



Reducing Sea Turtle Bycatch in the Mediterranean Mixed Demersal Fisheries

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The sea turtle (*Caretta caretta*) is the most common sea turtle in the Mediterranean, where incidental catches due to fishing activities are considered the main threat to its conservation. Over 50,000 capture events and likely over 10,000 deaths are estimated to occur in the Italian waters alone. However, current knowledge on the interaction of sea turtles with fishing gears and the implementation of mitigation measures are still poor to hinder the decline of turtle populations in the Mediterranean. In this basin, where fisheries are multispecies, multi-gears and multinational, making demersal fishing activities profitable while preserving sea turtles is a challenge. This study aimed to develop bycatch reducer devices (BRDs) and alternative fishing gears to mitigate the impact of demersal fishing gears on sea turtles: (a) hard and flexible turtle excluder devices (TEDs) were tested in bottom trawling to immediately exclude turtles from the net; (b) visual deterrents (ultraviolet LEDs) were used to illuminate set nets and to alter turtle visual cues, avoiding entanglement during depredation activity. The results showed the different devices did not affect the commercial catch, while bycatch reduction was instead evident. Thus, the study highlights that introducing mitigation measures to reduce sea turtle bycatch in the Mediterranean, where the bycatch of vulnerable species seems as a global issue, can be possible at least in certain areas and periods. Considering fishermen reticence to change the gear traditionally used, determining the optimal gear configuration to minimize commercial loss while reducing bycatch, is the main issue while introducing new technologies. Therefore, a global effort should be done to introduce BRDs in different areas and fisheries of the Mediterranean.

Keywords: sea turtle bycatch, bycatch reducer devices, turtle excluder devices, visual deterrents, Mediterranean Sea

INTRODUCTION

Fisheries in the Mediterranean basin include a wide variety of fishing activities and different gears operating mainly on small and medium scale. The intense fishing pressure is responsible of a general overexploitation status of fish resources (Colloca et al., 2017) and a growing degradation of marine habitats (Lotze et al., 2011). Large vertebrates like sharks (Ferretti et al., 2005), cetaceans (Bearzi et al., 2008), and sea turtles (Casale, 2011) are heavily affected by commercial fisheries, mainly

because they are incidentally caught as bycatch. The loggerhead sea turtle (*Caretta caretta*) is the most common species of sea turtle in the Mediterranean, with densities estimated in summer of more than 0.046 individuals km⁻² (Lauriano et al., 2011).

Caretta caretta is a protected species, included in the list of Annex IV of animals requiring close protection under the Habitat Directive and assessed by the International Union of Conservation of Nature and Natural Resources (IUCN) as “vulnerable” at global scale (Casale and Tucker, 2015) and as “least concern” for the Mediterranean Sea (Casale et al., 2015; Lucchetti et al., 2016b). Lucchetti et al. (2017a) estimated more than 52,000 bycatch events and 10,000 deaths occurring only in Italian waters in 2014, highlighting how fishing activities represent the main threat to the conservation of loggerheads (Lucchetti and Sala, 2010). Individuals frequenting shallow waters in order to feed on benthic species close to the bottom (Tomas et al., 2001; Hochscheid et al., 2013) often interact with fishing gears operating on the seabed (Lucchetti et al., 2016b).

Bottom trawl and set nets fishing are among the most widespread gears targeting demersal stocks, and responsible of high sea turtle bycatch rates in the Mediterranean (Casale, 2011). Bottom trawl is a fishing gear actively towed on the seabed, and turtles accidentally caught during trawling activities have a direct mortality depending on tow duration: the longer the tow duration, the greater the prolonged apnoea and mortality (Sasso and Epperly, 2006). The direct mortality induced by bottom trawling is around 18%. Moreover, delayed mortality due to drowning, metabolic disturbance, decompression sickness upon release (García-Párraga et al., 2014) is suspected to be high. In the North Adriatic Sea (GFCM Geographical Sub-Area 17), where over 1,000 trawlers operate annual turtle bycatch due to bottom trawling has been estimated in 8,600 individuals (Lucchetti et al., 2017a). Passive set nets are among the principal gears used in the small-scale fisheries; set nets targeting demersal fish are fixed on the bottom usually for about 12 h and passively catch fish. An accidentally entangled sea turtle is subjected to forced apnoea due to the long soaking time of the nets and consequent drowning. For the North Adriatic Sea, Lucchetti et al. (2017a) estimated more than 6,200 turtles caught in the west GSA 17 each year with the largest number in summer. The direct mortality caused by passive nets is much higher than bottom trawling and estimated at around 51%.

