: 10.1080/23308249.2015.1119799

Graham, N., Fryer, R.J. (2006). Separation of fish from Nephrops norvegicus into a two-tier cod-end using a selection grid. Fish. Res., 82(1–3): 111–118. Doi: 10.1016/j.fishres.2006.08.011

Holst, R., Revill, A. (2009). A simple statistical method for catch comparison studies. Fish. Res., 95:254–259. Doi: 10.1016/j.fishres.2008.09.027

Hothorn, T., Bretz, F., Westfall, P. (2008). Simultaneous Inference in General Parametric Models. Biom. J. 50(3): 346–363. Doi: 10.1002/bimj.200810425

Jarboui, O., Ceriola, L., Fiorentino, F. (2022). Current fisheries management in the Strait of Sicily and progress towards an ecosystem approach. In Vasconcellos, M. and Ünal, V., eds. Transition towards an ecosystem approach to fisheries in the Mediterranean Sea – Lessons learned through selected case studies. FAO Fisheries and Aquaculture Technical Paper No. 681. Rome, FAO: 147-162.

Karlsen, J.D., Krag, L.A., Herrmann, B., Lund, H. (2019). Using vertical distribution to separate fish from crustaceans in a mixed species trawl fishery. Can. J. Fish. Aquat. Sci., 76(10): 1781–1794. Doi: 10.1139/cjfas-2018-0313

Larsen, R.B., Herrmann, B., Brčić, J., Sistiaga, M., Cerbule, K., Nielsen, K.N., et al. (2021) Can vertical separation of species in trawls be utilized to reduce bycatch in shrimp fisheries? PLoS ONE, 16(3): e0249172. Doi:10.1371/journal.pone.0249172

Lomeli, M.J., Wakefield, W.W., Herrmann, B., Dykstra, C.L., Simeon, A., Rudy, D.M., Planas, J.V. (2021). Use of artificial illumination to reduce Pacific halibut bycatch in a US West Coast groundfish Bottom trawl. Fish. Res., 233:105737. Doi: 10.1016/j.fishres.2020.105737

Lucchetti, A., Punzo, E., Virgili, M., (2016). Flexible Turtle Excluder Device (TED): An effective tool for Mediterranean coastal multispecies bottom trawl fisheries. Aquat. Living Resour., 29(2):201. Doi: 10.1051/alr/2016016

Lucchetti, A., Bargione, G., Petetta, A., Vasapollo, C., Virgili, M. (2019). Reducing Sea Turtle Bycatch in the Mediterranean Mixed Demersal Fisheries. Front. Mar. Sci., 6(July):387. Doi: 10.3389/fmars.2019.00387

Lucchetti, A., Virgili, M., Vasapollo, C., Petetta, A., Bargione, G., Li Veli, D., et al. (2021). An overview of bottom trawl selectivity in the Mediterranean Sea. Mediterr. Mar. Sci., 22(3): 566-585. Doi: 10.12681/mms.26969

Lucchetti, A., Virgili, M., Vasapollo, C., Petetta, A., Bargione, G., Li Veli, D., et al. (2021). An overview of bottom trawl selectivity in the Mediterranean Sea. Mediterr. Mar. Sci., 22(3): 566–585. Doi: 10.12681/mms.26969

Massutí, E., Ordines, F., Guijarro, B. (2009). Efficiency of flexible sorting grids to improve size selectivity of the bottom trawl in the Balearic Islands (western Mediterranean), with comparison to a change in mesh codend geometry. J. Appl. Ichthyol., 25(2):153-161. Doi: 10.1111/j.1439-0426.2009.01225.x

Maynou, F., García-de-Vinuesa, A.G., Martínez-Baños, P., Sánchez, P., Demestre, M. (2021). Relative Catch Performance of Two Gear Modifications Used to Reduce Bycatch of Undersized Fish and Shrimp in Mediterranean Bottom Trawl Fisheries. Mar. Coast. Fish., 13(5), 518-533. Doi: 10.1002/mcf2.10178

Melli, V., Herrmann, B., Karlsen, J.D., Feekings, J.P., Krag, L.A. (2020). Predicting optimal combinations of by-catch reduction devices in trawl gears: A meta-analytical approach. Fish Fish (Oxf). 21(2): 252-268. Doi: 10.1111/faf.12428

Micheli, F., Halpern, B. S., Walbridge, S., Ciriaco, S., Ferretti, F., Fraschetti, S., et al. (2013). Cumulative human impacts on Mediterranean and Black Sea marine ecosystems: assessing current pressures and opportunities. PloS one. 8(12): e79889. Doi: 10.1371/journal.pone.0079889

Milisenda G., Vitale S., Massi D., Enea M., Gancitano V., Giusto G.B., et al. (2017). Spatio-temporal composition of discard associated with the deep water rose shrimp fisheries (Parapenaeus longirostris, Lucas 1846) in the south-central Mediterranean Sea. Mediterr. Mar. Sci., 18(1):53–63. Doi: 10.12681/mms.1787

Millar, R.B. 1993. Analysis of trawl selectivity studies (addendum): implementation in SAS. Fish. Res., 17(3-4): 373-377. Doi: 10.1016/0165-7836(93)90137-V

Morrissey M.T., Almonacid S. (2005). Rethinking technology transfer. J. Food Eng., 67:135-145. Doi:10.1016/j.jfoodeng.2004.05.05

Pauly, D. (1980). A new methodology for rapidly acquiring basic information on tropical fish stocks: growth, mortality and stock-recruitment relationships. In: Stock assessment for tropical small-scale fisheries. Proc. Int. Workshop Univ. Rhode Island, Narragansett, 154-172 pp.

Petetta, A., Herrmann, B., Virgili, M., De Marco, R., Canduci, G., Li Veli, D., et al. (2020). Estimating selectivity of experimental diamond (T0) and turned mesh (T90) codends in multi-species Mediterranean bottom trawl. Mediterr. Mar. Sci., 21(3): 545-557. Doi: 10.12681/mms.22789

Petetta, A., Herrmann, B., Virgili, M., Li Veli, D., Brinkhof, J., Lucchetti, A. (2022) Effect of Extension Piece Design on Catch Patterns in a Mediterranean Bottom Trawl Fishery. Front. Mar. Sci. 9:876569. Doi: 10.3389/fmars.2022.876569

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Russo, T., D'Andrea, L., Franceschini, S., Accadia, P., Cucco, A., Garofalo, et al. (2019). Simulating the effects of alternative management measures of trawl fisheries in the Central Mediterranean Sea: application of a multi-species bio-economic modelling approach. Front. Mar. Sci., 6: 542. Doi: 10.3389/fmars.2019.00542.

Piroddi, C., Coll, M., Liquete, C., Macias, D., Greer, K., Buszowski, J., et al. (2017). Historical changes of the Mediterranean Sea ecosystem: modelling the role and impact of primary productivity and fisheries changes over time. Sci. Rep., 7(1):1-18. Doi: 10.1038/srep44491

Pravin, P., Gibinkumar, T.R., Sabu, S., Boopendranath, M. (2011). Hard bycatch reduction devices for bottom trawls: a review. Fishery Technology., 48(2):107-118. http://krishi.icar.gov.in/jspui/handle/123456789/54268

Sala, A., Sistiaga, M., Catchpole, T., Ebango Ngando, N., Einarsson, H.A., Feekings J.P., et al. (2020). ICES Workshop on Innovative Fishing Gear (WKING). ICES Scientific Reports, 2. Doi: 10.17895/ices.pub.7528

Sardà, F., Molí, B., Palomera, I. (2004). Preservation of juvenile hake (Merluccius merluccius L) in the western Mediterranean demersal trawl fishery by using sorting grids. Sci. Mar., 68(3):435-444. Doi: 10.3989/scimar

Sardà, F., Bahamón, N., Sardà-Palomera, F., Molí, B. (2005). Commercial testing of a sorting grid to reduce catches of juvenile hake (Merluccius merluccius) in the western Mediterranean demersal trawl fishery. Aquat. Living Resour., 18(1): 87-91. Doi: 10.1051/alr:2005010

Sardo, G., Okpala, C. O. R., Geraci, M. L., Fiorentino, F., Vitale, S. (2020a). The effects of different artificial light wavelengths on some behavioural features of juvenile pelagic Atlantic horse mackerel, Trachurus trachurus (Actinopterygii: Perciformes: Carangidae). Acta Ichthyol. Piscat., 50(1). Doi: 10.3750/AIEP/02709

Sardo, G., Geraci, M.L., Scannella, D., Falsone F., Vitale, S. (2020b). New records of two uncommon species, Calappa tuerkayana Pastore, 1995 (Decapoda, Calappidae) and Parasquilla ferrussaci (Roux, 1828) (Stomatopoda, Parasquillidae), from the Strait of Sicily (central Mediterranean Sea). Arxius de Miscellània Zoològica, 18:113–121. Doi: 10.32800/amz.2020.18.0113

Sbrana, M., De Carlo, F., Ligas, A., Massaro, A., Musumeci, C., Rossetti, I., Sartini, M., Vasapollo, C., Viva, C., Sartor, P., Pretti, C. (2022). Testing experimental devices in the extension piece to increase the selectivity of bottom trawl in the Nw Mediterranean. Front. Mar. Sci. 9:1017766. Doi: 10.3389/fmars.2022.1017766

Sola, I., Maynou, F. (2018). Bioeconomic analysis of the effects of modifying the trawl extension piece with T90 netting. Sci. Mar. 82(S1): 27–37. Doi: 10.3989/ scimar.04715.06A.

Sparre, P., Venema, S.C. (1998). Introduction to Tropical Fish Stock Assesment (Part 1 Manual). FAO Fish. Tech. Pap., 306.1, Rome, 407 p.

Tsagarakis K., Carbonell A., Brčić J., Bellido J.M., Carbonara P., Casciaro L., 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). Doi: 10.3389/fmars.2017.00099

Vasilakopoulos, P., Maravelias, C.D., Tserpes, G. (2014). The alarming decline of Mediterranean fish stocks. Curr. Biol., 24(14):1643-1648. Doi: 10.1016/j.cub.2014.05.070

Vitale, S., Milisenda, G., Gristina, M., Baiata, P., Bonanomi, S., Colloca, F., et al. (2018a). Toward more selective Mediterranean trawl fisheries: are the Juveniles Trash Excluder Devices effective tools to reduce the by-catch of juveniles? Sci. Mar. 82(S1):215–223. Doi: 10.3989/scimar.04751.28A

Vitale, S., Enea, M., Milisenda, G., Gancitano, V., Geraci, M.L., Falsone, F., et al. (2018b). Modelling the effects of more selective trawl nets on the productivity of European hake (Merluccius merluccius) and deep-water rose shrimp (Parapenaeus longirostris) stocks in the Strait of Sicily. Sci. Mar. 82(S1):199–208.

Wileman, D.A., Ferro, R.S.T., Fonteyne, R., Millar, R.B., 1996. Manual of methods of measuring the selectivity of towed fishing gears. ICES Coop. Res. Rep. No. 215, 126 pp.

Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Supplementary materials

Figures

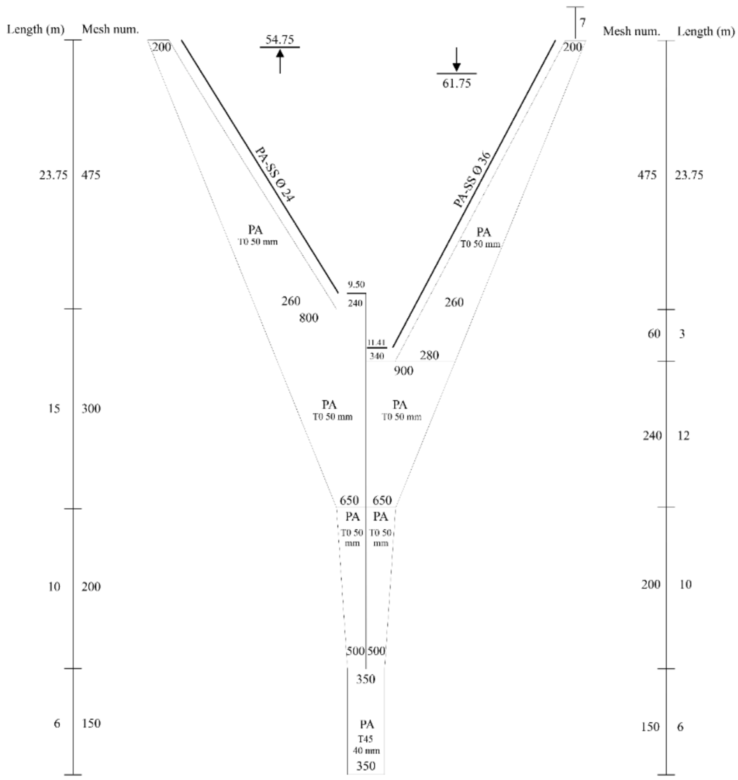

Figure S1 Scheme of the control net used in the campaign, with details of the length and mesh number by net portion.

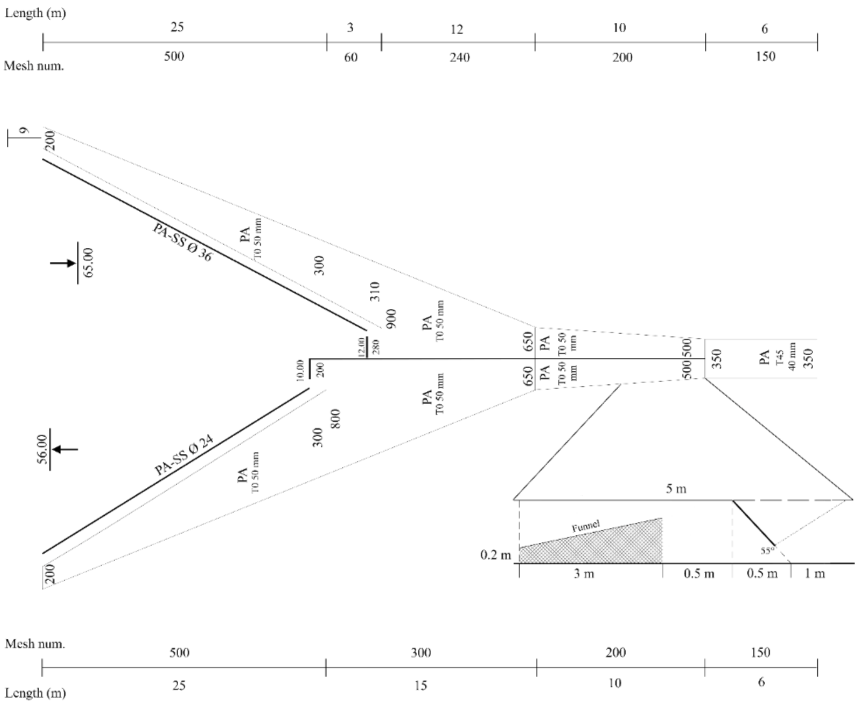

Figure S2 Scheme of the test net with sorting grid (G1-SM40) used in the campaign, with details of the G1-SM40 insertion, the length, and mesh number by net portion.

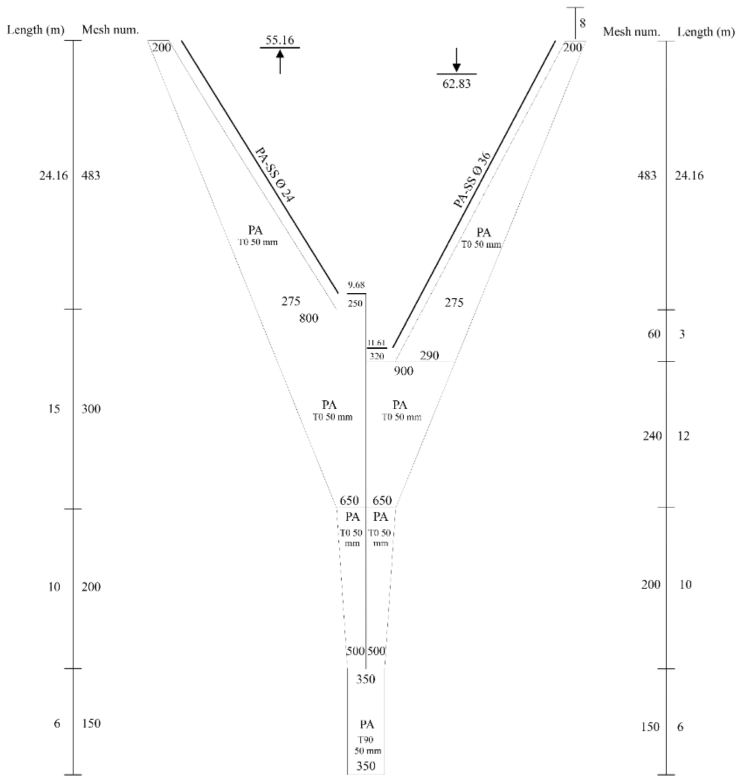

Figure S3 Scheme of the test net with T90 codend used in the campaign, with details of the length, and mesh number by net portion.

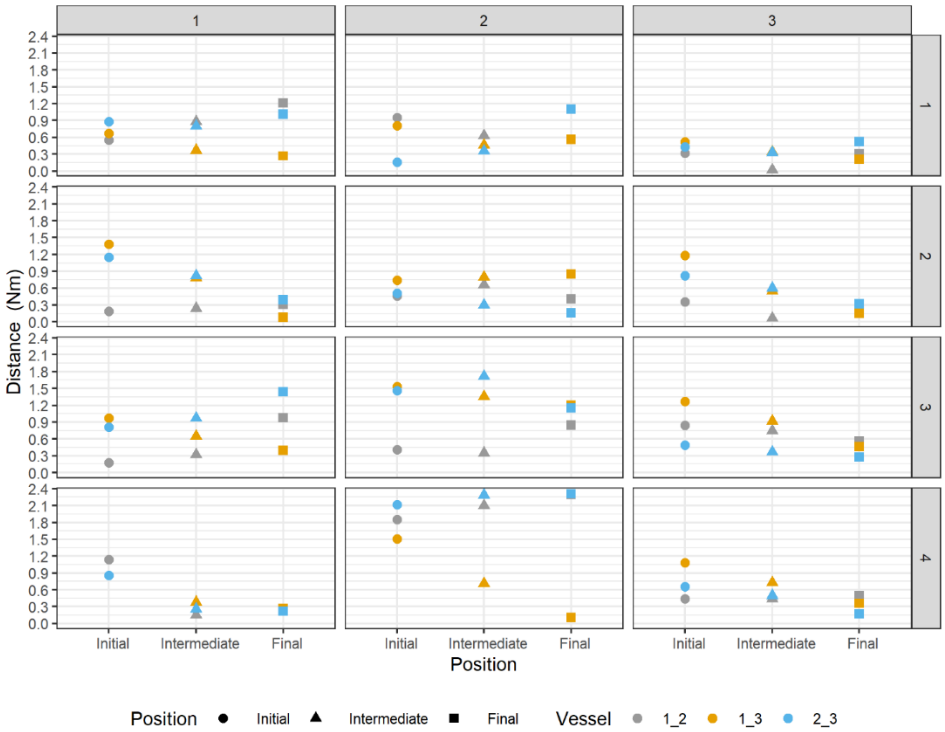

Figure S4 Distance of among vessels, in nautical miles, during the initial, intermediate, and final haul position over the days (columns), and hauls (rows).

Tables

Table S1 - The swept area of each vessel by haul is estimated as Km^2. Δ (%) represents the percentage difference between the higher swept area recorded by a vessel compared to the other ones.

Gear	Day	N haul	Speed (m/s)	Swept Area (Km^2)	Δ (%)
Control	1	1	1.54	0.24	
G1-SM40	1	1	1.44	0.23	1.6%
T90 codend	1	1	1.44	0.22	4.9%
Control	1	2	1.33	0.20	5.3%
G1-SM40	1	2	1.28	0.21	4.0%
T90 codend	1	2	1.38	0.22	
Control	1	3	1.54	0.24	1.8%

G1-SM40	1	3	1.49	0.24	
T90 codend	1	3	1.49	0.23	3.3%
Control	1	4	1.49	0.23	5.0%
G1-SM40	1	4	1.49	0.24	
T90 codend	1	4	1.54	0.24	0.1%
Control	2	1	1.49	0.23	1.7%
G1-SM40	2	1	1.44	0.23	
T90 codend	2	1	1.44	0.23	3.3%
Control	2	2	1.44	0.22	0.9%
G1-SM40	2	2	1.38	0.22	
T90 codend	2	2	1.38	0.22	3.3%
Control	2	3	1.44	0.22	5.0%
G1-SM40	2	3	1.44	0.23	
T90 codend	2	3	1.44	0.23	3.3%
Control	2	4	1.49	0.23	
G1-SM40	2	4	1.38	0.22	0.9%

T90 codend	2	4	1.44	0.23	1.7%
Control	3	1	1.44	0.22	5.0%
G1-SM40	3	1	1.44	0.23	
T90 codend	3	1	1.54	0.24	3.4%
Control	3	2	1.49	0.23	1.7%
G1-SM40	3	2	1.44	0.23	
T90 codend	3	2	1.44	0.23	3.3%
Control	3	3	1.44	0.22	1.7%
G1-SM40	3	3	1.38	0.22	0.9%
T90 codend	3	3	1.44	0.23	
Control	3	4	1.49	0.23	4.9%
G1-SM40	3	4	1.44	0.23	3.3%
T90 codend	3	4	1.54	0.24	

Paper 3: Unaccounted mortality

First escape survival and scale damage assessment of red mullet (*Mullus barbatus* Linnaeus, 1758*)* during bottom trawling in the central Mediterranean Sea

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Simple Summary: Fisheries are amongst the most important anthropogenic activities that strongly impact the marine environment. Therefore, stock assessments are routinely carried out to evaluate the status of the main commercial species to avoid overexploitation. However, these assessments do not take into account the possible mortality of fish due to interaction with fishing gear, and the evaluation of escape survival rates is needed. For the first time in the Central Mediterranean, this study evaluated the escape survival of the red mullet escaping from a bottom trawl. The survival rate of the control individuals (open codend) was higher compared to the treatment individuals (closed codend). Larger fish in the treatment group had a higher probability of dying, while the opposite was observed in the controls. In addition, treatment fish had significantly more wounds per fish than control fish, and were mainly injured around the head. The results highlighted that the sampling methodology was effective in collecting fish samples without affecting their survival rates. Although promising, these results need to be confirmed by further investigation before applying the survival rates in stock assessment models.

