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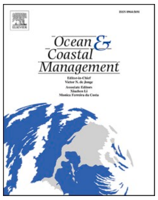

How is artificial lighting affecting the catches in deep water rose shrimp trawl fishery of the Central Mediterranean Sea?

Michele L. Geraci [a,b,*], Francesco Colloca [c], Federico Di Maio [a,b], Fabio Falsone [b], Fabio Fiorentino [b], Giacomo Sardo [b], Danilo Scannella [b], Vita Gancitano [b], Sergio Vitale [b]

[a] Department of Biological, Geological and Environmental Sciences (BiGeA), University of Bologna, Piazza di Porta San Donato 1, 40126, Bologna, Italy
[b] National Research Council - Institute of Marine Biological Resources and Biotechnologies (CNR IRBIM), Via L. Vaccara 61, 91026, Mazara del Vallo, TP, Italy
[c] Stazione Zoologica Anton Dohrn, Integrative Marine Ecology Department, Villa Comunale, 80121, Naples, Italy

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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.

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 and 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 and 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 and 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., 2019; Lomeli and 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 and 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 and Wakefield 2012; Grimaldo et al., 2018) and size-dependent (e.g., Lomeli et al., 2018a; Melli et al., 2018).

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* Corresponding author. Department of Biological, Geological and Environmental Sciences (BiGeA), University of Bologna, Piazza di Porta San Donato 1, 40126, Bologna, Italy.

E-mail addresses: micheleluca.geraci2@unibo.it (M.L. Geraci), francesco.colloca@szn.it (F. Colloca), federico.dimaio2@unibo.it (F. Di Maio), fabio.falsone@irbim.cnr.it (F. Falsone), fabio.fiorentino@irbim.cnr.it (F. Fiorentino), giacomo.sardo@irbim.cnr.it (G. Sardo), danilo.scannella@irbim.cnr.it (D. Scannella), vita.gancitano@irbim.cnr.it (V. Gancitano), sergio.vitale@cnr.it (S. Vitale).

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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 GFCM (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).

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 1 h each (six repeated in each of the three nights) were carried out at speeds ranging from 2.6 to 2.8 knots, alternating the trawl net with (hereinafter referred to as test) and without light (hereinafter referred to as control) (Table 1).

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

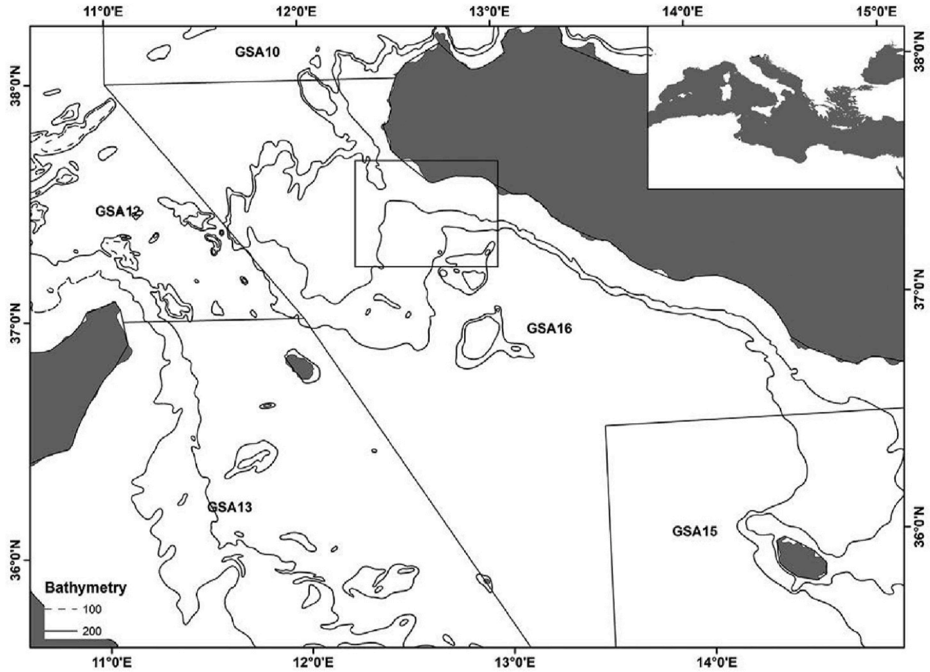

Fig. 1. The study area highlighted using a black square box (from Vitale et al., 2018a, b).

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

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).

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-g 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).

2.2. Statistical analysis

2.2.1. 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.

2.2.2. 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 and 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 and 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:

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

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 (R Core Team, 2020) 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 for *P. longirostris* the percentage of undersized specimens was higher in the control (Table 2).