Possible solutions to avoid bycatch reside in new technological fishing gear improvements and adoption of devices, that may potentially help in reducing turtle entanglement or entrapment and, therefore, animal mortality rates (Casale et al., 2007; Lucchetti et al., 2016b). Recently in Mediterranean some bycatch reducer devices (BRDs) directed at mitigating the fishing impact on sea turtles have been tested. In bottom trawl fisheries, turtle excluder devices (TEDs) consisting in rounded sorting grids with bars (Epperly, 2003), placed before the codend to stop large objects or animals, thus expelling them by an exit, have been successfully experimented (Atabey and Taskavak, 2001; Sala et al., 2011; Lucchetti et al., 2016b). TEDs have become mandatory in several countries in prawn trawl fisheries due to their effectiveness (Lucchetti and Sala, 2010) and preliminary sea trials in the Mediterranean Sea showed good

results especially in terms of fishing performance (no loss of commercial catch).

In the last years, the effect of a new prototype of TED, a flexible grid (Flexgrid), on the catching efficiency and performance of a commercial bottom trawl was tested in a gear comparison study for a Mediterranean coastal multispecies bottom trawl fishery (Lucchetti et al., 2016b). Findings demonstrated that this device did not affect neither bottom trawl technical performances (horizontal and vertical net opening and door spread) nor increased the required towing force, hence fuel consumption remained constant. Comparison of commercial catches for the major species showed that the use of this TED did not affect catching efficiency, while it reduced the amount of debris. The device did not influence the size of commercial species, leaving the selective performance of the trawl unmodified. Underwater video camera recordings documented that fish caught in the net swam through the grid and easily reached the cod-end, missing the TED escape opening. Easy storage and handling compared with previous devices tested in this area (Sala et al., 2011) make the flexible TED a practical and valuable solution to reduce turtle bycatch in coastal Mediterranean demersal multispecies fisheries.

In recent years, a potential bycatch reduction strategy for set nets fisheries has been connected to alteration of visual cues with lights. LED lamps and light sticks attached to gillnet float lines (Wang et al., 2010, 2013; Lucchetti et al., 2014; Ortiz et al., 2016; Virgili et al., 2018) have proven to be effective in decreasing turtle bycatch rates while preserving target species catch rates. The bycatch reduction observed ranged from 39.7 to 63.9% for Northern and Southern Pacific coasts by illuminating gillnets with green light (Wang et al., 2010; Ortiz et al., 2016) or UV light (Wang et al., 2013). For the Adriatic Sea (GSA 17), Virgili et al. (2018) observed a bycatch reduction of 100%, using UV light in bottom set-gillnet fisheries in deep waters (>70 m), while the efficiency of commercial catch was maintained.

Taken into account previous BRD tested in the Mediterranean Sea, the present study aims at:

- (i) comparing the capture performances of a hard (Supershooter) and a flexible (Flexgrid) TED in bottom trawling;
- (ii) assessing the efficacy of UV-LEDs to deter sea turtle bycatch in bottom gillnet fisheries set, to complete what has already been experimented by Virgili et al. (2018).

MATERIALS AND METHODS

Study Area and Period

The study was carried out in the Northern Adriatic Sea, in sandy–muddy bottoms lying south of the Po river mouth (Figure 1, Central Mediterranean Sea). This area was selected because its shallow waters and rich benthic communities provide a major feeding habitat for turtles in the demersal stage, especially for the populations nesting in Greece (Lazar et al., 2004; Casale et al., 2012). Since the area is an important fishing ground, the risk of interaction with turtles is high: Lucchetti et al. (2017a,b) estimated more than 6,000 and 8,000

sea turtles are annually caught respectively by set and trawl nets in the North-Western Adriatic Sea, with a mortality rate of 15 and 24%, respectively. Winter time was chosen taking into account that previous studies (Lucchetti et al., 2017a) demonstrated sea turtles heavily interact with fishing gears in this period.