Abstract: Stock assessments routinely evaluate the status of commercially harvested species, but seldom account for the possible mortality of released or escaping fish. This study presents a method for estimating the escape survival of the red mullet (Mullus barbatus) from demersal trawling in the Central Mediterranean Sea. Fish escaping from the trawl codend were collected in a detachable cage, which was lined to reduce water flow and protect the sampled fish from further fatigue and injury. Control fish (from an open codend) showed high survival, 94% (87–97%, 95% Confidence Interval), and minimal injuries, while fish escaping through codend meshes had significantly increased injuries and reduced survival, 63% (55–70%). During 7 days of captive monitoring, treatment group mortality was highest in the first 24 h and ceased for both groups within 48 h. Conflicting length-related mortality was observed, where larger treatment fish had a higher probability of dying, while the opposite was observed in the controls. Analysis showed that treatment fish were significantly more injured than control fish, with treatment fish predominantly injured in the head zone. In conclusion, this improved methodology should be repeated to provide accurate escape mortality estimates for the improved stock assessment of the red mullet in the Central Mediterranean.

Keywords: fishing mortality; trawl fishery; Strait of Sicily; MCRS

1. Introduction

Fishing activity is one of the most important anthropogenic impacts affecting marine resources and consequently the ecological equilibria in marine ecosystems [1–4]. Among the different fisheries, bottom trawling is considered one of the most impactful techniques in the Mediterranean due to high quantities of unwanted catch, including the incidental catch of non-target species and juveniles of both target and non-target species, which are either discarded because of their low economic value or because of legal restrictions, e.g., [5–7]. Excluding temporal and spatial closures, the most common way of addressing the issue of by-catch in towed gear has been to improve gear selectivity. Indeed, to mitigate the problem, the European Union established conservation measures such as minimum legal mesh size and the Minimum Conservation Reference Size (MCRS), under Reg. EU 1241/2019 [8], while Reg. EU 1380/2013 [9] encourages improving the selectivity of the fishing gear. Therefore, in recent years, physical modifications such as by-catch reduction devices (BRDs) have been tested to improve species selection, e.g., [10–14]. In some cases, compared to conventional gear, these latter sorts of BRDs have been demonstrated to mitigate problematic by-catches [10,11,15,16]. However, the survival rates of escaping fish, either from a traditional codend or from gear with a BRD, are not well-known, despite their potential to bias stock assessment estimates of yield and biomass [17]. Although stock assessments generally assume all escaping fish survive and grow, several experiments have shown that individuals escaping from nets during fishing may not always survive [18]. The objective of studies on escape mortality is to demonstrate that a sufficient proportion of the released fish survive to justify their short-term loss from the catch. In many cases, escape occurs after the fish have been subjected to a wide variety of capture-related stressors and possible injury through contact with other fish, debris, or the fishing gear itself (reviewed by [18–20]). For trawled gear, the key variables affecting escape survival include tow duration, catch composition, the weight of the catch, mesh size/shape, and the codend circumference [18,21–24]. In addition, the survival rates are species-specific; for example, Atlantic cod (*Gadus morhua*) has been found to be more resistant than other gadoids with respect to escape mortality from demersal trawls. Scale damage is a common injury of fish caught in trawled gear but not in hook fishing [25]. In Atlantic waters, initial works by Main and Sangster [26], Main and Sangster [27] and Main and Sangster [28] suggested that survival rates for haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*) could be quite high (80–90%), depending on the mesh size used. Soldal et al. [25] reported that mortality was less than 10% for haddock and 0% for Atlantic cod escaping from a demersal trawl. Robinson et al. [29], studying the survival rates of groundfish such as Atlantic cod, American plaice (*Hippoglossoides platessoides*), and yellowtail flounder (*Myzopsetta ferruginea*), concluded that survival rates were extremely variable and dependent on the season. Therefore, overall, the results of the studies on escape mortality suggest that the mortality associated with capture and escape may be relatively low for many species, particularly for gadoids and flatfishes. However, it is also obvious that not all fish survive the process of capture and escape. Measuring the survival of fish escaping from fishing gear under various fishing conditions is not an easy task. It is subject to high variability and methodological flaws. It is therefore not surprising that the accuracy of the escape mortalities estimated in various studies has been criticized. In the Mediterranean Sea, to date, the few studies carried out to assess escape survival have only been conducted in the Aegean Sea (eastern Mediterranean) [30–38]. In particular, Metin et al. [30] found that the survival rate of red mullet (*Mullus barbatus*) after escaping from a commercial bottom-trawl codend (40 mm) was on average 93%. More recently, Düzbastilar et al. [37] found a seasonal effect on the survival of M. barbatus, with mean escape mortality significantly higher in winter compared to summer. Furthermore, mortality was also highest among the smallest fish, particularly during winter. In the present study, the survival rate of red mullet escaping through a commercial trawl codend was estimated for the first time in the Central Mediterranean Sea

2. Materials and Methods

2.1. Study Area

In July 2018, a study to estimate the escape survival of the *M. barbatus* was carried out in the Strait of Sicily, located in the Central Mediterranean Sea and separating the eastern and the western basins (Figure 1).

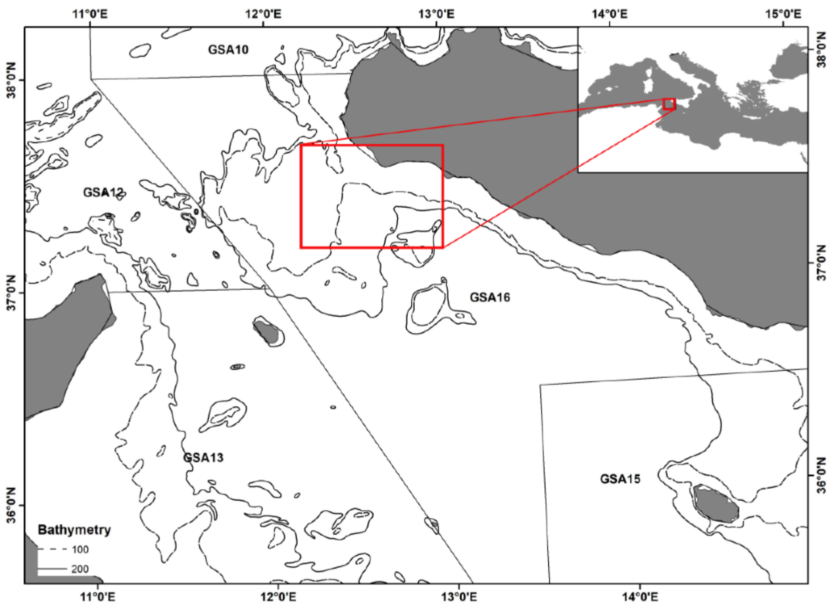

Figure 1 The study area is highlighted with a black square box (Maps from Vitale et al., 2018a,b)

In oceanographic terms, the Strait of Sicily is characterized by the cold and less salty Atlantic waters coming from the western side of the Mediterranean, and the Levantine Intermediate Waters (warmer and saltier) coming from the east. The Atlantic waters entering the Strait of Sicily area originate in two streams, the Atlantic Tunisian Current in the south and Atlantic Ionian Stream in the north. These two streams respectively generate upwelling and downwelling along the Sicilian and Tunisian coasts. The Atlantic Ionian Stream also generates two main vortexes, namely the Adventure Bank Vortex and the Ionian Shelf Break Vortex. These oceanographic features contribute to making the Strait of Sicily one of the most productive areas for demersal fishing in the Mediterranean, exploited mainly by trawl fisheries (Di Lorenzo et al., 2018; Jarboui et al., 2022). In particular, the trawling fleet exploits the deeper fishing ground, targeting deep-water crustaceans such as *Aristaeomorpha foliacea, Aristaeus antennatus, Parapenaeus longirostris, and Nephrops norvegicus* (Milisenda et al., 2017; Geraci et al., 2021) as well as the shallow fishing ground, targeting mainly *M. barbatus*, *M. surmuletus*, sparids and cephalopods (Pinello et al., 2018; Falsone et al., 2022; Di Maio et al., 2022).

2.2.Overview of the scientific approach

The approach used to assess the escape survival and the scale damage was based on a comparison of the state of fish caught by two configurations of trawl net, one with an open codend and another with a closed codend, in which escaping fish had to pass through the codend meshes. In both configurations, the codend was covered by a flexi-ble cover that retained fish escaping from the codend in a detachable cage. The adopt-ed procedure had three steps. The first step included the design and preparation of the experimental gear (cage—control and treatment, cover, and liner), the protocols of the manipulation of fish at sea as well as the scale damage and injury assessment proto-cols. The second step involved the placement of the cages at an inshore site and the monitoring of the fish sampled. Lastly, during the third step, the data were collected and analyzed (Figure 2).

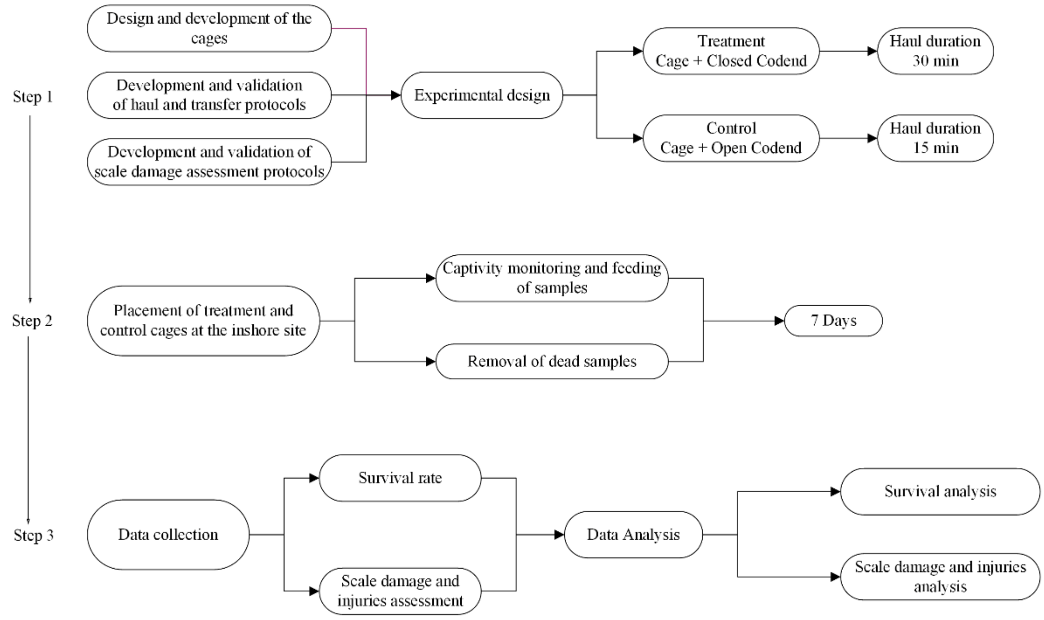

Figure 2 Diagram flows showing the steps followed to carry out the present study experiment.

2.3. Cage Description

To collect samples either from the treatment (closed codend) or control (open codend) hauls, a detachable cage (two identical, one for control and one for treatment) with a nominal mesh size of 20 mm square was attached to a fixed cover, in turn fixed to the forward end of the codend. The structure was stabilized using 5 rigid hoops of 2 m diameter. The cages were about 10 m long and rigged with two 1.0 m long horizon-tal zippers to retrieve any dead fish and feed the survivors. Based on Breen et al. [46], a liner was installed at the end of the codend cover and cage assembly to protect the fish in the cage from excessive water flow (Figure 3). This cage liner was removed after the cage was detached from the codend cover.

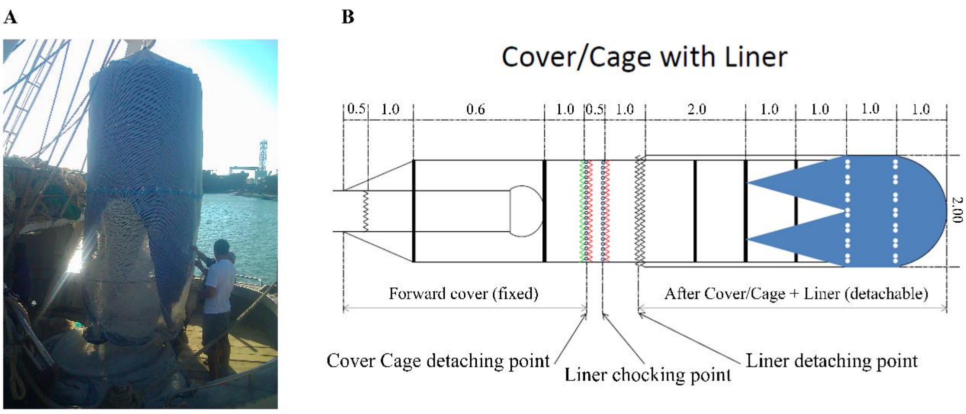

Figure 3 The cage with liner used during the experiment (A) and a schematic representation of the cover/cage with liner (B).

2.4. Sampling at Sea

The experiment was conducted between latitude 37° 31.690–37° 32.780 N and longitude 12° 38.730–12° 36.450 E, at a mean depth of 50 m (Figure 1). Two hauls were carried out on the same day, 18th July 2018; one of these, the treatment, was conducted with a closed commercial codend (40 mm square) according to Reg. EU 1241/2019 (see Geraci et al. [16] for a more detailed description of the gear) whereas during the control haul the codend was kept open (Figure 4).

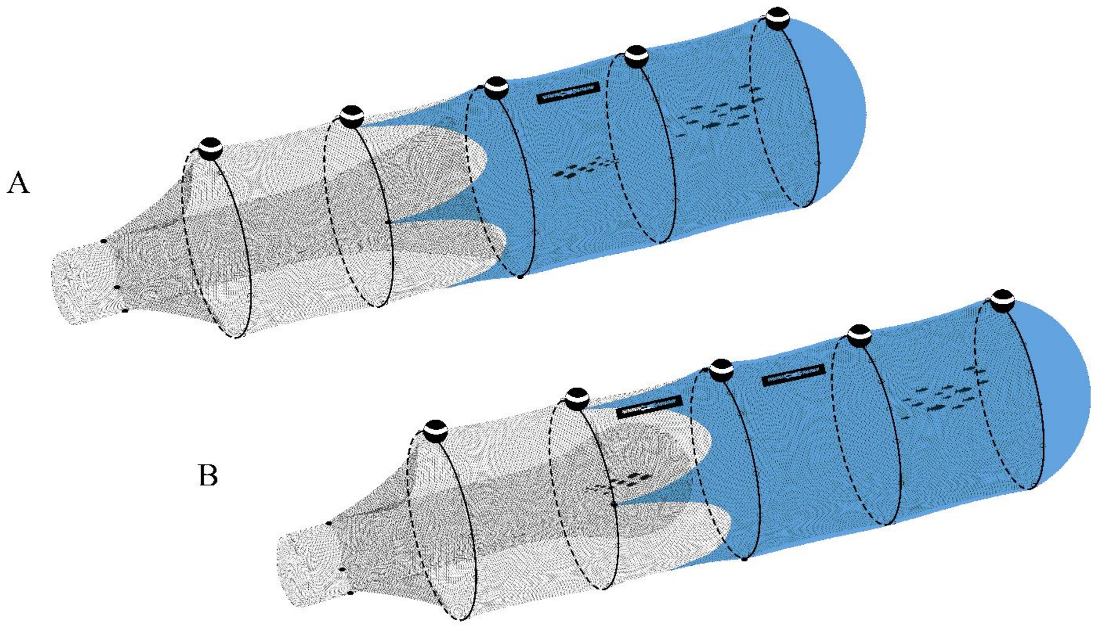

Figure 4 The gear used to sample red mullet individuals. (A) treatment, closed commercial codend; (B) control, opened commercial codend

Haul duration was fixed at 30 and 15 min, respectively, for treatment and control, with a mean towing speed of 2.8 knots. The main reason for limiting the towing duration of the control to 15 min was to avoid over-filling the sampling cages with fish. The difference in towing duration between the treatment and control should have a minimal effect on the samples of escaped fish because the cage lining specifically protects them from fatigue after escape.

Two professional divers were employed during the sampling activity. At the end of each haul, a speed of 0.2 knots was maintained in order to avoid the collapse of the cage. Then, the two divers descended to the cage (about 50 m); one held the cover while the other removed the cage from the liner (similar to removing a "sock"). After that, the divers detached the cage and gradually raised it up to about 10 m depth in 20 min. When the cage reached the predetermined depth (10 m), floats were attached to maintain the cage at this depth. Finally, a rubber dinghy was used to tow the cage, at a speed of 0.2 knots, to the inshore monitoring site, where it was anchored to the seabed. The same methodologies were repeated for each haul/cage (treatment and control).

2.5. Monitoring of Fish Survival

The cages for housing the sampled fish were anchored at depths of about 10 m (37° 34.041 N; 12° 39.148 E). The shallow depth was chosen to enable the divers to operate at safe depths to feed fish, extract dead individuals, and assess the vitality of survivors. The temperature at the fishing ground was 18 °C while in the monitoring site it was 20 °C. Fish were observed by divers three times a day ("early" at 09:00, "middle" at 14:00, and "late" at 19:00) over a period of 7 days (from 18th to 25th July 2018). After 2 days, they were fed with shrimps, worms, and feed pellets. In addition, the behavior of the captive fish was monitored and recorded by the divers using the same underwater camera systems used by Sardo et al. [47] (i.e., GoPro Hero 4, GmbH, München, Deutschland) (Figure 5). Given that the wild fish were kept in captivity, their behavior could be affected during the monitoring period. All surviving individuals were released into the sea 7 days after capture.

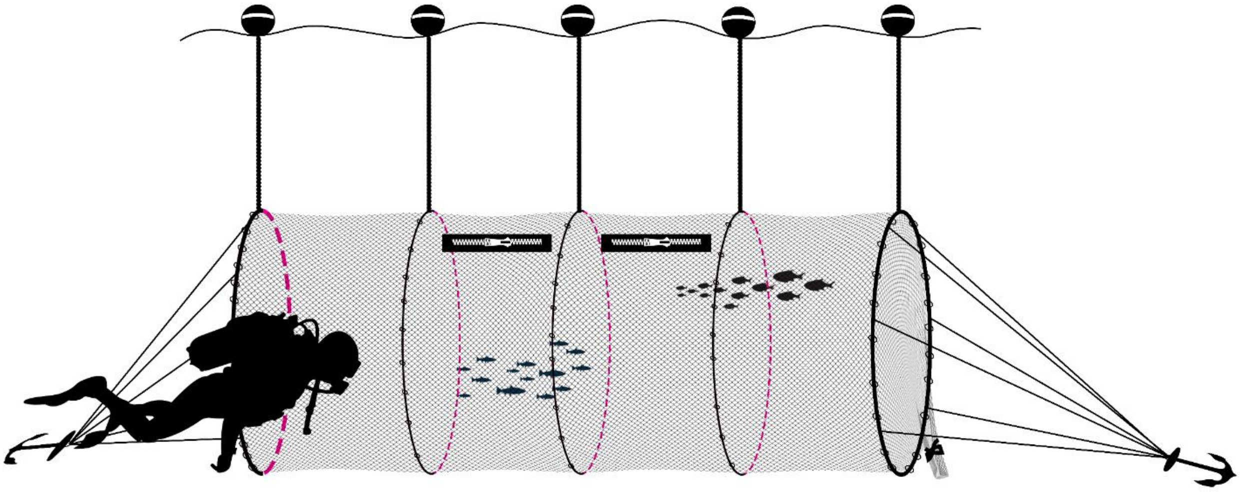

Figure 5 Drawing showing a diver who monitored the fish condition during the captivity period

2.6. Scale Damage and Injury Analysis

The *M. barbatus* specimens that died during the monitoring period were assessed for injuries and scale damage, whereas all surviving individuals were released into the sea at the end of the experiment. Dead specimens were photographed using the above-mentioned video camera mounted on an external tripod 3-Way 2.0 with an extension arm. The video camera was positioned at a height of 50 cm from the ichthyometer and pictures for both the right and left sides of each specimen were taken. During image processing, a grid-square was applied to the pictures to assess injuries to the specimens in each of the 4 zones: head, abdominal, anal, and caudal. Specifically, the head zone went from the mouth to the operculum, the abdominal zone from the operculum up to halfway between the tip of the pectoral fin and the origin of the anal fin, the anal zone from halfway between the tip of the pectoral fin and the origin of the anal fin to the insertion of the dorsal fin, and the caudal zone from the insertion of the dorsal fin to the origin of the caudal fin (Figure 6). A total of 118 pictures were analyzed with the help of ImageJ2 software [48].