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 ($\chi2 = 1.335$, $p = 0.124$), *M. merluccius* ($\chi2 = 0.276$, $p = 0.300$), and *T. trachurus* ($\chi2 = 1.335$, $p = 0.124$), whereas for *P. longirostris*, a significant increase in the test net was found ($\chi2 =$

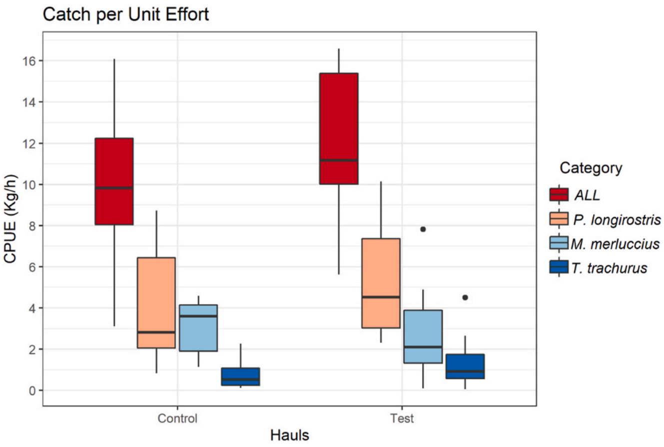

Fig. 3. Catch per Unit Effort (CPUE) expressed as kg/h for: ALL (all catch pooled by haul), *Parapenaeus longirostris*, *Merluccius merluccius*, and *Trachurus trachurus*

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

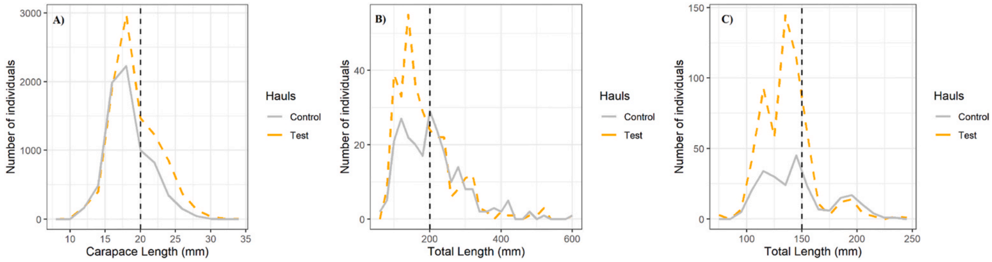

Fig. 4. Absolute length frequency distribution of A) *Parapenaeus longirostris*, B) *Merluccius merluccius*, and C) *Trachurus trachurus*. Black dashed lines indicate the minimum conservation reference size (MCRS).

2.823, p = 0.043).

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* ($D = 0.167$, $p < 0.0001$).

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				
P. longirostris	~ *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**	**2.06^{-10}**
	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**	**5.2^{-04}**
	***f*(size class, df = 3) 2:moonpresence**	**−2.624**	**0.599**	**−4.378**	**1.20^{-05}**
	f(size class, df = 3) 3:moonpresence	1.042	1.227	0.850	0.396
M. merluccius	~ *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**
	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 and B).

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 75 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).

The mean probability to catch undersized specimens ($P_u \pm$ 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 32 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).