Sea Trials and Gears

Bottom Trawl

Sea trials were conducted in December 2018 aboard a commercial fishing vessel from Porto Garibaldi (142 kW of engine power, 14.7 m length overall, and 12 GT of tonnage), in shallow waters (10–20 m deep) at distance of 5–10 nm off the coast (Figure 1). Twin trawl was used to compare directly the traditional trawl (Control) and the nets equipped with the TEDs. Each single net of the twin trawl was a typical “Americana” trawl, which is an asymmetric four-face trawl, generally used in this area to target crustaceans such as mantis shrimp (*Squilla mantis*) and caramote prawn (*Penaeus kerathurus*). This trawl is characterized by having two short bridles (~10 m), high attack angles of the otterboards (40–45°; Lucchetti and Sala, 2012) and tickler chain to increase the fishing performance. A nominal 50 mm diamond mesh codend was mounted in each net [in compliance with the Regulation (Ec) 1967/2006, 2006].

Set Nets

A traditional bottom-set gillnet targeting common sole (*Solea solea*) and mantis shrimp was used for the study. The netting panels, made of transparent polyamide monofilament (diameter, 0.20 mm), were joined in the same gang for a total length of 1,200 m. Each panel was 100 m in length, 2.8 m in stretched net drop and the real vertical opening during fishing was around 1.6 m; the mesh opening was 74 mm. The headline was a 5 mm polypropylene rope with oval floats (15 × 20 mm) 4.6 m apart from each other. The leadline was a 4 mm polypropylene rope weighing 150 g/m. The hanging ratio, i.e., the slack of the netting panel (Lucchetti et al., 2015) was 0.36 and 0.38 for the float line and lead line, respectively.

Experimental trials were conducted on board a fishing vessel (14.7 kW, 6.1 m overall length, 2 gross tonnage) employing gillnets throughout the year in coastal waters (3–5 nm off coast) at a depth of 8–15 m.

BRDs Specifications

Hard and Flexible TEDs

Two different types of TEDs were designed according to the technical specifications suggested by (Mitchell et al., 1995), manufactured and tested at sea. The tested TEDs differed in their material and shape, and were similar for size and bar