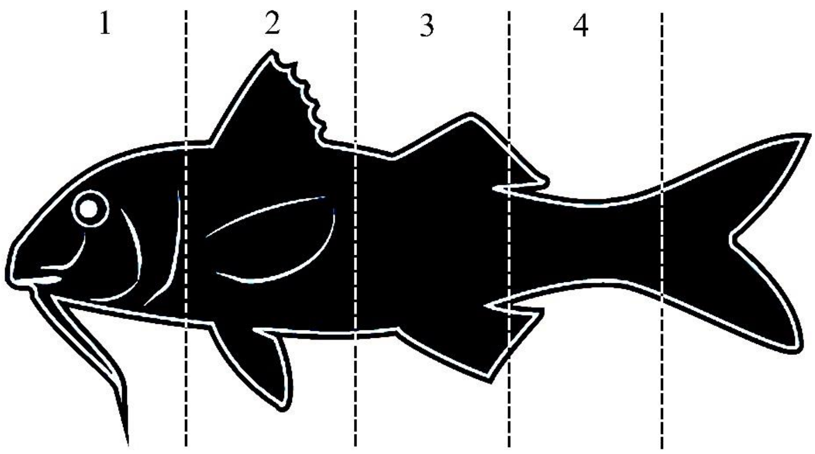

Figure 6 The body zones used in the present study to assess the scale damage and injuries of the *Mullus barbatus* individuals

In turn, each zone was further sub-divided into several equally distributed sub-squares. Four authors of the present study, M.L.G., G.S., F.Fa, and D.S., counted independently the number of squares per zone where scale damage and injuries were visible on the total number of squares covered by the body surface of each individual per zone, excluding the eyes and the fins. Therefore, the scale damage and the injuries were quantified as a proportion by body zone.

2.7. Survival Analysis

The sizes of the surviving individuals were estimated through ImageJ2 software [48] taking video frames from the GoPro 4 Hero black. The distance between two consecutive hoops in the cage (1 m) was used as a standard. Dead specimens were measured (Total Length, TL) and weighed (W) to the nearest 5 mm and 0.1 g, respectively.

All the analyses and graphical representations were carried out through R version 4.2.2 [49]. The survival rates of the treatment and control individuals were calculated as a percentage, namely the number of survivors at a given time divided by the total number of individuals at the beginning of the experiment. The Wilson method [50] was applied to calculate the 95% confidence interval for these estimates using the R package *binom* [51] as recommended by the ICES WKMEDS (International Council for the Exploration of the Sea—Workshop on Methods for Estimating Discard Survival) [52].

The probability of survival over time was estimated using the non-parametric Kaplan–Meier function applied to both treatment and control groups, with the R packages *binom* [51], *survminer*

[53], and *survival* [54], where time zero was hauling time for each haul and surviving individuals were right censored.

The relationship between survival and individual length (in 5 mm length classes) was investigated using a generalized linear model (GLM) [55], fitted using the binomial error distribution and logit-link functions. In the survival model, the survival proportion was used as a response variable while TL, the haul type (2 levels: treatment and control), and the interaction between them were used as predictors. The significance of the model terms was assessed using likelihood ratio testing.

The scale damage and injury data were assessed by fitting a Generalized Linear Mixed Model (GLMM). In the full model, the proportion of damage was the response variable and individual size, haul type (2 levels: treatment and control), body zone (4 levels: head, abdominal, anal, caudal), and the interaction of haul type and zone were used as predictors. All models were fitted with beta error distribution (logit link function) using the R package *glmmTMB* [56] and included a random intercept term for individual fish to account for autocorrelation between body zones on the same fish. Given that the beta distribution is bounded by the open interval 0 to 1, (i.e., excluding 0 and 1), the proportions of damage were transformed in accordance with the Smithson and Verkuilen [57] methods. The model's residual patterns were checked for the violation of assumptions using the R package *DHARMa* [58]. Residual homoscedasticity in the models was addressed using variance structures to account for differing residual dispersion in the haul types and body zone groups [56,59]. The significance of model terms was determined using likelihood ratio testing. The 95% confidence interval (CI) was estimated through the t-student distribution of the model prediction. The relationship between the proportion of damage, by body zone, and total length was presented using a linear model with splines (three degrees of freedom) with *ggplot2* [60] and *splines2* [61] packages.

3. Results

In total, 256 individuals belonging to 11 species were caught in the course of the experiments. The survival rate for the control samples of red mullet (i.e., escaping through an open codend) was high. By the end of the monitoring period, 54 and 5 red mullets had died from treatment and control hauls, respectively (Table 1). In addition, *Arnoglossus thori*, *Bothus podas*, *Dactilopterus volitans*, *Pagellus acarne*, *P. erythrinus*, *Serranus cabrilla*, *S. hepatus*, *Spicara flexuosa*, and *Synodus saurus* also appeared to have high survival rates but due to small sample sizes (n < 10) were not included in further analyses (Table 1).

Table 1 Number of survivors and dead individuals by species caught in treatment (closed codend) and control (open codend) hauls.

Species	Control			Treatment		
	Dead	**Survivors**	**Total**	**Dead**	**Survivors**	**Total**
Arnoglossus thori	//	//	//	3	0	3
Bothus podas	1	0	1	//	//	//
Dactilopterus volitans	//	//	//	1	0	1
Microchirus variegatus	//	//	//	1	0	1
Mullus barbatus	5	79	84	54	92	146
Pagellus acarne	//	//	//	0	3	3
Pagellus erythrinus	//	//	//	0	5	5
Serranus cabrilla	//	//	//	1	2	3
Serranus hepatus	//	//	//	0	4	4
Spicara flexuosa	//	//	//	0	1	1
Synodus saurus	//	//	//	4	0	4

Similar to the behavior described by Metin et al. [30], immediately after the detachment of the cage from the trawl *M. barbatus* individuals were resting with high operculum activity on the bottom. During the first observations, a few hours after anchoring the cages, red mullets were swimming actively in a shoal. Some species such as *P. erythrinus* also swam actively with the red mullet shoal whereas others such as *S. saurus* remained stationary on the bottom of the cage.

The observed survival rate of *M. barbatus* sampled during the treatment haul was 63% (55–70% upper and lower bounds of the 95% CI), while the control sample had a significantly higher survival of 94% (87–97% CI). The Kaplan–Meier plot (Figure 7) shows that most treatment specimens died between 12 and 24 h, after which the mortality rate slowed slightly and ceased after 48 h. The control mortality occurred between 24 and 48 h at a significantly lower rate, also ceasing after 48 h (Figure 7).

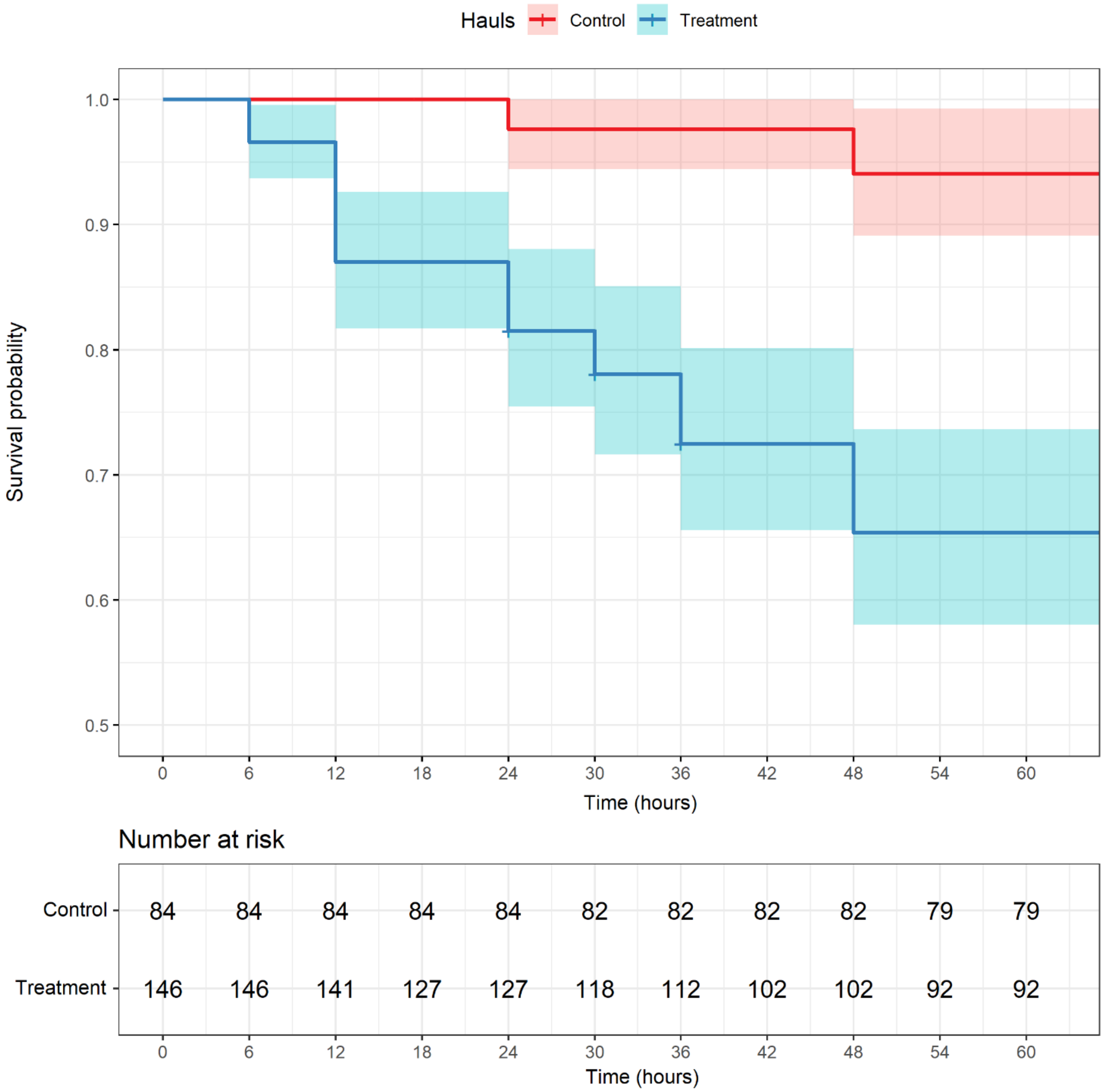

Figure 7 Kaplan Meier plot showing the probability of survival of the *Mullus barbatus* individual for treatment and control hauls.

The size distributions of the individuals caught during treatment and control hauls were mainly composed of fish larger than the MCRS, as defined by Reg. EU 1241/2019 (Figure 8).

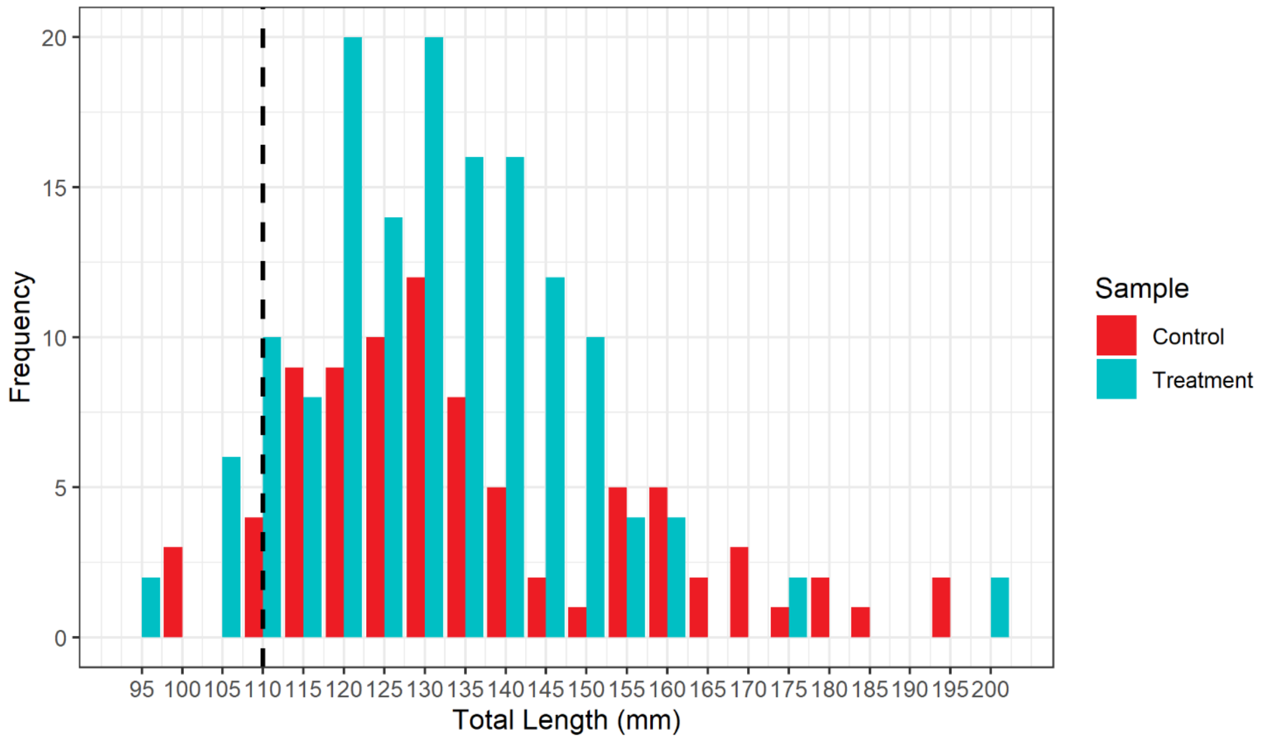

Figure 8 Length frequency distribution of *Mullus barbatus* sampled during the survey from treatment and control hauls. The vertical black dashed line denotes the MCRS defined by the Reg. EU 1241/2019.

The survival of red mullets in the treatment group (i.e., escaping through codend meshes) was inversely related to total length, with larger fish having a lower probability of surviving (Figure 9). Conversely, in the control group, the data suggest there may have been a lower probability of survival in the smallest fish (between 100 and 125 mm TL), although this is based on a small number of dead fish (five individuals) (Figure 9).

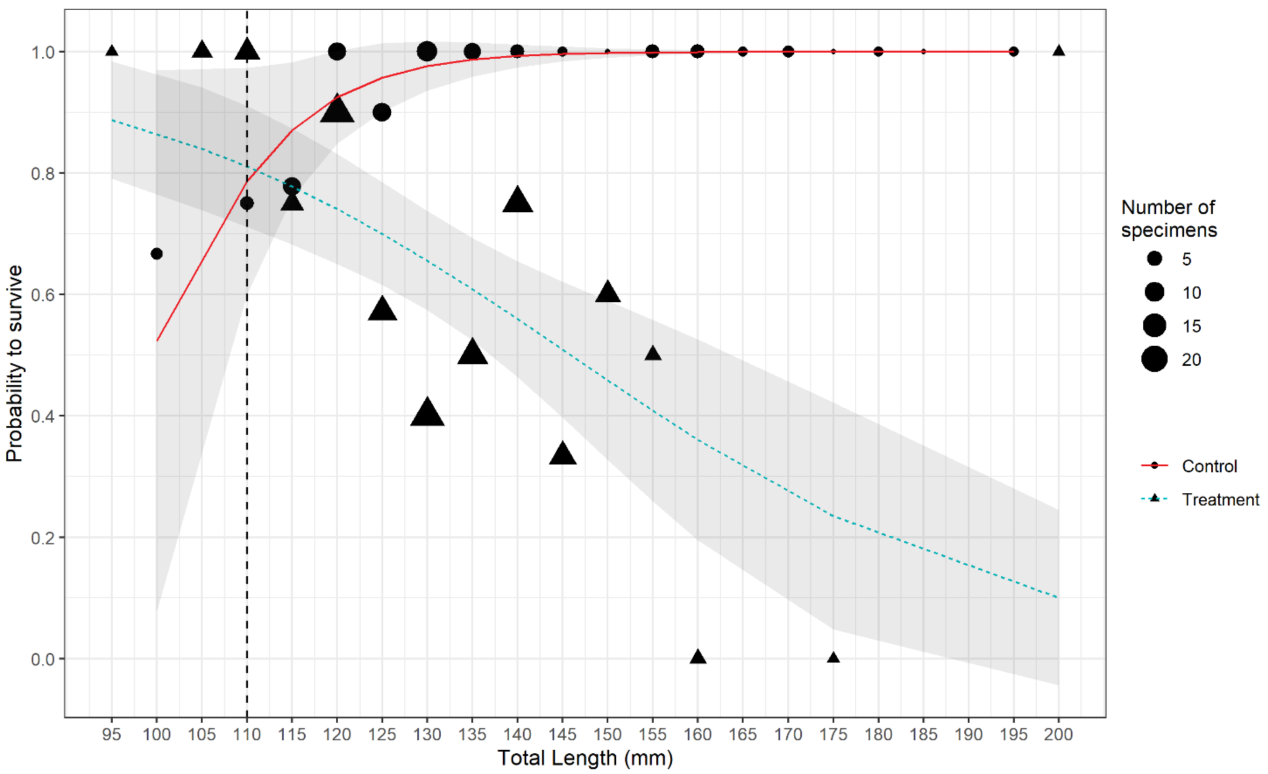

Figure 9 Probability to survive per class size of the individuals caught during the (A) treatment and control (B) hauls. Grey areas represent the 95% confidence intervals; the vertical black dashed line denotes the MCRS defined by the Reg. EU 1241/2019

The GLM of the survival data confirmed that the treatment group had a significantly lower survival than the controls (Table 2). It also confirmed that total length also significantly affected survival, with a highly significant interaction between the treatment and control groups, as described in Figure 9.

Table 2 Results of GLM analysis of *Mullus barbatus* survival. Std. error: standard error; TL: total length

Coefficients	Estimate	Std. error	z value	p-value	Resid. df	Resid. dev	p-value
Intercept	-11.975	5.789	-2.068	0.039			
TL	0.121	0.050	2.410	0.016	31	63.450	0.025
Haul_typeTreatment	17.892	6.007	2.978	0.003	31	93.010	<0.001
TL:haul_typeTreatment	-0.161	0.051	-3.132	0.002	30	58.405	<0.001

The proportion of damage was significantly higher in red mullets from the treatment group (Figure 10, Table 3). Moreover, the treatment fish had significantly more damage to the head (Figure 10). In the control fish, the damage was highest in the abdominal zone, but this was not significant compared to the other zones. The effect size on damage was not significant in the GLMM and so was excluded from the final model (Table 3). The residuals in the final model were marginally under-dispersed. This implies that inferences about the significance of the effects were marginally conservative, with an increased likelihood of a type-II error (i.e., false negative). The random variation for individual fish was low (standard deviation = 0.451), indicating that observed damage was proportionate across all zones within individual fish. No barotrauma-related injuries were observed.

Table 3. Results of GLMM of *Mullus barbatus* scale damage and injuries. Std. error: standard error; TL: total length; Df: degree of freedoms; logLik: logarithm of Likelihood; Chisq: chi square; Chi df: chi degree of freedom.

Coefficients	Estimate	Std. error	z value	*p*-value	Df	LogLik	Deviance	Chisq	Chi df	*p*-value
Intercept	−0.860	0.107	−8.001	1.23^{-15}						
ZoneAbdominal	−2.056	0.159	−12.893	$<2^{-16}$						
ZoneAnal	−2.353	0.168	−13.991	$<2^{-16}$	11	587.07	−1174.2	0	0	<0.001
ZoneCaudal	−2.212	0.166	−13.328	$<2^{-16}$						
Haul_typeControl	−4.182	0.636	−6.578	4.76^{-11}	11	587.07	−1174.2	0	0	<0.001
ZoneAbdominal:haul_typeControl	2.587	0.636	4.068	4.74^{-05}						
ZoneAnal:haul_typeControl	1.675	0.670	2.503	0.012	11	587.07	−1174.2	17.878	3	<0.001
ZoneCaudal:haul_typeControl	1.534	0.669	2.293	0.022						

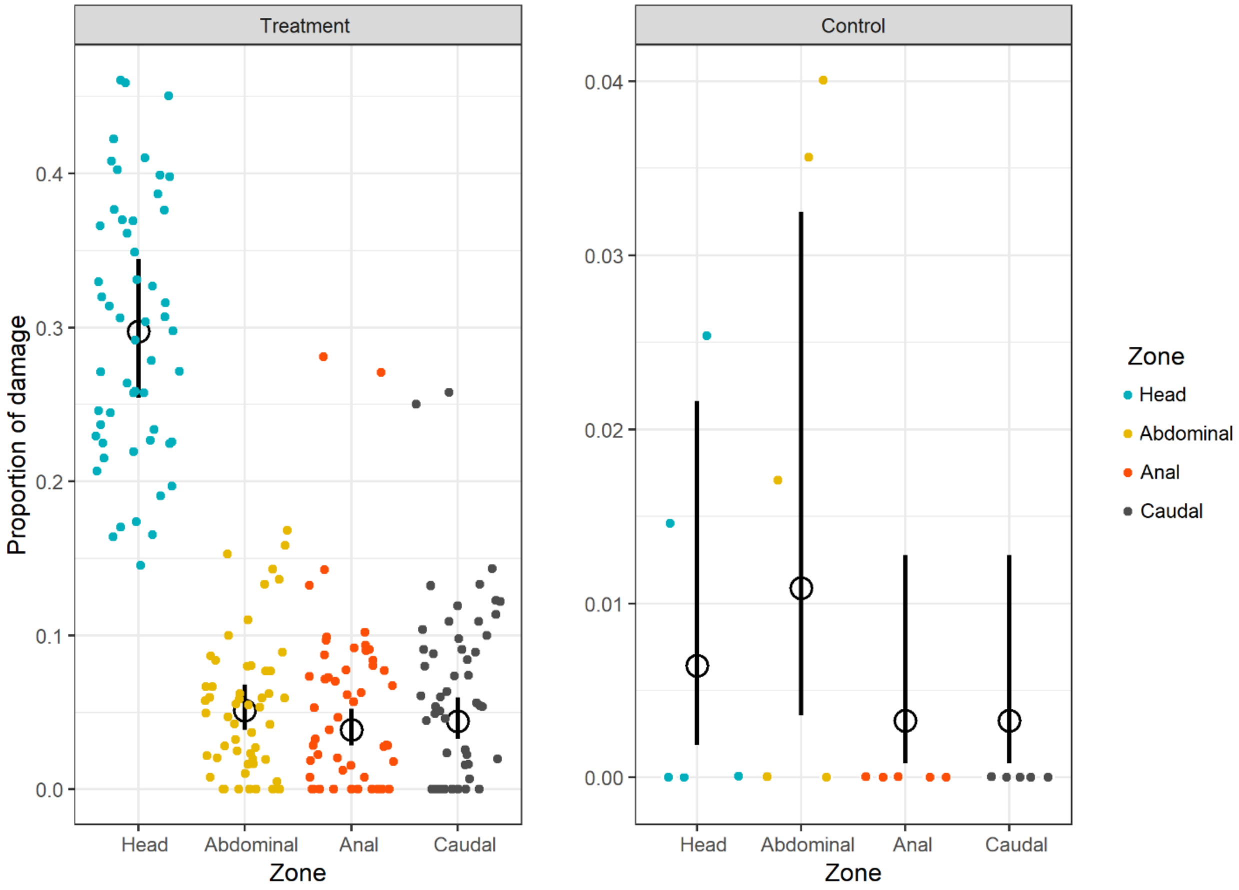

Figure 10. Proportion of skin damage (%) to red mullet (*Mullus barbatus*) in different body zones in the treatment and control hauls. Filled dots are the observed damage proportion for individual fish, black open circles are the mean GLMM predictions, and the bars are the 95% confidence intervals.