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

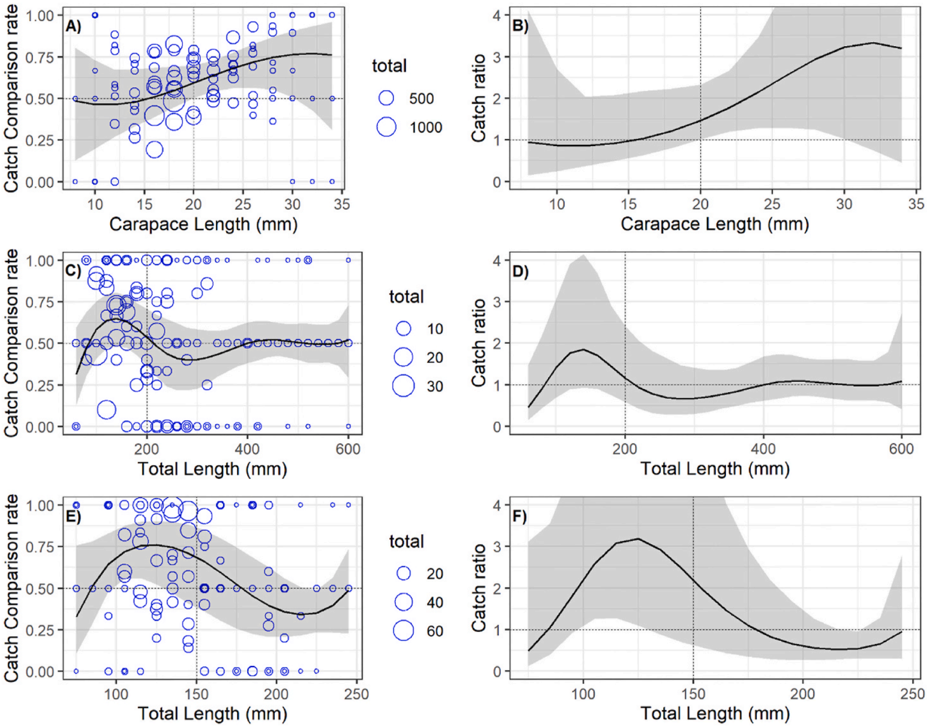

Fig. 5. Catch comparison curves (left) and Catch Ratio curves (right) for (A, B) *Parapenaeus longirostris*, (C, D) *Merluccius merluccius*, and (E, F) *Trachurus trachurus*. (Left) blue circles are observed proportions, black dashed lines represent the model prediction, the grey band indicates the 95% 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

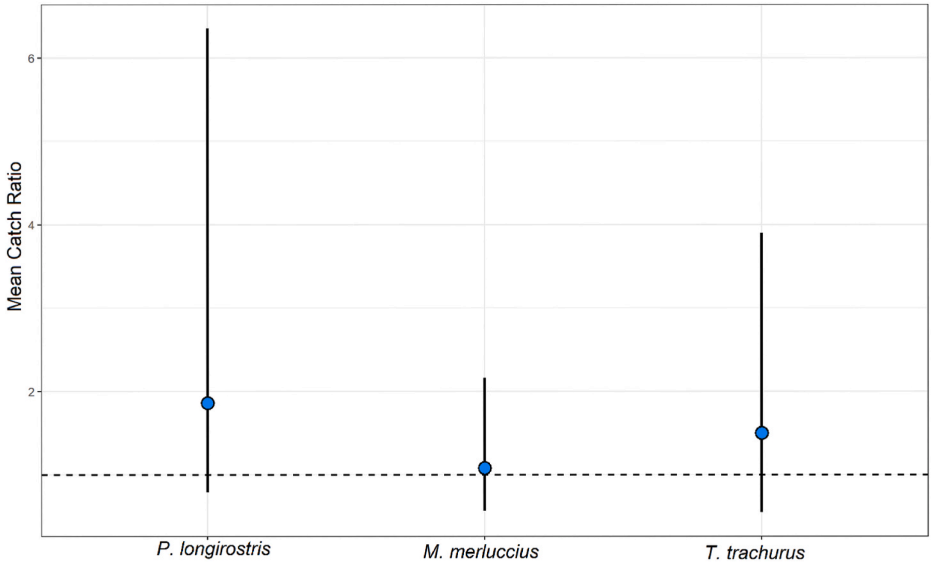

Fig. 6. Mean Catch Ratio for *Parapenaeus longirostris*, *Merluccius merluccius*, and *Trachurus trachurus* between test and control nets is depicted by blue dots; bars indicate the 95% confidence limit. The level of no effect (mean CRl = 1.0) is depicted by the horizontal black dashed lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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 unwanted 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

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 and 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 and 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							-	

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Table 4 (*continued*)

Area	Trawl type	Species	Target/ by-catch	Light type	Colour/wavelength	Power/Flux/ intensity	Number of lights	Placement	Effect on size	Catch rates	Author
		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						$Y^{\#}$, $Y^{\#\#}$, $Y^{\#\#\#}$	$-^{\#}$, $-^{\#\#}$, $-^{\#\#\#}$	
			B								

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Table 4 (*continued*)

Area	Trawl type	Species	Target/ by-catch	Light type	Colour/wavelength	Power/Flux/ intensity	Number of lights	Placement	Effect on size	Catch rates	Author
		Merluccius productus							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)$^{\#}$	About 61 cm apart over the distance of two escape windows	NA$^{\#}$, N$^{\#\#}$	-$^{\#}$, -$^{\#\#}$	Lomeli & Wakefield (2019)
		Other rockfishes	B				24 (in cluster of two)$^{\#\#}$		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# Lower part of the extension piece, in front a square mesh panel##	N$^{\#}$, N$^{\#\#}$	+/−$^{\#}$, +/−$^{\#\#}$	Cuende et al., 2020
		Micromesistius poutassou	T						N$^{\#}$, N$^{\#\#}$	+/−$^{\#}$, +/−$^{\#\#}$	

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Table 4 (*continued*)

Area	Trawl type	Species	Target/ by-catch	Light type	Colour/wavelength	Power/Flux/ intensity	Number of lights	Placement	Effect on size	Catch rates	Author
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 et al. (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 separated)	*Nephrops norvegicus*	T	Luminous net	Green (520 nm)	NA	A v-shape ascending stripe of net	Just before the codend	N	NA	Karlsen et al. (2021)
		Gadus morhua	B						Y	NA	
		Melanogrammus aeglefinus	B						Y	NA	
		Merlangius merlangus									
		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.

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. 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 (G.F.C.M, 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.

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Data availability statement

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

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2021.105970.

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