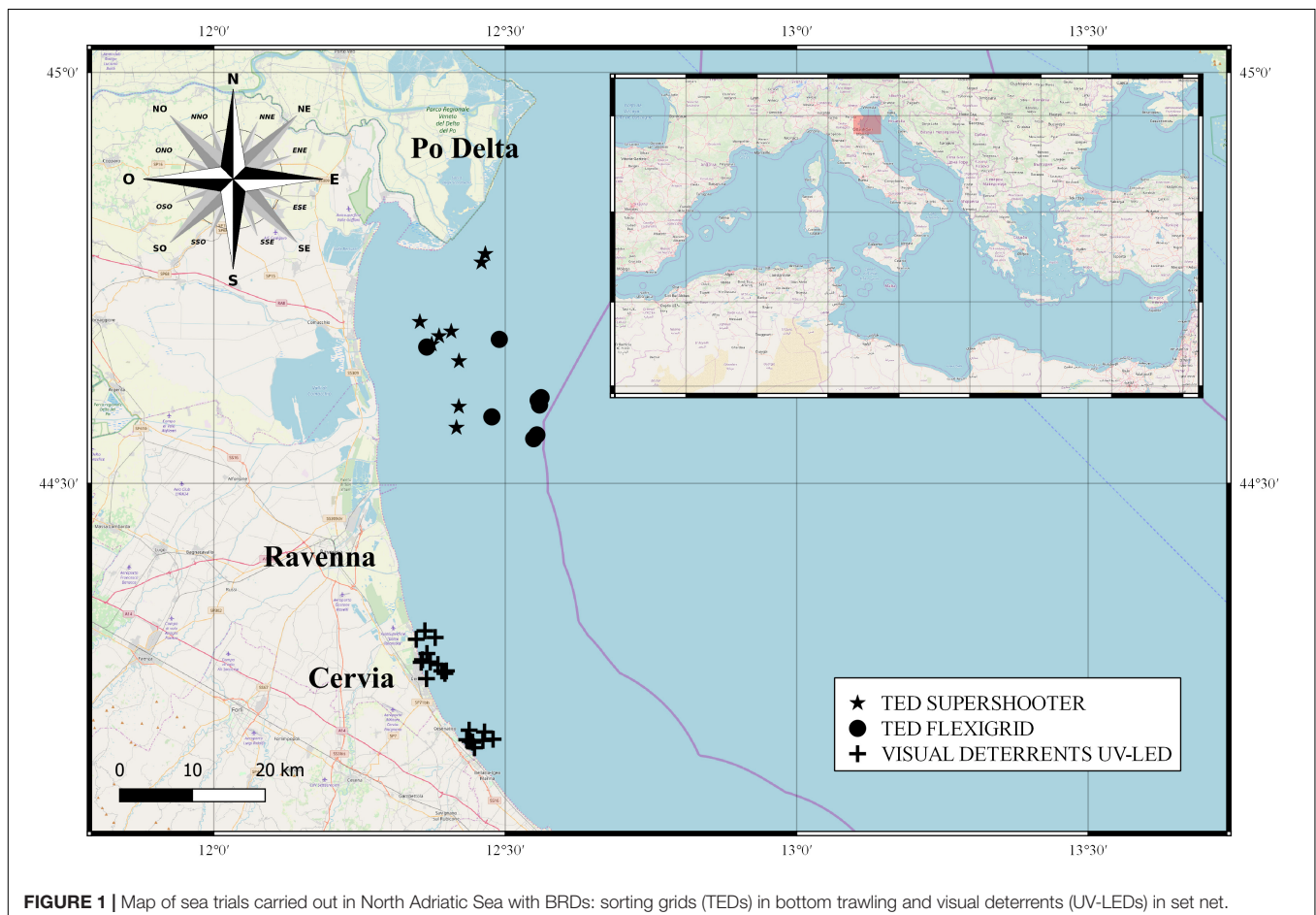


FIGURE 1 | Map of sea trials carried out in North Adriatic Sea with BRDs: sorting grids (TEDs) in bottom trawling and visual deterrents (UV-LEDs) in set net.