The proportion of skin damage in the head zone of the red mullet from the treatment group was lowest in the smallest fish, increasing between 120 and 130 mm TL to a maximum of approximately 0.3 at 140 mm TL, after which it remained approximately constant (Figure 11). Damage in the other zones was consistently low across the size range.

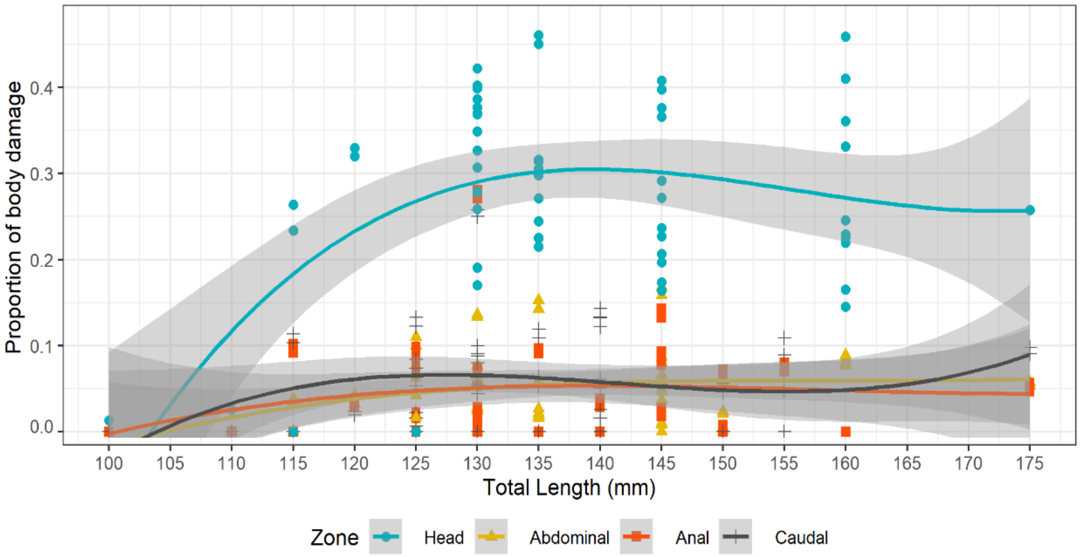

Figure 11. Proportion of skin damage to dead red mullet in the treatment group per class size and body zone. Trend lines indicate linear model fitting. Grey areas are 95% confidence interval.

Discussion

The survival rate of red mullet (*M. barbatus*) escaping from a commercial trawl codend (40 mm square) was evaluated for the first time in the Central Mediterranean. Overall, the survival rate of *M. barbatus* was high in the treatment group (63%; 55–70% CI) and very high in the control (94%; 87–97% CI). All observed mortality occurred within the first 2 days, which agrees with previous studies reporting that mortalities occur during the first 2–3 days [30,62,63] and suggests that the monitoring period (7 days) is adequate to estimate the survival rates of the red mullet escaping from a trawl codend.

The survival rate of the red mullet sampled in the present study (63%; 55–70% CI) from the treatment haul was lower than that reported in the Aegean Sea. In particular, Metin et al. [30] reported an average of 93% survival for red mullet escaping from a square mesh 40 mm PE codend in the experiments conducted in September, whereas Duzbastillar et al. [32], using the same codend, found a 95.1% mean mortality in October. In addition, Duzbastillar et al. [32] also tested a 40 mm diamond mesh codend, which showed lower survival rates (81.2%) than the square mesh, suggesting an effect of the mesh shape on red mullet survival. Lastly, Duzbastillar et al. [35], testing three different codends (40 mm square, 44 mm diamond, and 50 mm diamond), found survival rates of red mullet lower than the present study with the 44 mm diamond (about 54%) and higher survival rates with 40 mm (about 74%) and 50 mm (about 73%) codends. Given that our experiment was carried out in July, the higher temperature might have caused such differences. Conversely, Duzbastillar et al. [37] found higher mortality in winter from small red mullet specimens and suggested that the observed mortality may be related to the physical condition of the fish, being that fish are less nourished during winter and less able to recover from exhaustion and physical injuries during the catching process. On the other hand, red bandfish (*Cepola macrophthalma*) caught in the Aegean Sea showed a significant effect of temperature on the survival of escaped specimens [34] whereas no seasonal effects on survival were observed in common pandora (*Pagellus erythrinus*) [38].

Surprisingly, Duzbastillar et al. [37] and Metin et al. [30] in the Aegean Sea, using a similar sampling methodology, found that red mullet controls had significantly higher mortality than the treatment groups. The higher control survival rates (94%; 87–97% CI) observed in our experiment are likely due to sampling and handling procedures that aimed to minimize stress on the sampled fish, including minimizing barotrauma through controlled decompression and reducing additional fatigue by reducing water flow in the cover with the cage liner [46]. The very high survival of the control fish in this study provides strong evidence that the methodological approach did not adversely affect the survival of the samples of red mullet in this experiment. However, it should be noted that these observations are not properly representative of the conditions experienced during commercial fishing hauls with respect to depth, towing duration, and catch size. Mediterranean trawl fisheries typically target multiple species and operate at depths of up to 800 m [64], whereas the red mullet lives at depths of <200 m [65]. The experimental hauls in this study were carried out in shallow waters (about 50 m), as fishing in deeper waters would have exposed fish to higher decompression stress compromising their vitality, as with other Mediterranean studies [30,36,37]. Furthermore, the towing durations (15 min control and 30 min treatment) were short compared with 1–2.5 h in commercial fishing hauls (deeper than 50 m). Therefore, in order to provide valid scientific justification for the implementation of regulations on trawl codend mesh size and MCRS in the Mediterranean (as defined by Reg. EU 1241/2019), further studies using methods similar to those describe here should be repeated with sufficient replicates to provide a robust description of the natural variation in escape survival rates. These studies should also attempt to replicate variations in commercial fishing operations, including seasonality, fishing depth, towing duration, and associated catch sizes and compositions. Data from these studies could be used to reduce the uncertainty in stock assessment modeling associated with unaccounted mortality and its bias of fishing mortality estimates [17–20,66,67]. In the meantime, the sensitivity of stock assessment models to such escape mortality data could be assessed using simulation exercises (e.g., [17]).

A significantly negative effect of total fish length (TL) on red mullet survival was observed in the treatment group in this study (Figure 9). This contrasts with observations showing the opposite effect in red mullet in the Aegean Sea [30,37] as well as several other teleost species in the Mediterranean [31,36] and Atlantic [18,33,68]. While species-specific variation in the effect of fish size upon escape mortality is recognized [18,21,33,69], the contradiction with similar studies on the same species is noteworthy. Our observation that survival decreases with increasing size in fish escaping through codend meshes better fits the hypothesis that these fish are more likely to experience fatal injuries and stresses as they struggle to pass through the codend meshes [18,25]. Furthermore, the degree of injury, particularly to the head, was significantly greater in the treatment group fish relative to the controls (which did not pass through codend meshes), further supporting this hypothesis (Table 3; Figure 10). However, evidence that injuries were also length-related was non-conclusive (Table 3; Figure 11).

Several studies have observed, using video cameras, that after escaping from the trawl codend some fish, particularly smaller ones, are unable to sustain swimming against the water flow in the cover/cage and fall back to the rear where they likely sustain further injuries [25,70–72]. These observations have been used to explain some length-related mortality and injury effects observed in escape survival studies [71,72], as well as to propose and demonstrate the effectiveness of reducing water flow in the sampling cover and its benefits for survival estimation [46]. The survival studies on red mullet in the Aegean Sea [21,28] used a similar method to the current study, except they did not use a liner in the cover to reduce water flow in the sample cage during towing. These and related studies observed increased mortality in the smallest fish [30,37], as well as increased injuries in the tail region [35], which better fits the hypothesis of sampling-induced mortality. This contrast with our results further supports the conclusion that the methods used in the present study have provided more reliable estimates of escape survival.

5. Conclusions

This study has described an effective method for estimating escape mortality in red mullets escaping from trawl codends, in particular the use of a cover line to protect fish from injurious water flows during sampling. The observed survival rate of *M. barbatus* in the treatment group was 63% (55–70% CI), while in the control group it was 94% (87–97% CI). It is recommended that further studies using methods similar to those described here should be conducted to provide valid scientific justification for the implementation of regulations for trawl codend mesh size and MCRS in the Mediterranean (as defined by Reg. EU 1241/2019). These studies should have sufficient replicates to provide a robust description of the natural variability in escape survival rates, as well as attempt to replicate variations in commercial fishing operations including seasonality, fishing depth, towing duration, and associated catch sizes and compositions. The data resulting from this work will be essential for removing biases in fishing mortality estimates because of the inherent assumption in most stock assessment models that all escaping fish survive. Furthermore, they will enable fishery managers to make more informed decisions about the implementation of different gear selectivity scenarios based on more reliable projections of yield and biomass in the exploited populations.

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References

1. Jennings, S.; Kaiser, M.J. The effects of fishing on marine ecosystems. In *Advances in Marine Biology*; Academic Press: Cambridge, MA, USA, 1998; Volume 34, pp. 201–352.
2. Pauly, D.; Christensen, V.; Dalsgaard, J.; Froese, R.; Torres, F., Jr. Fishing down marine food webs. *Science* 1998, *279*, 860–863.
3. Crowder, L.B.; Murawski, S.A. Fisheries bycatch: Implications for management. *Fisheries* 1998, *23*, 8–17.
4. Santiago, J.L.; Ballesteros, M.A.; Chapela, R.; Silva, C.; Nielsen, K.N.; Rangel, M.; Erzini, K.; Wise, L.; Campos, A.; Borges, M.F.; et al. Is Europe ready for a results-based approach to fisheries management? The voice of stakeholders. *Mar. Pol.* 2015, *56*, 86–97. https://doi.org/10.1016/j.marpol.2015.02.006.
5. Pravin, P.; Gibinkumar, T.R.; Sabu, S.; Boopendranath, M. Hard bycatch reduction devices for bottom trawls: A review. *Fish. Technol.* 2011 *48*, 107–118.
6. Gorelli, G., Sardà, F., and Company, J.B. Fishing effort increase and resource status of the deep-sea red shrimp *Aristeus antennatus* (Risso 1816) in the Northwest Mediterranean Sea since the

1950s. *Rev. Fish. Sci. Aquac.* 2016, *24*, 192–202. https://doi.org/10.1080/23308249.2015.1119799.

7. Geraci, M.L.; Ragonese, S.; Scannella, D.; Falsone, F.; Gancitano, V.; Mifsud, J.; Gambin, M.; Said, A.; Vitale, S. Batoid Abundances, Spatial Distribution, and Life History Traits in the Strait of Sicily (Central Mediterranean Sea): Bridging a Knowledge Gap through Three Decades of Survey. *Animals* 2021, *11*, 2189. https://doi.org/10.3390/ani11082189.

8. EU. Regulation (EU) 2019/1241 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* 2019, *198*, 97.

9. EU. Regulation (EU) 1380/2013 of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. *Off. J. Eur. Union* 2013, 22–61.

10. Vitale, S.; Milisenda, G.; Gristina, M.; Baiata, P.; Bonanomi, S.; Colloca, F.; Gancitano, V.; Scannella, D.; Fiorentino, F.; Sala, A. Towards more selective Mediterranean trawl fisheries: Are juveniles and trash excluder devices effective tools for reducing undersized catches? *Sci. Mar.* 2018, *82*, 215–223. https://doi.org/10.3989/scimar.04751.28a.

11. Vitale, S.; Enea, M.; Milisenda, G.; Gancitano, V.; Geraci, M.L.; Falsone, F.; Bono, G.; Fiorentino, F.; Colloca, F. Modelling the effects of more selective trawl nets on the productivity of European hake (*Merluccius merluccius*) and deep-water rose shrimp (*Parapenaeus longirostris*) stocks in the Strait of Sicily. *Sci. Mar.* 2018, *82*, 199–208. https://doi.org/10.3989/scimar.04752.03a.

12. Sardo, G.; Vecchioni, L.; Milisenda, G.; Falsone, F.; Geraci, M.L.; Massi, D.; Rizzo, P.; Scannella, D.; Vitale, S. Guarding net effects on landings and discards in Mediterranean trammel net fishery: Case analysis of Egadi Islands Marine Protected Area (Central Mediterranean Sea, Italy). *Front. Mar. Sci.* 2023, *10*, 1011630. https://doi.org/10.3389/fmars.2023.1011630.

13. Sbrana, M.; De Carlo, F.; Ligas, A.; Massaro, A.; Musumeci, C.; Rossetti, I.; Sartini, M.; Vasapollo, C.; Viva, C.; Sartor, P.; Pretti, C. Testing experimental devices in the extension piece to increase the selectivity of bottom trawl in the Nw Mediterranean. *Front. Mar. Sci.* 2022, *9*, 1017766. https://doi.org/10.3389/fmars.2022.1017766.

14. Petetta, A.; Herrmann, B.; Virgili, M.; Li Veli, D.; Brinkhof, J.; Lucchetti, A. Effect of extension piece design on catch patterns in a Mediterranean bottom trawl fishery. *Front. Mar. Sci.* 2022, *9*, 876569. https://doi.org/10.3389/fmars.2022.876569.

15. Maynou, F.; García-de-Vinuesa, A.G.; Martínez-Baños, P.; Sánchez, P.; Demestre, M. Relative Catch Performance of Two Gear Modifications Used to Reduce Bycatch of Undersized Fish and Shrimp in Mediterranean Bottom Trawl Fisheries. *Mar. Coast. Fish.* 2021, *13*, 518–533. https://doi.org/10.1002/mcf2.10178.

16. Geraci, M.L.; Sardo, G.; Scannella, D.; Falsone, F.; Di Maio, F.; Gancitano, V.; Fiorentino, F.; Chirco, P.; Massi, D.; Vitale, S. Exploring the feasibility of technological transfers of two by-catch reduction devices in the crustacean bottom trawling of the central Mediterranean. *Front. Mar. Sci.* 2023, *10*, 1011605. https://doi.org/10.3389/fmars.2023.1011605.

17. Breen, M.; Cook, R. *Inclusion of Discard and Escape Mortality Estimates in Stock Assessment Models and its likely impact on Fisheries Management*; ICES CM 2002/V; 2002; Volume 27, 15p.

18. Suuronen, P. *Mortality of Fish Escaping Trawl Gears*; FAO Fisheries Technical Paper No. 478; Food and Agriculture Organization of the United Nations: Rome, Italy, 2005; 72p.

19. Chopin, F.S.M.; Arimoto, T. The condition of fish escaping from fishing gears—A review. *Fish. Res*. 1995, *21*, 315–327.

20. ICES. Report of the FTFB Topic Group on Unaccounted Mortality in Fisheries. In: Proceedings of the ICES FTFB Working Group, The Netherlands, 10–11 April 2000.

21. Broadhurst, M.K.; Suuronen, P.; Hulme, A. Estimating collateral mortality from towed fishing gear. *Fish Fish*. 2006, *7*, 180–218. https://doi.org/10.1111/j.1467-2979.2006.00213.x.

22. Sala, A.; Priour, D.; Herrmann, B. Experimental and theoretical study of red mullet (Mullus barbatus) selection in codends of Mediterranean bottom trawls. *Aquat. Living Resour*. 2006, *19*, 317–327. https://doi.org/10.1051/alr:2007002.

23. Sala, A.; Herrmann, B.; De Carlo, F.; Lucchetti, A.; Brčić, J. Effect of codend circumference on the size selection of square-mesh codends in trawl fisheries. *PLoS ONE* 2016, *11*, e0160354 . https://doi.org/10.1371/journal.pone.0160354.

24. Brčić, J.; Herrmann, B.; Sala, A. Can a square-mesh panel inserted in front of the codend improve size and species selectivity in Mediterranean trawl fisheries? *Can. J. Fish. Aquat.* 2018, *75*, 704–713. https://doi.org/10.1139/cjfas-2017-0123.

25. Soldal, A.V.; Isaksen, B.; Marteinsson, J.E.; Engås, A. *Scale Damage and Survival of Cod and Haddock Escaping from a Demersal Trawl*; ICES CM 1991/B:44; International Council for the Exploration of the Sea: Copenhagen, Denmark, 1991; 9p.

26. Main, J.; Sangster, G.I. *A Report on an Investigation to Assess the Scale Damage and Survival of Young Fish Escaping from a Demersal Trawl*; Working *Paper* No. 3/88; Scott. Fish. Res. Rep. 1988; 3.

27. Main, J.; Sangster, G.I. *An Assessment of the Scale Damage to and Survival Rates of Young Gadoid Fish Escaping from the Cod-End of a Demersal Trawl*; Scott. Fish. Res. Rep. 1990; 46, p. 28.

28. Main, J.; Sangster, G.I. *Do Fish Escaping from Codends Survive*? Working Paper No. 18/91; D.A.F.S. 1991; 18.

29. Robinson, W.E.; Carr, H.A.; Harris, J. *Assessment of Juvenile Bycatch and Cod-End Survivability in the Northeast Fishing Industry*; A Report of the New England Aquarium to the National Oceanic and Atmospheric Administration Pursuant to NOAA Award No. NA26FD 0039-01; 1993.

30. Metin, C.; Tokaç, A.; Ulaş, A., Duzbastilar, O.F.; Lok, A.; Ozbilgin, H.; Metin, G.; Tosunoglu, Z.; Kaykac, H.; Aydin, C. Survival of red mullet (*Mullus barbatus* L., 1758) after escape from a trawl codend in the Aegean Sea. *Fish. Res.* 2004, *70*, 49–53. https://doi.org/10.1016/j.fishres.2004.06.013.

31. Düzbastılar, F.O.; Özgül, A.; Aydın, İ.; Gul, B.; Soykan, O. A preliminary study on the survival of brown comber, Serranus hepatus (Actinopterygii, Perciformes, Serranidae), escaping from the codend of a bottom trawl. *Acta Ichthyol. Piscat.* 2010, *40*, 27–36. https://doi.org/10.3750/AIP2010.40.1.04.

32. Düzbastılar, F.O., Özbilgin, H., Aydın, C., Metin, G.; Ulas, A.; Lok, A.; Metin, C. Mortalities of fish escaping from square and diamond mesh codends in the Aegean Sea. *Fish. Res.* 2010, *106*, 386–392. https://doi.org/10.1016/j.fishres.2010.09.008.

33. Düzbastılar, F.O., Aydın, C., Metin G., Lok, A.; Ulas, A.; Ozgul, A.; Gul, B.; Metin, C.; Ozbilgin, H.; Sensurat, T.; Tokac, A. Survival of fish after escape from a 40 mm streched diamond mesh trawl codend in the Aegean Sea. *Sci. Mar.* 2010, *74*, 755–761. https://doi.org/10.3989/scimar.2010.74n4755.

34. Düzbastılar, F.O. Determining escape mortality of red bandfish (*Cepola macrophthalma*) escaping from bottom trawl. *Ege J. Fish. Aqua. Sci.* 2014, *31*, 61–68. https://doi.org/10.12714/egejfas.2014.31.2.02.

35. Düzbastılar, F.O.; Laleli, T.; Özgül, A.; Metin, G. Determining the severity of skin injuries of red mullet, Mullus barbatus (Actinopterygii: Perciformes: Mullidae), inflicted during escape from trawl codend. *Acta Ichthyol. Piscat.* 2015, *45*, 75–83.

36. Düzbastılar, F.O.; Aydın, C.; Gül, B. Mortality of non-target flatfishes escaping from demersal trawl codends. *J. Appl. Ichthyol.* 2016, *32*, 1194–1204. https://doi.org/10.1111/jai.13220.

37. Düzbastilar, F.O.; Breen, M.; Aydin, C.; Özbilgin, H.; Özgül, A.; Ulaş, A.; Metin, G.; Gül, B.; Lök, A. Seasonal variation in mortality of red mullet (*Mullus barbatus*) escaping from codends of three different sizes in the Aegean Sea. *Sci. Mar.* 2017, *81*, 339–349. https://doi.org/10.3989/scimar.04600.19A.

38. Düzbastılar, O.; Lök, A.; Ulaş, A. Mortality of Common pandora (*Pagellus erythrinus* Linnaeus, 1758) escaping from demersal trawl codends: Water temperature effect. *Ege J. Fish. Aqua. Sci.* 2018, *35*, 181–188. https://doi.org/10.12714/egejfas.2018.35.2.11.

39. Di Lorenzo, M.; Sinerchia, M.; Colloca, F. The north sector of the Strait of Sicily: A priority area for conservation in the Mediterranean Sea. *Hydrobiologia* 2018, *821*, 235–253. https://doi.org/10.1007/s10750-017-3389-7.

40. Jarboui, O.; Ceriola, L.; Fiorentino, F. Current fisheries management in the Strait of Sicily and progress towards an ecosystem approach. In *Transition towards an Ecosystem Approach to Fisheries in the Mediterranean Sea—Lessons Learned through Selected Case Studies*; Vasconcellos, M., Ünal, V., Eds; FAO Fisheries and Aquaculture Technical Paper: Rome, FAO, 2022; Volume 681, pp. 147–162.

41. Milisenda, G.; Vitale, S.; Massi, D.; Enea, M.; Gancitano, V.; Giusto, G.B.; Badalucco, C.; Gristina, M.; Garofalo, G.; Fiorentino, F. Spatio-temporal composition of discard associated with the deep water rose shrimp fisheries (*Parapenaeus longirostris*, Lucas 1846) in the south-central Mediterranean Sea. *Med. Mar. Sci.* 2017, *18*, 53–63.

42. Geraci, M.L.; Colloca, F.; Di Maio, F.; Falsone, F.; Fiorentino, F.; Sardo, G.; Scannella, D.; Gancitano, V.; Vitale, S. How is artificial lighting affecting the catches in deep water rose shrimp trawl fishery of the Central Mediterranean Sea? *Ocean Coast. Manag.* 2021, *215*, 105970. https://doi.org/10.1016/j.ocecoaman.2021.105970.

43. Pinello, D.; Gee, J.; Accadia, P.; Sabatella, E.C.; Vitale, S.; Polymeros, K.; Fiorentino, F. Efficiency of shallow- and deep-watertrawling in the Mediterranean and its implications for discard reduction. *Sci. Mar.* 2018, *82*, 97.

44. Falsone, F.; Gancitano, V.; Geraci, M.L.; Sardo, G.; Scannella, D.; Serena, F.; Vitale, S.; Fiorentino, F. Assessing the stock dynamics of Elasmobranchii off the southern coast of Sicily by using trawl survey data. *Fishes* 2022, *7*, 136. https://doi.org/10.3390/fishes7030136.

45. Di Maio, F.; Geraci, M.L.; Scannella, D.; Russo, T.; Fiorentino, F. Evaluation of the Economic Performance of Coastal Trawling off the Southern Coast of Sicily (Central Mediterranean Sea). *Sustainability* 2022, *14*, 4743. https://doi.org/10.3390/su14084743.

46. Breen, M.; Huse, I.; Ingolfsson, I.; Madsen, N.; Soldal, A.V. *SURVIVAL: An Assessment of Mortality in Fish Escaping from Trawl Codends and Its Use in Fisheries Management*; EU Final Report. [s.n.]; 2007; 300p.

47. Sardo, G.; Okpala, C.O.R.; Geraci, M.L.; Vitale, S. The effects of different artificial light wavelengths on some behavioural features of juvenile pelagic Atlantic horse mackerel, *Trachurus trachurus* (Actinopterygii: Perciformes: Carangidae). *Acta Ichthyol. Piscat.* 2020, *50*, 85–92. https://doi.org/10.3750/AIEP/02709.

48. Rueden, C.T., Schindelin, J., Hiner, M.C., DeZonia, B.E., Walter, A.E., Arena, E.T., Eliceiri, K.W. (2017). ImageJ2: ImageJ for the next generation of scientific image data. *BMC Bioinform.* 2017, *18*, 529. https://doi.org/10.1186/s12859-017-1934-z.

49. R Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, 2020. Available online: https://www.R-project.org/ (accessed on 20 August 2022).

50. Wilson, E.B. Probable inference, the law of succession, and statistical inference. *J. Am. Stat. Assoc.* 1927, *22*, 209–212. https://doi.org/10.1080/01621459.1927.10502953.

51. Dorai-Raj, S. Binomial Confidence Intervals for Several Parameterizations. 2014. Available online: https://CRAN.R-project.org/package=binom (accessed on).

52. Breen, M.; Catchpole, T. *ICES Guidelines for Estimating Discard Survival*; Breen, M., Catchpole, T., Eds.; ICES Cooperative Research Reports; 2021; 351, p. 219. https://doi.org/10.17895/ices.pub.8006.

53. Kassambara, A.; Kosinski, M.; Biecek, P.; Scheipl, F. Drawing Survival Curves using 'ggplot2. 2021. Available online: https://rpkgs.datanovia.com/survminer/index.html (accessed on 20 August 2022).

54. Therneau, T. A Package for Survival Analysis in R. R Package Version 3.4-0. 2022. Available online: https://cran.r-project.org/package=survival (accessed on 20 August 2022).

55. McCullagh, P.; Nelder, J. *Generalized Linear Models*, 2nd Ed.; Chapman and Hall/CRC: London, UK, 1999.

56. Brooks, M.E.; Kristensen, K.; Benthem, K.J.; Magnusson, A.; Berg, C.W.; Nielsen, A.; Skaug, H.J.; Mächler, M.; Bolker, B.M. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *R J.* 2017, *9*, 378–400.

57. Smithson, M.; Verkuilen, J. A better lemon squeezer? Maximum-likelihood regression with beta-distributed dependent variables. *Psychol. Methods* 2006, *11*, 54–71.

58. Hartig, F.; Lohse, L. *DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models*; 2022.

59. Zuur, A.; Ieno, E.N.; Walker, N.; Saveliev, A.A.; Smith, G.M. *Mixed Effects Models and Extensions in Ecology with R*; Springer: New York, NY, USA, 2009.

60. Wickham, H.; Chang, W.; Wickham, M.H. *Package 'ggplot2'. Create Elegant Data Visualisations Using the Grammar of Graphics*; 2016, Volume 2, pp. 1–189.

61. Wang, W.; Yan, J. Shape-Restricted Regression Splines with R Package splines2. *J. Data Sci*. 2021, *19*, 498–517. https://doi.org/10.6339/21-JDS1020.

62. Sangster, G.I.; Lehmann, K.; Breen, M. Commercial fishing experiments to assess the survival of haddock and whiting after escape from four sizes of diamond mesh cod-ends. *Fish. Res*. 1996, *25*, 323–345.

63. Wileman, D.A.; Sangster, G.I.; Breen, M.; Ulmestrand, M.; Soldal, A.V.; Harris, R.R. *Roundfish and Nephrops Survival after Escape from Commercial Fishing Gear*; EU Contract Final Report. EC Contract No: FAIR-CT95-0753; European Commission: Brussels, Belgium, 1999.

64. Papaconstantinou, C.; Farrugio, H. Fisheries in the Mediterranean. *Med. Mar. Sci*. 2000, *1*, 5–18. https://doi.org/10.12681/mms.2.

65. Tserpes, G.; Massuti, E.; Fiorentino, F.; Facchini, M.T.; Viva, C.; Jadaud, A.; Joksimovic, A.; Pesci, P.; Piccinetti, C.; Sion, L.; et al. Distribution and spatio-temporal biomass trends of red mullets across the Mediterranean. *Sci. Mar*. 2019, 83S1, 43-55. https://doi.org/10.3989/scimar.04888.21A.

66. ICES. *Report of the Study Group on Unaccounted Fishing Mortality*; ICES CM 2004/B:09; ICES: Copenhagen, Denmark, 2004.

67. ICES. *Joint Report of the Study Group on Unaccounted Fishing Mortality (SGUFM) and the Workshop on Unaccounted Fishing Mortality (WKUFM)*; ICES CM 2005/B:08; ICES: Copenhagen, Denmark, 2005.

68. Soldal, A.V.; Engås, A. Survival of young gadoids excluded from a shrimp trawl by a rigid deflecting grid. *ICES J. Mar. Sci.* 1997, *54*, 117–124.

69. Ingólfsson, Ó.A.; Soldal, A.V.; Huse, I.; Breen, M. Escape mortality of cod, saithe, and haddock in a Barents Sea trawl fishery. *ICES J. Mar. Sci.* 2007, *64*, 1836–1844.

70. Breen, M.; Sangster, G.I.; Soldal, A.V. *Evidence of Cover Induced Mortality in Fish Survival Experiments—A Cautionary Note*; ICES CM 1998/Open: 2; ICES: Copenhagen, Denmark, 1998.

71. Breen, M.; Sangster, G.; O'Neill, B.; Kynoch, R.; Jones, E.; Soldal, A.V. *Evidence of Sampling Induced Biases in Mortality Estimates from Experiments Investigating Mortality in Fish Escaping from Towed Fishing Gears*; ICES CM 2002/V:25; ICES: Copenhagen, Denmark, 2002.

72. Breen, M. Investigating the mortality of fish escaping from towed fishing gears—A critical analysis. Ph.D. Thesis, University of Aberdeen, Aberdeen, UK, 2004; 313p.

Paper 4: Unaccounted mortality

Discard survival of Atlantic horse mackerel (*Trachurus trachurus* Linnaeus 1758) caught during crustacean trawl fisheries

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In preparation

Abstract

Crustacean trawl fisheries, at least, in the central Mediterranean is the most important fishing techniques in terms of revenue and employment, despite its impacts on the ecosystems. Indeed, large amounts of unwanted species are caught and discarded for various reasons. In this context, the European community introduced the so-called Landing Obligation, LO, (Reg. EC 1380/2013) which banned the discarding of regulated species. However, where it can be demonstrated that a species has an acceptably high likelihood of survival when rejected at the sea (discard survival), exemptions to this ban may be granted. In this study, the probability of survival of the *Trachurus trachurus* (Linnaeus, 1758) was estimated by combining vitality assessment on board and captive observation, i.e. in an aquarium facility. The probability of survival was estimated through the Kaplan-Meier model using the time to dead. In addition, the Weibull model was applied to identify important covariates determining the susceptibility of *T. trachurus*. Overall, results showed that after a commercial fishing operation the probability of *T. trachurus* surviving is very low. The most important factor in affecting the probability of survival resulted to be delta T, depth, and haul duration even if also condition factor, air exposure, season, injuries affected significantly the probability of survive of the Atlantic horse mackerel. In conclusion, according to the LO, all the juveniles of the species should be landed.

Key-words: Landing obligation, unwanted by-catch, survival analysis, survival rates, Weibull regression model, Kaplan Meier model, Strait of Sicily

Introduction

Fishing activity is one of the most important human stressors for marine ecosystems leading to generalized overfishing of most of the stocks (Murawsky, 2000; Colloca et al., 2017). In particular, the bottom otter trawl is the most impactful technique producing the highest amount of organisms rejected at the sea (the so-called discard) (Perez-Roda et al., 2019) because of economic or legal issues. In this context, the European Union introduced Regulation 1380/2013/UE (which came into force in 2019) a phased discard ban or Landing Obligation (LO) for regulated species, as part of the

Common Fisheries Policy (CFP) Basic Regulation (Article 15), to try to reduce the current high levels of discard as they represent: (i) a waste of natural resources in the sense that fish are caught and killed for no apparent benefit or; (ii) that removing these fish without utilization represents a waste in terms of future reproductive potential thereby negatively impacting on stock sustainability; (iii) a waste in the context of foregone future yield thereby negatively impact on the financial viability of fisheries sector and (iv) waste in terms of costs associated with onboard catch sorting. However, the LO policy includes a high survival exemption for "species for which scientific evidence demonstrates high survival rates, taking into account the characteristics of the gear, of the fishing practices and of the ecosystem" (Article 14, paragraph 4b). Research aimed at determining whether aquatic organisms survive after being caught and subsequently released has been conducted over the last decades. While no threshold has been defined for a "high survival rate", exemptions will be allowed for species and fisheries where survival levels are assessed to be sufficiently high. In this context, there has been a recent enhanced focus on the estimation of discards survival and the identification of stressors involved in discard mortality in European marine fisheries (e.g. Breen et al., 2012; Depestele et al., 2014; Barragán-Méndez et al., 2020; Masnadi et al., 2020; Falco et al., 2022). In particular, the impacts of fishing on the marine biota occur during three main phases: (i) capture, e.g. gear type, active/passive gear encounter, duration of the fishing, temperature, salinity, depth, size and condition of the fish; (ii) handling on board, e.g. hauling/towing speed, crew experience, air exposure, air temperature, catch composition; (iii) release, e.g. release devices such as chutes, recovery boxes, live wells, halo- thermoclines, habitat, predation, and displacement (Breen and Catchpole, 2021). Approaches that evaluate fish vitality, such as semi-quantitative assessment (SQA) or quantitative vitality assessment, can be used as survival proxies (e.g. Benoıt et al., 2010; ICES, 2014) but do not yield actual survival rates. In isolation, captive observation allows obtaining survival rate estimations that exclude predation (Schram and Molenaar, 2018), whereas the addition of tagging information can provide an estimation that includes post-release predation and natural mortality for particular conditions (Benoıt et al., 2020). A proxy to estimate survival in a representative range of conditions (management unit/fishery) can be generated only by combining vitality assessment and captive observation and/or tagging techniques. When the relationship between vitality levels and survival estimates has been determined, the vitality assessment made on board can be complemented with models using the determined relationships to infer survival (Catchpole et al., 2015). In the present study, the discard survival of undersized Atlantic horse mackerel *Trachurus trachurus* (Linnaeus, 1758) was assessed for the first time in the Strait of Sicily (south-central Mediterranean) after bottom trawl crustacean fishing operations coupling on board vitality assessment and monitoring in an aquarium facility. The species, *T. trachurus*, was chosen because: (i) it represents the most abundant unwanted by-catch (according to the definition of ICES, 2020) in the crustacean trawl fisheries of the study area (Milisenda et al., 2017; Geraci et al., 2021a), and (ii) it is frequently caught all over the year in discrete quantities.

Material and Methods

Study area

The study area was located on the Italian side of the Strait of Sicily. The Strait of Sicily is an important transitional area in the central Mediterranean Sea, separating the eastern and the western basins (Figure 1).

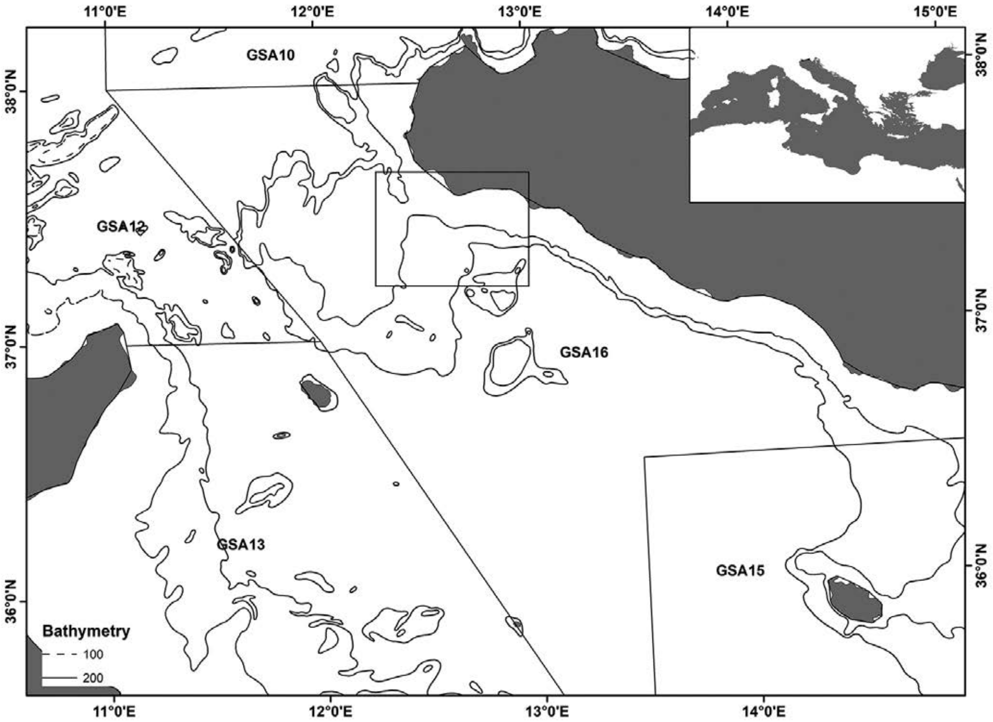

Figure 1 The study area is highlighted with a black square box (Maps from Vitale et al., 2018a,b)

In particular, is defined as the entire marine area which separates Italy, Malta, and Tunisia, and which extends to the western coast of Libya. The European and the African continental shelves are separated by deep water in the middle part of the Strait of Sicily. The shelf is wider off the south coast of Tunisia than it is off Sicily. In its narrowest part, between Cap Feto (Italy) and Cap Bon (Tunisia), the Strait of Sicily is 145 km wide. In oceanographic terms, the Strait of Sicily is characterized by the cold and less salty Atlantic waters coming from the western side of the Mediterranean, and the Levantine Intermediate Waters (warmer and saltier) coming from the east. The Atlantic waters entering the Strait of Sicily area originate in two streams, the Atlantic Tunisian Current in the south and Atlantic

Ionian Stream in the north. These two streams respectively generate upwelling and downwelling along the Sicilian and Tunisian coasts. The Atlantic Ionian Stream also generates two main gyres or vortexes, namely the Adventure Bank Vortex and the Ionian Shelf Break Vortex. These oceanographic features contribute to making the Strait of Sicily one of the most productive areas for demersal fishing in the Mediterranean, exploited mainly by trawl fisheries (Jarboui et al., 2022). In particular, the trawling fleet exploits the deeper fishing ground, targeting deep-water crustaceans such as *Aristaeomorpha foliacea* (Risso, 1827), *Aristaeus antennatus* (Risso, 1816), *Parapenaeus longirostris* (Lucas, 1846), and *Nephrops norvegicus* (Linnaeus, 1758) (Milisenda et al., 2017*;* Geraci et al., 2021) as well as the shallow fishing ground, targeting mainly *Mullus barbatus* (Linnaeus, 1758), *Mullus surmuletus* (Linnaeus, 1758), sparids and cephalopods (Pinello et al., 2018; Falsone et al., 2022; Di Maio et al., 2022).

Sampling at the sea

The sampling at the sea was carried out from November 2021 to October 2022. Professional bottom trawlers belonging to the Mazara del Vallo harbor were employed to collect samples. Before starting the experiment, the fishers were informed about the aims and sampling procedures to evaluate the immediate discard survival on board. In addition, a scientific observer was employed to assess the horse mackerel survival rates once hauled on board. The trips were conducted under normal fishing operations: the mean duration of the tows was 132 (range: 90–195 min), the mean towing speed was 3.1 knots, the codend mesh size was 40 mm square (see Geraci et al., under review for a more detailed description of the gear), the mean fishing depth was about 117 m, and the mean water temperature at the bottom was 15.16 ºC. The operating conditions were exactly the same as the commercial one and per each haul were recorded: (i) vessel position, (ii) towing speed and duration, (iii) air temperature (onboard instrumentation), (iv) temperature profile over the water column, i.e. from bottom to surface through, StarOddi Minilog; Garðabær, Iceland and HOBO TidbiT MX Temperature 5000', probes, (v) the time elapsed since the last trawl catch was unloaded on deck (air exposure; minutes), (vi) and total catch. In particular, the total catch per haul was photographed for the subsequent analysis, and also estimated onboard and categorized into three classes (low, medium, and high). A maximum number of 30 undersized individuals (specimens below the MCRS, 15 cm total length) per haul were sampled throughout catch sorting, at the time when the fishermen would have had the opportunity to reject them. Then, individuals were placed in a tank on board and their vitality was assessed after 10 s by a simplified version of the Benoit et al. (2010) protocol (Table 1). Moreover, to obtain air exposure the exact time between the opening of the cod-end on deck and the placement of the specimens into the tank was recorded. The water inside the tank was changed continuously thanks to a pump which generated a water flow.

Table 1: Description of the codes used to score the vitality of captured fishes during commercial fishing trips in the Strait of Sicily

Vitality	Code	Description
Excellent	1	Vigorous body movement; no or minor external injuries only
Good	2	Weak body movement; responds to touching/prodding; minor external injuries
Poor	3	No body movement but fish can move operculum; minor or major external injuries;

After Vitality Assessment (herein VA) on board, live specimens were immediately released. In particular, the VA was carried out, at least, twice a week each month when the weather condition allows it.

Monitoring of fish in laboratory

During the last haul of each fishing trip, a subset of a maximum of 30 individuals was retained for captive observation. Once landed at the harbor, fishes were assessed for VA, placed in tanks with oxygenators, transported to the CNR of Mazara del Vallo by means of a refrigerated van, placed in an aquarium, and assessed again for VA. Individuals were housed separately in three compartments according to their vitality score. According to Breen and Catchpole (2021) the most vital individuals were classified with a vitality score of 1 and used as pseudo-control. In particular, samples were kept in a rectangular fiberglass aquarium tank (Juwel AquariumGmbH, Rotenburg, Deutschland) of 450 L (length × width× height: 1.51 × 0.51 × 0.66 m) filled with seawater, replaced with approximately 25% of its volume after each batch of fishes. Water quality was maintained using a submersible Bioflow Filter (Juwel Aquarium GmbH, filtering 1000/h) plus an external filter 500 (Sicce Whale Canister 500, filtering 1300 l/h), an internal Blueskimmer 550 (Ferplast Spa, Castelgomberto, Italy), a heater (AquaHeat 300) in winter and a cooler (Teco, Italy; mod. TK2000) in spring-summer. The temperature was maintained the same as at the bottom where they are caught (about 15.2 °C). Water quality was monitored two times a day by measuring nitrates, nitrites, phosphates, and dissolved oxygen through water tests (Pro JBL Aquatest, GmbH & Co.KG, Germany). Fish were assessed three times a day visually for their vitality and were monitored continuously through an external video camera (Hikvision, model DS-2CD2H85FWD-IZS). The collection of juvenile specimens for discard survival assessment was carried out with specific permission from the Italian Ministry of Health - Directorate General for Animal Health and Veterinary Drugs (authorization n. 0016666-12/07/2021-DGSAF-MDS-P). Euthanasia was performed with anesthetic overdose and all efforts were made to minimize animals' suffering.

Monitoring of fish in the natural environment

To check if a negative effect of captivity monitoring in the aquarium, three times a sub-sample of fish was brought to the entrance of a small marina located in Mazara del Vallo and placed in a trap at a 5-meter depth, and the same parameters of the aquarium were checked for water quality. The fish were monitored three times a day using a GoPro Hero4 Black video camera (GoPro GmbH, München, Deutschland) attached to a stick long enough to view them without bringing the trap to the surface.

Laboratory analysis

Only dead individuals, either from the aquarium or from the marina, were analyzed for total length - TL (to the nearest 0.5 cm), total weight (0.01 g), eviscerated weight (0.01 g), liver weight (0.01 g), sex, and maturity stage, according to the maturity scale proposed by Anon. 2017. In addition, the presence of injuries (if any) was recorded as well.

Survival analysis

The probability of the Atlantic horse mackerel survival over the hours was estimated through a seasonal non-parametric Kaplan-Meier function. This function does not make any assumption about the distribution of the response variable but if censoring data is removed the model will get biased at the time of fitting. However, given that all individuals died before the monitoring period and the exact moment of the event was known the data were analyzed as uncensored. Differences over the seasons were assessed through the Log-Rank test. To identify important covariates determining the susceptibility of *T. trachurus*, the parametric Weibull model was applied contrasting the time to dead (response variable) *vs* VA on board and in the laboratory as well as the other variables collected.

In the Weibull model, the distribution of time to dead, TTD, as a function of a single covariate is written as (1):

$$In(TTD) = \beta_0 + \beta_1 x + \sigma\varepsilon \qquad [1]$$

Where β_1 is the coefficient for corresponding covariate, ε follows extreme minimum value distribution G(0, σ) and σ is the shape parameter. This is also called the accelerated failure-time model because the effect of the covariate is multiplicative on a time scale and it is said to "accelerate" survival time. The accelerated failure-time form of the hazard function can be written as:

$$h(t, x, \beta, \lambda) = \lambda t^{\lambda-1} e^{-\lambda(\beta 0+\beta 1x)} = \lambda\gamma(te^{-\beta 1x})^{\lambda-1} e-^{\beta 1x} \qquad [2]$$

Weibull regression model can be written also as proportional forms, allowing for the simultaneous description of treatment effect in terms of hazard ratio (HR) and relative change in survival time, i.e. Event time Ratio (ETR) (Zhang, 2016). Firstly, the variables were checked for correlation through Spearman test. Secondly, the full model here applied was constructed starting from vitality score, delta T (calculated as the difference between the temperature in the air and at the bottom), season, presence of injuries, air exposure, haul duration, depth, catch weight, TL, liver weight, condition factor calculated as [total weight/(TL)$^{\wedge 3}$]*100 (as calculated by Geraci et al., 2018). Then, the variables to be included for the Weibull distribution model were selected according to the p-value and χ^2 after running an Analysis of Variance (ANOVA).

All the analyses were carried out through R studio (version 3.6.3) using *survminer* (Kassambara et al., 2021), *GGally* (Schloerke et al., 2022), *SurvRegCensCov* (Hubeaux and Rufibachand, 2022), *eha* (Broström and Jin, 2022), *rms* (Harrell, 2022), and *survival* (Therneau, 2022) packages. Lastly, the relation between TL and time to dead was explored graphically by fitting a curve from a Generalised Linear Model (GLM) predictions.

Results

A total of 29 daily fishing trips (in average 4 haul per trip) with 115 hauls were taken into account to estimate the discard survival of the Atlantic horse mackerel. The overall number of fishes assessed for VA on board was 1707 and within this those retained for monitoring in the laboratory were 422. A total number of 105 individuals were seriously injured with a total percentage of about 25% (Figure 2).

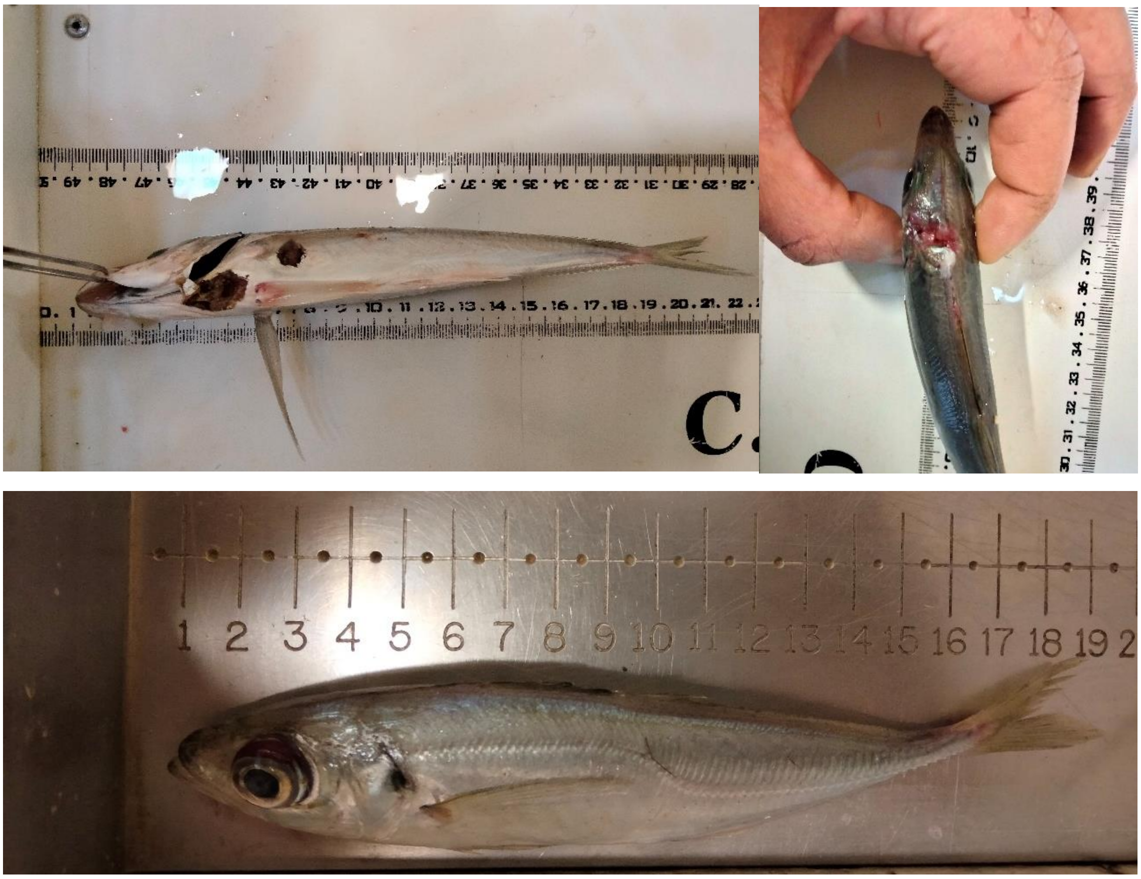

Figure 2: Individuals of Atlantic horse mackerel with injuries (A) in the abdominal zone, (B) head, (C) eye.

In particular, a Kaplan-Meier model was applied by season, showing that significant differences were detected among seasons. In winter *T. trachurus* juveniles were more resistant having more probability to survive whereas in summer with the increase in the temperature the probability of survival was the lowest and more abrupt than in the other seasons (Figure 3).

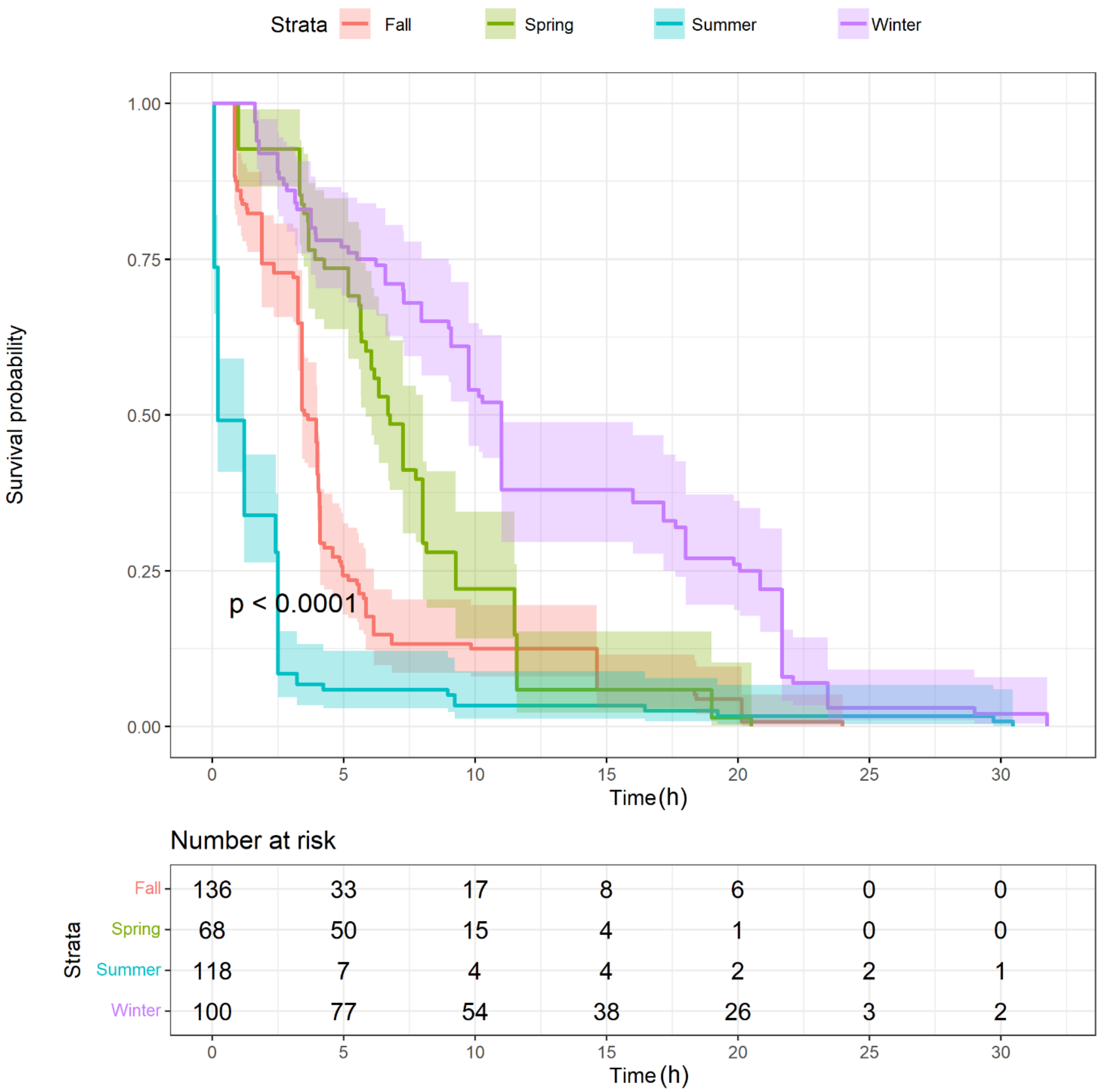

Figure 3: Atlantic horse mackerel seasonal survival probability estimated by Kaplan-Meier model. The ribbon areas represent the 95% confidence interval

From the number at risk table, it seems clear that most of the specimens died within the first 5 hours after being hauled on deck; this trend seems less pronounced in the winter season than in the other ones (Figure 3). The significant variables included in final model were: condition factor, air exposure, season, injuries, haul duration, depth, and delta T. The most important factor in affecting the probability of survival resulted to be delta T, depth, and haul duration (Figure 4).

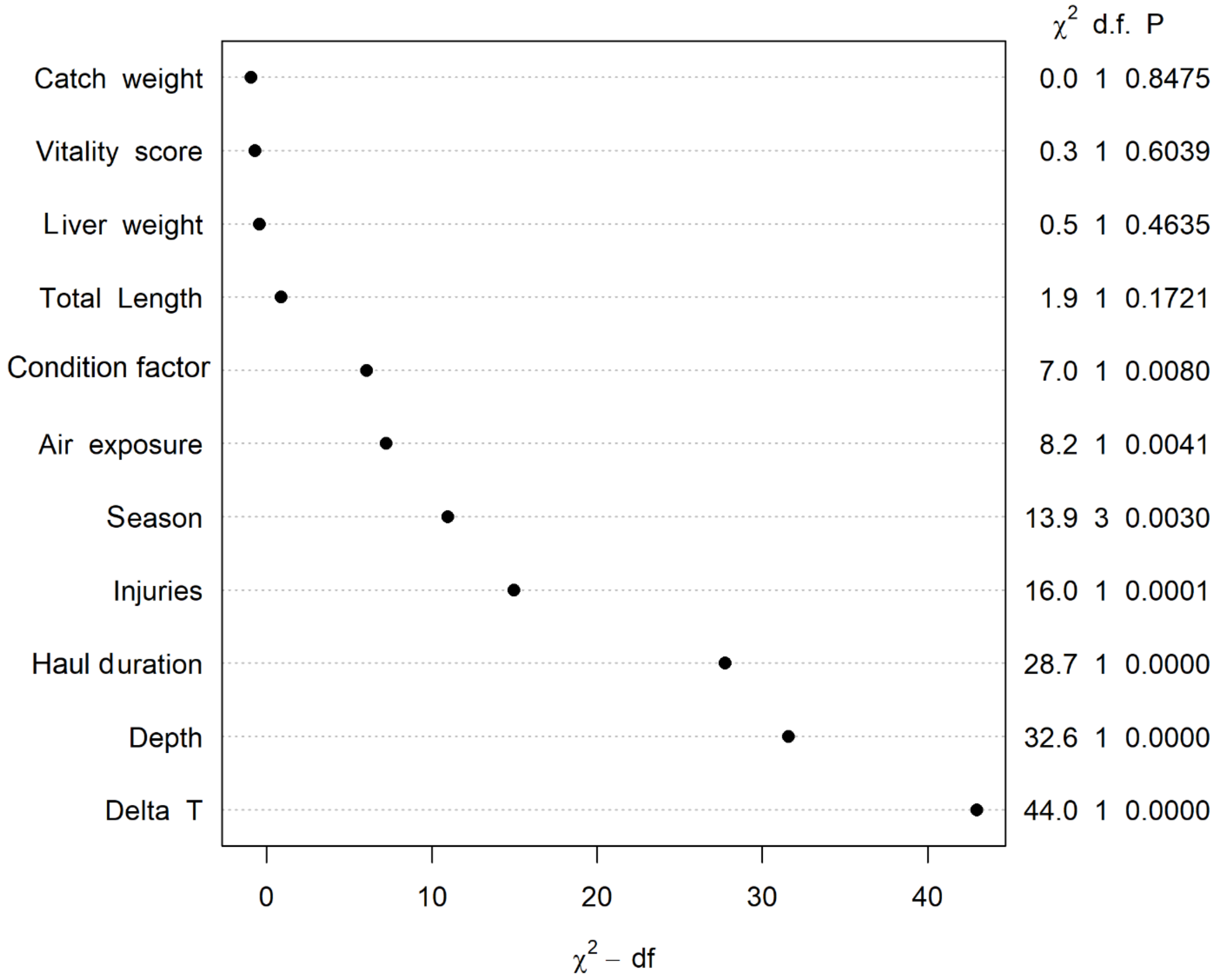

Figure 4 Plot showing the importance of each variable in explaining the probability of survival

The parameters and the estimation of each variable included in the final model are showed in Table 2.

Table 2 Scale (lambda), shape (gamma) parameters, including the estimates of the variable and their associated standard error

Variables and parameter	**Estimate**	**Standard Error**
Lambda	58.035	57.066
Gamma	1.00433836	0.036
InjuriesN	-0.556	0.135
InjuriesY	0.000	0.000
Depth	-0.015	0.003
Duration	-0.026	0.005
Delta T	0.238	0.036
seasonSpring	0.759	0.244
seasonSummer	0.310	0.368
seasonWinter	0.441	0.243
Air exposure	0.104	0.04
Condition factor	-3.219	1.16

The HR showed, for example, as Delta T increases the risk of death of *T. trachurus* by about 27% while the absence of injuries reduced the risk of death by 63% compared to the injured individuals.

Table 3 Hazard ratio (HR) of each variable and their associated 95% confidence interval

Variables	**HR**	**95% CI**
InjuriesN	0.574	0.440-0.747
InjuriesY	1.000	0.990-1.120
Depth	0.98	0.979-0.990
Duration	0.974	0.964-0.984
Delta T	1.269	1.183-1.362
seasonSpring	2.136	1.325-3.443
seasonSummer	1.363	0.662-2.805
seasonWinter	1.554	0.965-2.500
Air exposure	1.110	1.024-1.203
Condition factor	0.040	0.004-0.389

The ETR showed, for example, as delta T and air exposure significantly reduced the survival time by approximately 21% and 10% whereas the absence of injuries increased the survival time by 74% (Table 4).

Table 4 Event time ratio (ETR) of each variable and their associated 95% confidence interval

Variables	ETR	95% CI
InjuriesN	1.739	1.340-2.258
InjuriesY	1.000	0.980-1.120
Depth	1.015	1.010-1.021
Duration	1.027	1.016-1.037
Delta T	0.789	0.736- 0.845
seasonSpring	0.470	0.292-0.756
seasonSummer	0.735	0.357-1.51
seasonWinter	0.645	0.401-1.037
Air exposure	0.901	0.832-0.977
Condition factor	2.465	2.202-2.657

Discussion

The present study has shown that the survival probability of undersized Atlantic horse mackerel, after being hoisted on board following a demersal trawling haul, is very low. The plausible captivity stress hypothesis was negated by the fact that (i) other species such as *Conger conger*, crustacean (*Parapeaneus longirostris*, *Squilla mantis*) survived more than 10 days in the same aquarium and they were released still alive; the sub-sampled individuals brought to the marina died after the first day; (iii) previously in the same aquarium 13 juvenile individuals of the same species were kept successfully (Sardo et al., 2020). Indeed, after a period of acclimatization of 20 days without any dead individuals (Okpala et al., 2017) and a subsequent 10 days' experiment, testing the effect of different wavelengths, the Atlantic horse mackerel were released into the sea still alive. The differences in the survival rates probably are due to the different sampling methodology, indeed the individuals monitored by Sardo et al. (2020) were sampled during the International bottom trawl survey in the Mediterranean (MEDITS) at 47 m depth in a haul lasting 30′. The MEDITS trawl survey protocol foresees the haul durations were 30′ and 60′ at stations between 10 and 200 m (shelf) and 201–800 m (slope) respectively (e.g. Garofalo et al., 2020; Falsone et al., 2021; Falsone et al., 2022b; Geraci et al., 2021b, c) whereas the crustacean trawl fisheries targeting DPS mainly operates over the shelf (between 100 and 200 m depth) and the haul duration is typically 150′-180′. In addition, the catch weight between a survey and a commercial fishing operation is quite different being the commercial catches higher than a survey. Lastly, given that during the survey fishes were placed immediately in the tank after their arrival on deck whereas during the sampling of the present study the fishes were placed in the tank when possible by simulating the sorting usually done by fishers during fishing operation; therefore, the air exposure may have affected the survival rates of the Atlantic horse mackerel. To further confirm this, the most important factor in affecting the survival rates of the

Atlantic horse mackerel were delta T, depth, and haul duration but also air exposure, season, and the presence of injuries affected significantly its survival rates. Similarly, to the present study, in the rapido trawl fisheries of the Adriatic Sea the most important factor in explaining survival rates of *Solea solea* resulted to be delta T, air exposure, and haul duration (Masnadi et al., 2020). In the Mediterranean, this is the first attempt to estimate the discard survival of the Atlantic horse mackerel during bottom trawl crustacean fisheries therefore no comparison with other studies is available. A preliminary study was carried out in Algarve (southern Portugal) during crustacean trawl fisheries but due to the small number of samples, some species such as the mackerel and monkfish were assessed as combined (Adão et al., 2018). The low survival rates of mackerel were confirmed also in Algarve being the spotted dogfish and conger eel the only species that survived at the end of the monitoring period (65-h). Indeed, the 50% of probability dead was in most cases/species, including mackerels, less than 20 min (Adão et al., 2018). In Algarve crustacean fisheries the mackerels conserved their scales but had bruises on the pectoral fins whereas in the present study many individuals were seriously injured. Similarly, in this study, they applied a Weibull model relating vitality score with time to dead, fish size, and biological traits (i.e. deciduous scales loss, injuries, presence and type of gas bladder, and metabolic rates) and found that time to mortality was positively correlated with vitality score 3 and 4 whereas injuries had no effect on mortality but deciduous scale loss and closed gas bladder accelerated time to mortality. It must be said that most of the individuals included in the analysis were injured (367) than uninjured (40).

In conclusion, the survival rates of *T. trachurus* subjected to a commercial trawl fishing operation were very low, and even if it would seem that when they arrive on deck are vital and displayed intense activity these signs could be an extreme stress response (Adão et al., 2018). For a more in-depth understanding of the stress experienced by the fishes during fishing operations physiological analysis such as cortisol, glucose, and ions (Na^+, Cl^- and K^+) from blood would be desirable (e.g. Marçalo et al. 2008; Falco et al., 2022). Given the multi-specific characteristic of the bottom trawl fisheries and the amount of unwanted by-catch species caught, other species/*taxa* should be evaluated for discard survival (Scannella et al., 2022) or escape survival (Geraci et al., in preparation). The survival rates of the Atlantic horse mackerel shown in the present study suggested that, according to Reg. EU 1380/2013, all the juvenile specimens should be landed and therefore the adoption of a more selective trawl net in the next future will be of paramount importance to try to ensure the long-term sustainability of this fisheries (Geraci et al., under review).

References

Barragán-Méndez, C., González-Duarte, M. M., Sobrino, I., Vila, Y., Mancera, J. M., Ruiz-Jarabo, I. (2020). Physiological recovery after bottom trawling as a method to manage discards: The case study of *Nephrops norvegicus* and *Squilla mantis*. Marine Policy, 116, 103895.

Benoıt, H. P., Hurlbut, T., and Chasse´, J. (2010). Assessing the factors influencing discard mortality of demersal fishes using a semi-quantitative indicator of survival potential. Fisheries Research, 106: 436–447

Benoıt, H. P., Morfin, M., and Capizzano, C. W. (2020). Improved estimation of discard mortality rates with in situ experiments involving electronic and traditional tagging. Fisheries Research, 221: 105398

Breen, M., Isaksen, B., Ona, E., Pedersen, A.O., Pedersen, G., Saltskår, J., Svardal, B., Tenningen, M., Thomas, P.J., Totland, B. (2012). A review of possible mitigation measures for reducing mortality caused by slipping from purse-seine fisheries. ICES CM 100, 12.

Breen, M. and Catchpole, T. (Eds.). (2021). ICES guidelines for estimating discard survival. ICES Cooperative Research Reports No. 351. 219 pp. https://doi.org/10.17895/ices.pub.8006

Brooks ME, Kristensen K, van Benthem KJ, Magnusson A, Berg CW, Nielsen A, Skaug HJ, Maechler M, Bolker BM (2017). glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. *The R Journal*, **9**(2), 378–400. https://journal.r-project.org/archive/2017/RJ-2017-066/index.html.

Broström, G., Jin, J. (2022). Package 'eha'. http://ehar.se/r/eha/

Catchpole, T. L., Randall, P., Forster, R., Santos, A. R., Armstrong, F., Bendall, V., Maxwell, D. (2015). Estimating the discard survival rates of selected commercial fish species (plaice—*Pleuronectes platessa*) in four English fisheries. CEFAS Report 108.

Colloca, F., Scarcella, G., Libralato, S. (2017). Recent trends and impacts of fisheries exploitation on Mediterranean stocks and ecosystems. Frontiers in Marine Science, 4, 244.

Depestele, J., Desender, M., Benoît, H.P., Polet, H., Vincx, M. (2014). Short-term survival of discarded target fish and non-target invertebrate species in the "eurocutter" beam trawl fishery of the southern North Sea. Fish. Res. 154, 82–92. https://doi.org/10.1016/j.fishres.2014.01.018

Geraci, M.L., Colloca, F., Falsone, F., Fiorentino, F., Gancitano, V., Sardo, G., et al. (2021). How is artificial lighting affecting the catches in deep water rose shrimp trawl fishery of the Central Mediterranean Sea? Ocean & Coastal Management. 215: 105970. https://doi.org/10.1016/j.ocecoaman.2021.105970

Harrell, F.E. Jr. (2022). Regression Modeling Strategies. https://hbiostat.org/R/rms/, https://github.com/harrelfe/rms

Hubeaux, S., & Rufibach, K. (2022). coef. src 5. Package ‘SurvRegCensCov’, 5.

ICES. 2014. Report of the Workshop on Methods for Estimating Discard Survival (WKMEDS). ICES HQ, Copenhagen, Denmark. ICES CM 2014/ACOM: 51. 114 pp.

Kassambara A, Kosinski M, Biecek P, Scheipl F. (2021). Drawing Survival Curves using 'ggplot2. https://rpkgs.datanovia.com/survminer/index.html

Masnadi, F., Armelloni, E. N., Guicciardi, S., Pellini, G., Raicevich, S., Mazzoldi, C., ... Scarcella, G. (2020). Relative survival scenarios: an application to undersized common sole (Solea solea L.) in a beam trawl fishery in the Mediterranean Sea. ICES Journal of Marine Science, 77(7-8), 2646-2655.

Milisenda, G., Vitale, S., Massi, D., Enea, M., Gancitano, V., Giusto, G.B., Badalucco, C., Gristina, M., Garofalo, G., Fiorentino, F., 2017. Discard composition associated with the deep water rose shrimp fisheries (Parapenaeus longirostris, Lucas 1846) in the south-central Mediterranean Sea. Mediterr. Mar. Sci. 18 (1), 53. https://doi.org/10.12681/mms.1787.

Murawski, S. A. (2000). Definitions of overfishing from an ecosystem perspective. ICES Journal of Marine Science, 57(3), 649-658.

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Roda, P., Gilman, E., Huntington, T., Kennelly, S. J., Suuronen, P., Chaloupka, M., Medley, P. (2019). Third assessment of global marine fisheries discards. FAO.

Schloerke B, Cook D, Larmarange J, Briatte F, Marbach M, Thoen E, Elberg A, Crowley J (2022). *GGally: Extension to 'ggplot2'*. https://ggobi.github.io/ggally/, https://github.com/ggobi/ggally.

Schram, E., and Molenaar, P. 2018. Discards Survival Probabilities of Flatfish and Rays in North Sea Pulse-Trawl Fisheries. 40 pp. https://library.wur.nl/WebQuery/wurpubs/538463.

Therneau T (2022). A Package for Survival Analysis in R. R package version 3.4-0, https://CRAN.R-project.org/package=survival.

Zhang, Z. (2016). Parametric regression model for survival data: Weibull regression model as an example. Annals of translational medicine, 4(24).

4. Discussion

The application of artificial light deep water crustacean fisheries confirmed the general positive effects on *P. longirostris* catch rates during the night reported by local fishers, who are increasingly using green and white artificial lights on the headrope of trawl nets. Moreover, the use of 20 LED lights mounted symmetrically to the centre of the head rope in the crustacean trawl net might have an important effect on the size selectivity of the trawl, particularly for legal-sized *P. longirostris* and undersized individuals of *M. merluccius* and *T. trachurus*. As the estimated annual costs of approximately 500 € are associated with the use/maintenance of light (Pinello et al., 2018) as well as the work for managing these lights on board, it is reasonable to suppose that the cost-benefit ratio should be positive. Traditionally, crustacean trawl fisheries are mainly carried out during the day owing to the higher catchability of the gear than the night. Indeed, during the daytime, *P. longirostris* stays on or relatively close to the bottom to avoid predators (Aguzzi et al., 2009); however, at night, they migrate from the seafloor to prey on water columns (Rodríguez-Climent et al., 2016). In the last few years, the use of artificial lights has enabled shrimp fishing activity during the night, abandoning the traditional alternation between deep-water trawling during the day, targeted to shrimp, and shallow-water trawling during the night, targeted to fish and cephalopods. Owing to such recent widespread use of artificial light in deep-water crustacean fisheries, a further evaluation of its impact on the catch is needed to avoid the fact that an increase in CPUE can lead to a depletion of the exploited stocks. Fishing fleets using artificial lights should be carefully considered because of their expected effect on improving the catchability of target and non-target species. In the well-known situation of high overexploitation of stocks in the Mediterranean (e.g., Colloca et al., 2017), including *P. longirostris* and *M. merluccius* in the Strait of Sicily (Falsone et al., 2021; Gancitano et al., 2021), lights and other technological tools may be increasingly used by fishers to “buffer” the reduction in the catch rate of traditional fishing gear. An expected consequence of the use of light in trawling could be an increase in fishing mortality that eliminates the reduction of the fishing effort implemented by the European CFP and contributes to a deterioration of the stocks status. To mitigate the problem a possible management measure can be either a limitation in the number of lights applied to the headrope or a limitation in terms of the number of fishing days using a trawl net rigged with artificial lights. Although more quantitative data should be gathered to generalise the results obtained, this study shows clear trade-offs between gains due to higher CPUE of commercial *P. longirostris* specimens and risks linked to higher unwanted by-catch of juveniles below the MCRS of *M. merluccius* and *T. trachurus*.

Given that for most aquatic vertebrates, vision is a key sensory input for day-to-day survival (Atema, 1980) the underlying physiological reasons for the differential reaction of different species (or biological stages within a species) to artificial light should be taken into account. Indeed, there are differences in the structure of eyes between fish, crustaceans (i.e., shrimp, crab, and horseshoe crab), and cephalopods (i.e., squid, cuttlefish, and octopus). Understanding these visual systems, especially for commercially important species, is a key step in the development of modern and sustainable fishing technologies and operations. A substantial number of studies have been conducted on aquatic vertebrate vision in the last few decades (see Yami, 1976; Detto, 2007; Arimoto et al., 2010; Land and Nilsson, 2012). Although the structure of the eye and the mechanisms of vision have been determined for many marine species, detailed knowledge and understanding of the role of vision in their reaction to fishing gears during capture processes are not well known (Arimoto et al., 2010).

The application of BRDs, such as the T90 50 mm codend and the Grid-T45 40 mm, in the deep water crustacean trawl fisheries of the Strait of Sicily showed an improvement of the exploitation pattern of both *P. longirostris* and *M. merluccius* reducing the number of undersized specimens of the two species. In particular, the Grid-T45 40 mm seems to be the technological solution that might be capitalized on commercial trawlers targeting *P. longirostris*. As a matter of fact, Grid-T45 40 mm provides higher LPUE and a significant reduction of undersized *P. longirostris* when compared to the other trawl net configurations. On the other hand, T90 50 mm codend, for the first time tested in the Strait of Sicily, strongly reduced the catch of both legal and undersized *P. longirostris*, not ensuring the economic sustainability of the *P. longirostris* fisheries. Regarding *M. merluccius*, the most efficient gear turned out to be the T90 50 mm codend. It is worth noting that, although the T90 50 mm codend excluded almost all of the undersized *M. merluccius*, higher catch rates were recorded for *M. merluccius* due to an elevated number of legal-sized specimens. Taking into account the intrinsic relation between the ecological purpose of the MCRS and mesh size, it seems clear that the common goal is to avoid catching juveniles until they are large enough to spawn (Beverton and Holt, 1957). From an economic standpoint, this means that juveniles are given time to grow to an economically valuable size before they are harvested. Indeed, according to Vasilakopoulos et al. (2014), overexploitation of *M. merluccius* juveniles was particularly severe, since they were harvested during the first and second year of life before reaching sexual maturity. Despite the basic nature of this notion, the identification of an adequate legal mesh size can involve practical difficulties and management problems, mainly in fisheries where small-sized species, such as *P. longirostris* are caught together with fish that can reach a large size, such as *M. merluccius* (Caddy, 1990; Fiorentino and Vitale, 2021). In other words, the adoption of a more selective mesh size for *M. merluccius* would imply the loss of a large amount of shrimps and other small-sized species, reducing significantly fishery profitability (Lucchetti et al., 2021). Previously, Vitale et al. (2018a) using the Grid-T45 40 mm in the same area, found a high sorting capability for *P. longirostris* and *M. merluccius* in reduction of undersized with a minor loss of the marketable fraction for *P. longirostris*; however, similarly to the present study, a low amount of legal sized *M. merluccius* was retained by Grid-T45 40 mm (Vitale et al., 2018a). Similarly, Vitale et al. (2018a) further reported a higher number of bigger-sized *P. longirostris* individuals caught with the Grid-T45 40 mm compared to the control. These confirmed results could be due to a slightly higher vertical aperture of the trawl equipped with the Grid-T45 40 mm allowing it to catch larger *P. longirostris* individuals while remaining at a greater height from the bottom. To support this hypothesis, by studying catch of the lower, middle, and upper compartment in the codend of the bottom trawl fisheries of the Barents Sea, Larsen et al. (2021), found that the majority of deep water shrimps (*Pandalus borealis*) which entered in the highest compartments of the trawl net were larger-sized individuals. Although further investigations through ad-hoc experiments are needed, the size-depth separation of the shrimps in the water column (vertical separation) can help to improve the species/size selectivity of the Mediterranean *P. longirostris* bottom trawl fisheries, as suggested by Oceanic studies (e.g. Engås et al., 1998; Ferro et al., 2007; Graham and Fryer, 2006; Karlsen et al., 2019).

The T90 50 mm codend was quite selective for *P. longirostris*, however, the catch rates were very low and probably not able to ensure the economic sustainability of shrimps fishing activity. Similarly, for *M. merluccius*, the T90 50 mm codend resulted very selective. It is worth highlight as, although with the T90 50 mm codend were lost almost all of the undersized *M. merluccius*, higher CPUEs were recorded due to an elevated number of legal-sized specimens (mean size= 307 ± 93 mm TL). Similarly to the present study, Petetta et al. (2020) trialling a T90 54 mm codend found an improvement of the selectivity of the *M. merluccius*, even if, the nominal mesh size was excessively selective for the red mullet (*Mullus barbatus*), the Mediterranean horse mackerel (*T. mediterraneus*), squid (*Loligo vulgaris*) and whiting (*Merlangius merlangus*) being inefficient at retaining specimens of commercial size, such as for *P. longirostris* of the Strait of Sicily. Conversely, they recorded an increase of selectivity for mantis shrimp (*Squilla mantis*) allowing the escapement of juvenile individuals often discarded by fishers (Petetta et al., 2020). In Aegean Sea, the T90 codend with a nominal mesh size of 44 and 40 mm allowed an improvement of the size of the first capture of *M. merluccius* (Genç et al., 2018). Moreover, Dereli and Aydin (2016) have found that the adoption of T90 40 mm codend improved selectivity for *M. barbatus* and *T. trachurus*. Recently, on the eastern coast of Spain modifying trawl extension with a T90 50 mm panel resulted in decreased fishing mortality for younger age classes of *M. merluccius* and *M. barbatus* (Maynou et al., 2021) while in the Adriatic

Sea (Petetta et al., 2022) and northern Tyrrhenian Sea (Sbrana et al., 2022) the application of a T90 40 mm panel in the extension piece did not significantly reduce the catch of juveniles of target species.

The survival rates of *M. barbatus* individuals escaping from a commercial trawl net (40 mm square) were evaluated for the first time in the Strait of Sicily. Mortality events were detected only within the first 2 days and after that, all individuals survived. This result confirmed previous studies reporting that mortalities events occur during the first 2-3 days (e.g. Sangster et al., 1996; Wileman et al., 1999; Metin et al., 2004) and that the monitoring period (7 days) can be considered enough to estimate the survival rates of the red mullet. Overall, the survival rate of *M. barbatus* was high in treatment (63%) and very high in control (94%) haul. Conversely, Duzbastillar et al. (2017) and Metin et al. (2004) in the Aegean Sea, using a similar sampling methodology, found that red mullet specimens of the controls showed significantly higher mortality than the specimens from treatment. The survival rates of the individuals in control (94%) recorded in our experiment could be due to a sampling capable of minimizing the stress on the fish (e.g. barometric trauma, different temperatures, injuries) also thanks to the use of the liner that reduced the hydrodynamic flow inside the net (Breen et al., 2007). The experimental hauls considered in this study, such as other Mediterranean studies (Metin et al., 2004; Duzbastillar et al., 2016; Duzbastillar et al., 2017), were shallower (50 m, compared with 50-150 m), as fishing in deeper waters would have exposed fish to higher decompression stress compromising their vitality, and shorter (15 min control and 30 min treatment, compared with 1-2 and half hours) than commercial fishing hauls. The consistent and high survival rates observed in the treatment and the almost complete survival of the control individuals provide strong evidence that the methodological approach applied in the present study not affected the survival of red mullets escaping from trawl codend. However, it should be noted that these observations are not properly representative of the conditions experienced during commercial fishing hauls with respect to depth, towing duration, and catch size. Mediterranean trawl fisheries typically target multiple species and operate at depths of up to 800 m, whereas the red mullet lives at depths of <200 m (Papacostantinou et al., 2000). The experimental hauls in this study were carried out in shallow waters (about 50 m), as fishing in deeper waters would have exposed fish to higher decompression stress compromising their vitality, as with other Mediterranean studies (Metin et al., 2004; Duzbastillar et al., 2016; 2017). Furthermore, the towing durations (15 min control and 30 min treatment) were short compared with 1–2.5 h in commercial fishing hauls (deeper than 50 m). Therefore, in order to provide valid scientific justification for the implementation of regulations on trawl codend mesh size and MCRS in the Mediterranean (as defined by Reg. EU 1241/2019), further studies using methods similar to those describe here should be repeated with sufficient replicates to provide a robust description of the natural variation in escape survival rates. These studies should also attempt to replicate variations in commercial fishing operations, including seasonality, fishing depth, towing duration, and associated catch sizes and compositions.

A significant effect of survival rates by size classes was found with an opposite trend between treatment (decrease of survival with increasing sizes) and control (increase of survival with increasing sizes) individuals. Conversely, even if it seems that for the head zone an increase of damage was found for bigger individuals, no significant effect of size on the proportion of damage was detected.

The discard survival of *T .trachurus* has shown that the survival probability of undersized, after being hoisted on board following a demersal trawling haul, is very low. The most important factors affecting the survival rates of *T .trachurus* were delta T, depth, and haul duration but also air exposure, season, and the presence of injuries affected significantly its survival rates. Similarly, to the present study, in the rapido trawl fisheries of the Adriatic Sea, the most important factor in explaining survival rates of *Solea solea* resulted delta T, air exposure, and haul duration (Masnadi et al., 2020). In the Mediterranean, this is the first attempt to estimate the discard survival of *T .trachurus* during bottom trawl crustacean fisheries therefore no comparison with other studies is available. A preliminary study was carried out in Algarve (southern Portugal) during crustacean trawl fisheries but due to the small number of samples, some species such as the mackerels and monkfish were assessed as combined (Adão et al., 2018). The low survival rates of mackerel were confirmed also in Algarve being the spotted dogfish and conger eel the only species that survived at the end of the monitoring period (65-h). Indeed, the 50% of probability dead was in most cases/species, including mackerels, less than 20 min (Adão et al., 2018). In Algarve crustacean fisheries the mackerels conserved their scales but had bruises on the pectoral fins whereas in the present study, many individuals were seriously injured. Similarly, in this study, they applied a Weibull model relating vitality score with time to dead, fish size, and biological traits (i.e. deciduous scales loss, injuries, presence and type of gas bladder, and metabolic rates) and found that time to mortality was positively correlated with vitality score 3 and 4 whereas injuries had no effect on mortality but deciduous scale loss and closed gas bladder accelerated time to mortality. It must be said that most of the individuals included in the analysis were injured (367) than uninjured (40).

5. Conclusions

The use of underwater lights in Mediterranean trawl fisheries should be carefully regulated through ad hoc measures that are currently lacking. The study showed how the catch rates were not statistically significantly higher, but the size structure of the catch shifted towards higher yields of undersized fish, which is contrary to the conservation objectives of the CFP. The meta-synthesis of the effect of artificial lights during trawling highlights that, in the next years, scientists will face a new challenge in enhancing knowledge on the impact of artificial lighting on marine ecosystems during fishing activities, which are only now beginning to be examined in detail, at least in the Mediterranean. In the absence of sound scientific understanding, precautionary management measures should be taken to minimise the potential impacts of artificial light on some already overexploited stocks, where possible. Thus, more studies are needed to explore trade-offs in mixed trawl fisheries using different experimental artificial light settings (number location, intensity, and wavelengths) on different fishing grounds and species assemblages. Lastly, the different behaviour of species when approaching the gear should be considered. The aim would be to establish rules for the use of underwater lights in trawl fisheries, and to identify more suitable settings to improve fishery selectivity, thereby avoiding unwanted increases in both fishing mortality and unwanted by-catch. The construction of a solid baseline of knowledge on the impacts of artificial lighting in fishing practices will enable the potential design of realistic and effective management strategies that can benefit both marine ecology and society.

As for the grid T45 40 mm and T90 50 mm codend, in the near future, it will be of vital importance to take into account the trade-off between the socio-economic and ecological points of view, also engaging as many fishers as possible in developing and optimizing more selective gears (e.g., Geraci et al., 2021; Sardo et al., 2020; Geraci et al., 2019) to be translated into the decision process of the management regulations. However, before transferring the tested BRDs to fishing enterprises and to improve the selectivity of bottom trawling, it would be desirable to carry out generously planned surveys by using commercial vessels, fishing in different conditions (time, season, and grounds) with a shared protocol, and with fishing gears that are comparable as much as possible. Once obtained more robust data on the effect of BRDs, mitigation of the current poor exploitation pattern of *P. longirostris* and *M. merluccius* could be reached by adopting a set of management measures. In particular, the Fisheries Restricted Areas where the bottom trawling is prohibited, implemented by the GFCM to protect juveniles of *M. merluccius* and *P. longirostris* in the Strait of Sicily (Russo et al., 2019; Di Maio et al., 2022) could be coupled with the adoption of a boundary zone in which trawling is allowed only for vessels that mount on the net a BRD that minimizes the capture of undersized individuals. Another measure could be the introduction of a total allowable catch for *P. longirostris* and the application of the T90 50 mm codend when the quota is reached. All these potential management rules should be carefully monitored to check their effective application. In addition, as already shown in Vitale et al. (2018b), in the near future to simulate the effect of mounting the tested BRDs or the adoption of the above-mentioned management rules it will be worthy of interest to incorporate the selectivity results in an ecosystem model (e.g. Ecopath With

Ecosim) to assess the effects not only on commercial target species but also on the other component of the trophic web in the area (Agnetta et al., 2022).

In conclusion, although further works should be carried out in the next future to test different fishing arrangements, the investigated gears rigged with BRDs seem promising tools to contribute to reducing the overexploitation of *P. longirostris* and *M. merluccius* helping at the same time to ensure long-term socio-economic sustainability of the fishing process in line with the goals of the EU Common Fisheries Policy (reg. EC 1380/2013).

As for *M. barbatus* escape survival, it is recommended that further studies using methods similar to those described here should be conducted to provide valid scientific justification for the implementation of regulations for trawl codend mesh size and MCRS in the Mediterranean (as defined by Reg. EU 1241/2019). These studies should have sufficient replicates to provide a robust description of the natural variability in escape survival rates, as well as attempt to replicate variations in commercial fishing operations including seasonality, fishing depth, towing duration, and associated catch sizes and compositions. The data resulting from this work will be essential for removing biases in fishing mortality estimates because of the inherent assumption in most stock assessment models that all escaping fish survive. Furthermore, they will enable fishery managers to make more informed decisions about the implementation of different gear selectivity scenarios based on more reliable projections of yield and biomass in the exploited populations.

The survival rates of *T. trachurus* subjected to a commercial trawl fishing operation were very low, and even if it would seem that when they arrive on deck are vital and displayed intense activity these signs could be an extreme stress response (Adão et al., 2018). For a more in-depth understanding of the stress experienced by the fish during fishing operations physiological analysis such as cortisol, glucose, and ions (Na^+, Cl^- and K^+) from blood would be desirable (e.g. Marçalo et al. 2008; Falco et al., 2022). Given the multi-specific characteristic of the bottom trawl fisheries and the number of unwanted by-catch species caught, other species/*taxa* should be evaluated for discard survival (Scannella et al., 2022) or escape survival (Geraci et al., 2023). The survival rates of *T. trachurus* shown in the present study suggested that, according to Reg. EU 1380/2013, all the juvenile specimens should be landed and therefore the adoption of a more selective trawl net in the next future will be of paramount importance to try to ensure the long-term sustainability of this fisheries.

Note

The formal presentation of the text in the four manuscripts here presented is the same of that already published in the scientific journals.

References

Adão, A. C., Breen, M., Eichert, M., & Borges, T. C. (2018). By-catch species susceptibilities and potential for survival in Algarve (southern Portugal) deep-water crustacean trawl fishery. Scientia Marina, 82(S1), 141. https://doi.org/10.3989/scimar.04740.02a

Abella, A.; Mancusi, C.; Serena, F. *Raja clavata*. In Sintesi delle Conoscenze di Biologia, Ecologia e pesca delle Specie Ittiche dei mari Italiani; Sartor, P., Mannini, A., Carlucci, R., Massaro, E., Queirolo, S., Sabatini, A., Scarcella, G., Simoni, R., Eds.; Società Italiana di Biologia Marina (S.I.B.M.): Genoa, Italy, 2017; pp. 150–156.

Agnetta, D., Badalamenti, F., Colloca, F., Cossarini, G., Fiorentino, F., Garofalo, G., et al. (2022). Interactive effects of fishing effort reduction and climate change in a central Mediterranean fishing area: Insights from bio-economic indices derived from a dynamic food-web model. Front. Mar. Sci., 9: 909164. Doi: 10.3389/fmars.2022.909164.

Aguzzi, J., Costa, C., Antonucci, F., Company, J. B., Menesatti, P., Sarda, F., 2009. Influence of diel behaviour in the morphology of decapod natantia. Biological Journal of the Linnean Society, 96(3), 517–532. https://doi.org/10.1111/j.1095-8312.2008.01162.x

Arimoto, T., C. W. Glass, and X. Zhang. Fish vision and its role in fish capture, pp. 25–44. In: Behavior of Marine Fishes: Capture Processes and Conservation Challenges (Pingguo H., Ed.). Ames, Iowa, USA: Blackwell Publishing (2010).

Atema, J. Chemical senses, chemical signals and feeding behavior in fishes, pp. 57–101 In: Fish Behaviour and its Use in the Capture and Culture of Fishes (Bardach, J. E., Magnuson, J.J., May, R.C., Reinhart, J.M., Eds). Manila, Philippines: The International Center for Living Aquatic Resources Management (1980).

Brcic, J.; Herrmann, B.; De Carlo, F.; Sala, A. Selective characteristics of a shark-excluding grid device in a Mediterranean trawl.Fish. Res. 2015, 172, 352–360

Breen M., Huse I., Ingólfsson O.A., et al. 2007. An assessment of mortality in fish escaping from trawl codends and its use in fisheries management. Quality of Life and Management of Living Resources Q5RS-2002-01603, 300 pp

Bundy, A., Bohaboy, E. C., Hjermann, D. O., Mueter, F. J., Fu, C., and Link, J. S. (2012). Common patterns, common drivers: comparative analysis of aggregate surplus production across ecosystems. Mar. Ecol. Prog. Ser. 459, 203–218

Chosid, D.M.; Pol, M.; Szymanski, M.; Mirarchi, F.; Mirarchi, A. Development and observations of a spiny dogfish Squalus acanthias reduction device in a raised footrope silver hake Merluccius bilinearis trawl. Fish Res. 2012, 114, 66–75, doi:10.1016/j.fishres.2011.03.007.

Colloca, F., Scarcella, G., Libralato, S., 2017. Recent Trends and Impacts of Fisheries Exploitation on Mediterranean Stocks and Ecosystems. Frontiers in Marine Science, 4, 244. http://dx.doi.org/10.3389/fmars.2017.00244

Colloca, F.; Carrozzi, V.; Simonetti, A.; Di Lorenzo, M. Using local ecological knowledge of fishers to reconstruct abundancetrends of elasmobranch populations in the Strait of Sicily. Front. Mar. Sci. 2020, 7, 508.

Demirel, N.; Zengin, M.; Ulman, A. First large-scale eastern Mediterranean and Black Sea stock assessment reveals a dramatic decline. Front. Mar. Sci. 2020, 7, 103

Dereli, H., Aydin, C. (2016). Selectivity of commercial and alternative codends for four species in the Eastern Mediterranean demersal trawl fishery. Turk. J. Fish. Aquat. Sci., 16(4). Doi:10.4194/1303-2712-v16_4_25

Detto, T. (2007). The fiddler crab Uca mjoebergi uses colour vision in mate choice. Proc. Biol. Sci., 274: 2785–2790

Di Maio, F., Geraci, M.L., Scannella, D., Russo, T., Fiorentino, F. (2022). Evaluation of the Economic Performance of Coastal Trawling off the Southern Coast of Sicily (Central Mediterranean Sea). Sustainability, 2022(14): 4743. Doi: 10.3390/su14084743

Düzbastılar FO, Aydın C, Gül B. (2016). Mortality of non-target flatfishes escaping from demersal trawl codends. Journal of Applied Ichthyology. 32(6):1194–204. http://dx.doi.org/10.1111/jai.13220

Düzbastilar F.O., Breen M., Aydin C., Özbilgin H., Özgül A., Ulaş A., Metin G., Gül B., Lök A. (2017). Seasonal variation in mortality of red mullet (*Mullus barbatus*) escaping from codends of three different sizes in the Aegean Sea. Sci. Mar. 81(3): 339-349. http://dx.doi.org/10.3989/scimar.04600.19A

Engås, A. (1998). A species-selective trawl for demersal gadoid fisheries. ICES Journal of Marine Science, 55(5), 835–845. https://doi.org/10.1006/jmsc.1998.0352

Fakıoglu, Y.E.; Özbilgin, H.; Gökçe, G.; Herrmann, B. Effect of ground gear modification on bycatch of rays in Mediterraneanbottom trawl fishery. Ocean Coast. Manag. 2022, 223, 106134

Falco F, Bottari T, Ragonese S, Killen SS. (2022). Towards the integration of ecophysiology with fisheries stock assessment for conservationpolicy and evaluating the status of the Mediterranean Sea. Conserv Physiol 10(1): coac008; doi:10.1093/conphys/coac008

Falsone, F., Scannella, D., Geraci, M. L., Vitale, S., Colloca, F., Di Maio, F., et al. (2020). Identification and characterization of trammel net métiers: a case study from the southwestern Sicily (Central Mediterranean). Reg. Stud. Mar. Sci. 39:101419. doi: 10.1016/j.rsma.2020.101419

Ferro, R.S.T., Jones, E.G., Kynoch, R.J., Fryer, R.J., Buckett, B.E. (2007). Separating species using a horizontal panel in the Scottish North Sea whitefish fishery. ICES J. Mar. Sci., 64(8): 1543–1550. Doi: 10.1093/icesjms/fsm099

Falsone, F., Fiorentino, F., Gancitano, V., Scannella, D., Colloca, F., Ben Abdellah, O., Ben Mariem, S., Jarboui, O., Di Maio, F., Gambin, M., Fezzani, S., Quattrocchi, F., Vitale, S., Ceriola, L., Arneri, E. & Cardinale, M. (2021). GFCM-WGSAD Scientific Advisory Committee on Fisheries (SAC) Working Group on Stock Assessment of Demersal Species (WGSAD), Online, 25–30 January 2021

Fiorentino, F., Vitale, S. (2021). How Can We Reduce the Overexploitation of the Mediterranean Resources? Front. Mar. Sci., 8:674633. Doi: 10.3389/fmars.2021.674633

Gancitano, V., Scannella, D., Falsone, F., Ben Meriem, S., Ben Abdallah, O., Arneri, E., Ceriola, L., Jarboui, O., Gambin, M., Mifsud, J., Pisani, L., Vitale, S. & Fiorentino, F. (2021). GFCM-WGSAD Scientific Advisory Committee on Fisheries (SAC) Working Group on Stock Assessment of Demersal Species (WGSAD), Online, 25–30 January 2021

Garofalo, G.; Gristina, M.; Fiorentino, F.; Cigala Fulgosi, F.; Norrito, G.; Sinacori, G. Distributional pattern of rays (Pisces, Rajidae) in the Strait of Sicily in relation to fishing pressure. Hydrobiologia 2003, 503, 245–250, doi:10.1023/b:hydr.0000008487.25578.d4.

Genç, T.Ş., Atamanalp, M., Aydın, C. (2018). Selectivity of turned meshes codends for Deepwater Rose Shrimp (Parapenaeus longirostris), Horse Mackerel, (Trachurus trachurus) and European Hake (Merluccius merluccius) in the Aegean Sea. Ege Journal of Fisheries and Aquatic Sciences, 35(2), 157-168. Doi: 10.12714/egejfas.2018.35.2.08

Geraci, M.L.; Ragonese, S.; Norrito, G.; Scannella, D.; Falsone, F.; Vitale, S. A Tale on the Demersal and Bottom Dwelling Chondrichthyes in the South of SicilySouth Sicily through 20 Years of Scientific Survey. In Chondrichthyes—Multidisciplinary Approach; Rodrigues-Filho, L.F., de Luna Sales, J.B., Eds.; IntechOpen: London, UK, 2017; pp. 13–37, doi:10.5772/intechopen.69333

Geraci, M.L.; Di Lorenzo, M.; Falsone, F.; Scannella, D.; Di Maio, F.; Colloca, F.; Vitale, S.; Serena, F. The occurrence of Norwegian skate, Dipturus nidarosiensis (Elasmobranchii: Rajiformes: Rajidae), in the Strait of Sicily, central Mediterranean. Acta Ichthyol. Piscat. 2019, 49, 203–208, doi:10.3750/aiep/02566

Geraci, M.L.; Ragonese, S.; Scannella, D.; Falsone, F.; Gancitano, V.; Mifsud, J.; Gambin, M.; Said, A.; Vitale, S. Batoid Abundances, Spatial Distribution and Life History Traits in the Strait of Sicily (Central Mediterranean Sea): Bridging a Knowledge Gap throughThree Decades of Survey. Animals 2021, 11, 2189. doi: 10.3390/ani11082189

Geraci, M.L.; Sardo, G.; Falsone, F.; Scannella, D.; Breen, M.; Fiorentino, F.; Sala, A.; Vitale, S. (2023). Escape Survival and Scale Damage Assessment of Red Mullet (*Mullus barbatus* Linnaeus, 1758) during Bottom Trawling in the Central Mediterranean Sea. Biology, 12, 649. doi:10.3390/biology12050649

General Fisheries Commission for the Mediterranean (GFCM) 2022. Deepwater Red Shrimp in the Eastern-Central MediterraneanSea Week, Online Presentation 7–11 February 2022. Available online: https://www.fao.org/gfcm/meetings/info/en/c/1469548/(accessed on 19 April 2022).

G.F.C.M., 2019. Working Group on Stock Assessment of Demersal Species (WGSAD). FAO headquarters, Rome, Italy, 9–14 December 2019

Graham, N., Fryer, R. J. (2006). Separation of fish from Nephrops norvegicus into a two-tier cod-end using a selection grid. Fisheries Research, 82(1–3), 111–118. https://doi.org/10.1016/j.fishres.2006.08.011

Heupel, M.R.; Kanno, S.; Martins, A.P.B.; Simpfendorfer, C.A. Advances in understanding the roles and benefits of nursery areasfor elasmobranch populations. Mar. Freshw. Res. 2018, 70, 897.

Karlsen, J.D., Krag, L.A., Herrmann, B., Lund, H. (2019). Using vertical distribution to separate fish from crustaceans in a mixed species trawl fishery. Can. J. Fish. Aquat. Sci., 76(10): 1781–1794. Doi: 10.1139/cjfas-2018-0313

Keller, S., Robin, J.-P., Valls, M., Gras, M., Cabanellas-Reboredo, M., and Quetglas, A. (2015). The use of Depletion Methods to assess Mediterranean cephalopod stocks under the current EU Data Collection Framework. Med. Mar. Sci. 16:513. doi: 10.12681/mms.1127

Kynoch, R.J.; Fryer, R.J.; Neat, F.C. A simple technical measure to reduce bycatch and discard of skates and sharks in mixedspecies bottom-trawl fisheries. ICES J. Mar. Sci. 2015, 72, 1861–1868, doi:10.1093/icesjms/fsv037.

Land, M. F. and D. E. Nilsson. (2012). Animal Eyes, p. 288. Oxford, UK: Oxford University Press.

Larsen, R.B., Herrmann, B., Brčić, J., Sistiaga, M., Cerbule, K., Nielsen, K.N., et al. (2021) Can vertical separation of species in trawls be utilized to reduce bycatch in shrimp fisheries? PLoS ONE, 16(3): e0249172. Doi:10.1371/journal.pone.0249172

Lauria, V.; Gristina, M.; Attrill, M.J.; Fiorentino, F.; Garofalo, G. Predictive habitat suitability models to aid conservation of elasmobranch diversity in the central Mediterranean Sea. Sci. Rep. 2015, 5, 13245, doi:10.1038/srep13245

Lauria, V., Garofalo, G., Gristina, M., and Fiorentino, F. (2016). Contrasting habitat selection amongst cephalopods in the Mediterranean Sea: when the environment makes the difference. Mar. Env. Res. 119, 252–266. doi: 10.1016/j. marenvres.2016.06.011

Lucchetti, A., Virgili, M., Vasapollo, C., Petetta, A., Bargione, G., Li Veli, D., et al. (2021). An overview of bottom trawl selectivity in the Mediterranean Sea. Mediterr. Mar. Sci., 22(3): 566-585. Doi: 10.12681/mms.26969

Maynou, F., García-de-Vinuesa, A.G., Martínez-Baños, P., Sánchez, P., Demestre, M. (2021). Relative Catch Performance of Two Gear Modifications Used to Reduce Bycatch of Undersized Fish and Shrimp in Mediterranean Bottom Trawl Fisheries. Mar. Coast. Fish., 13(5), 518-533. Doi: 10.1002/mcf2.10178

Marçalo, A., Pousão-Ferreira, P., Mateus, L., Duarte Correia, J. H., & Stratoudakis, Y. (2008). Sardine early survival, physical condition and stress after introduction to captivity. Journal of Fish Biology, 72(1), 103–120. https://doi.org/10.1111/j.1095-8649.2007.01660.x

Masnadi, F., Armelloni, E. N., Guicciardi, S., Pellini, G., Raicevich, S., Mazzoldi, C., Scanu, M., Sabatini, L., Tassetti, A. N., Ferra`, C., Grati, F., Bolognini, L., Domenichetti, F., Cacciamani, R., Calı`, F., Polidori, P., Fabi, G., Luzi, F., Giovanardi, O., Bernarello, V., Pasanisi, E., Franceschini, G., Breggion, C., Bozzetta, E., Sambo, A., Prioli, G., Gugnali, A., Piccioni, E., Fiori, F., Caruso, F., and Scarcella, G. Relative survival scenarios: an application to undersized common sole (Solea solea L.) in a beam trawl fishery in the Mediterranean Sea. ICES Journal of Marine Science, 77: 2646–2655. doi:10.1093/icesjms/fsaa128

Metin C., Tokaç A., Ulaş A., et al. (2004). Survival of red mullet (*Mullus barbatus* L., 1758) after escape from a trawl codend in the Aegean Sea. Fish. Res. 70: 49-53. https://doi.org/10.1016/j.fishres.2004.06.013

Papaconstantinou, C.; Farrugio, H. (2000). Fisheries in the Mediterranean. Med. Mar. Sci. 1, 5–18.

Petetta, A., Herrmann, B., Virgili, M., De Marco, R., Canduci, G., Li Veli, D., et al. (2020). Estimating selectivity of experimental diamond (T0) and turned mesh (T90) codends in multi-species Mediterranean bottom trawl. Mediterr. Mar. Sci., 21(3): 545-557. Doi: 10.12681/mms.22789

Petetta, A., Herrmann, B., Virgili, M., Li Veli, D., Brinkhof, J., Lucchetti, A. (2022) Effect of Extension Piece Design on Catch Patterns in a Mediterranean Bottom Trawl Fishery. Front. Mar. Sci. 9:876569. Doi: 10.3389/fmars.2022.876569

Pinello, D., Gee, J., Accadia, P., Sabatella, E.C., Vitale, S., Polymeros, K., Fiorentino, F., 2018. Efficiency of shallow- and deep-water trawling in the Mediterranean and its implications for discard reduction. Scientia Marina, 82 (S1), 97–106. https://doi.org/10.3989/scimar.04749.22a

Ragonese, S.; Vitale, S.; Dimech, M.; Mazzola, S. Abundances of demersal sharks and chimaera from 1994-2009 scientific surveys in the central Mediterranean Sea. PLoS ONE 2013, 8, e74865, doi:10.1371/journal.pone.0074865.

Rodríguez-Climent, S., Sonderblohm, C.P., Fonseca, P., Erzini, K., Campos, A., 2016. Diel variation in the deep-water rose shrimp Parapenaeus longirostris (Lucas, 1846) catches off the Portuguese south coast. In: Front. Mar. Sci. Conference Abstract: XIX Iberian Symposium on Marine Biology Studies. https://doi.org/10.3389/conf. FMARS (Vol. 73)

Russo, T., Carpentieri, P., D'Andrea, L., De Angelis, P., Fiorentino, F., Franceschini, S., et al. (2019). Trends in effort and yield of trawl fisheries: a case study from the Mediterranean Sea. Front. Mar. Sci. 6:153. doi: 10.3389/fmars.2019.00153

Sardo, G., Geraci, M.L., Scannella, D., Falsone F., Vitale, S. (2020). New records of two uncommon species, *Calappa tuerkayana* Pastore, 1995 (Decapoda, Calappidae) and *Parasquilla ferrussaci* (Roux, 1828) (Stomatopoda, Parasquillidae), from the Strait of Sicily (central Mediterranean Sea). Arxius de Miscellània Zoològica, 18:113–121. Doi: 10.32800/amz.2020.18.0113

Sangster, G.I., Lehmann, K., Breen, M. (1996). Commercial fishing experiments to assess the survival of haddock and whiting after escape from four sizes of diamond mesh cod-ends. Fisheries Research 25(1996) 323-345.

Sbrana, M., De Carlo, F., Ligas, A., Massaro, A., Musumeci, C., Rossetti, I., Sartini, M., Vasapollo, C., Viva, C., Sartor, P., Pretti, C. (2022). Testing experimental devices in the extension piece to increase the selectivity of bottom trawl in the Nw Mediterranean. Front. Mar. Sci. 9:1017766. Doi: 10.3389/fmars.2022.1017766

Scannella, D., Bono, G., Di Lorenzo, M., Di Maio, F., Falsone, F., Gancitano, V., Garofalo, G., Geraci, M. L., Lauria, V., Mancuso, M., Quattrocchi, F., Sardo, G., Titone, A., Vitale, S., Fiorentino, F., & Massi, D. (2022). How does climate change affect a fishable resource? The case of the royal sea cucumber (Parastichopus regalis) in the central Mediterranean Sea. Frontiers in Marine Science, 9. https://doi.org/10.3389/fmars.2022.934556

Szuwalski, C. S., and Hollowed, A. B. (2016). Climate change and non-stationary population processes in fisheries management. ICES J. Mar. Sci. 73, 1297–1305.

Scannella, D.; Geraci, M.L.; Falsone, F.; Colloca, F.; Zava, B.; Serena, F.; Vitale, S. A new record of a great white shark, Carcharodon carcharias (Chondrichthyes: Lamnidae) in the Strait of Sicily, Central Mediterranean Sea. Acta Adriat. 2020, 61, 181–186, doi:10.32582/aa.61.2.13

Vitale, S., Milisenda, G., Gristina, M., Baiata, P., Bonanomi, S., Colloca, F., Gancitano, V., Scannella, D., Fiorentino, F., Sala, A. 2018a. Towards more selective Mediterranean trawl fisheries: are juveniles and trash excluder devices effective tools for reducing undersized catches? Scientia Marina, 82 (S1), 215–223. https://doi.org/10.3989/scimar.04751.28a

Ward-Paige, C.A.; Keith, D.M.; Worm, B.; Lotze, H.K. Recovery potential and conservation options for elasmobranchs. J. Fish Biol.2012, 80, 1844–1869.

Wileman, D.A., Sangster, G.I., Breen, M., Ulmestrand, M., Soldal, A.V., Harris, R.R. (1999) Roundfish and Nephrops survival after escape from commercial fishing gear. EU Contract Final Report. EC Contract No: FAIR-CT95-0753

Yami, B. (1976). Fishing with Light. FAO Fishing Manuals, p. 121. Farnham, Surrey, England: Arrangement with the Food and Agriculture and Organization of the United Nations by Fishing News Books Ltd.