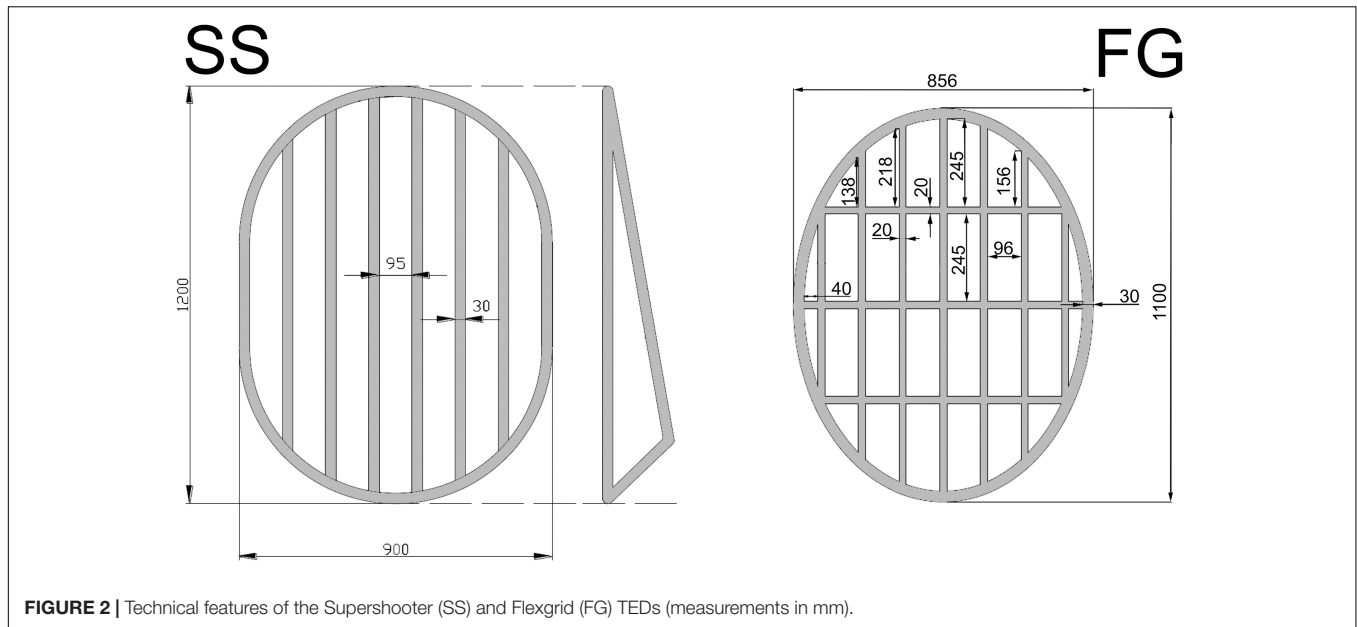


FIGURE 2 | Technical features of the Supershooter (SS) and Flexgrid (FG) TEDs (measurements in mm).

spacing. The hard TED was a classic aluminum Supershooter grid (Figure 2), commonly used in shrimp fisheries in several countries. By considering the complex Adriatic fishing composition (crustaceans, molluscs, and fishes caught together), we kept the space between reflector bars greater than in standard models. The Supershooter had the following features: height: 1,200 mm; width: 900 mm; bar diameter: 30 mm; spacing between bars: 95 mm.

The flexible TED (Flexgrid – Comet trawl, Denmark), made of an alloy of high strength plastic material, allowed to maintain a stiff configuration during trawling and to ride on the net drum as the net was recovered. The flexible TED dimensions were: height: 1,130 mm; width: 845 mm; circumference: 3,110 mm; bar diameter: 20 mm; spacing between bars: 96 mm.

Both grids were mounted on a tubular netting section (6 m in length) and placed immediately in front of the codend. An escape opening was cut on the lower portion of the net just before the TED and covered by a netting panel with three sides sewn to the net to prevent loss of commercial species. The fourth side was free and functioned as a valve, as it opened only when it was hit by large and heavy objects, and thus allowing sea turtles and other bycatch species to out the net. In both the TEDs tested, TED angle was set to 45–48°, which is an important factor in preventing commercial losses during the tow (Mitchell et al., 1995; Eayrs, 2007). In fact, an angle less than 40° may involve catch loss due to water diversion through the exit hole. Angles greater than 55° can prevent turtle escape and deflection of trash, clogging the grid.

The use of a twin trawl was the ideal solution to compare directly the catch performance of TED and the traditional net; the net with TED installed was considered as the TEST net, the net without TED was the Control (CTRL) net.

Visual Deterrents

The low water transparency characterizing the study area, which is affected by massive river inputs (Ludwig et al.,

2009), prompted the use of UV-LED lamps (Electralume, Lindgren-Pitman, United States). UV-LED lamps perform better than common light sticks, because they provide consistent high-intensity illumination, they last longer, and their light penetrates deeper into the water compared with chemical light sticks. Each lamp is fitted with two batteries that provide approximately 30 days of function. The intensity of the light was checked before each trial and low batteries were replaced as necessary.

The optimal distance between the lamps was established in preliminary tests based on the studies carried out by Wang et al. (2013) and Ortiz et al. (2016), who suggested a distance between lamps of 5 and 10 m, respectively. The negative lamps buoyancy (around 108.6 g each with the batteries) and the low net height required a visual check, to assess that lamp's weight did not reduce the headline floatability, thus impairing fishing performance. Underwater video recordings have shown that setting the distance between UV-LED lamps ≤ 10 m, as suggested by Wang et al. (2013) and Ortiz et al. (2016), would involve an excessive weight on the float line, with a partial closure of the net and a reduction of the fishing surface. Therefore, a distance ~ 15 m (corresponding to 70 lamps/km) was found to maximize gear performance and illumination as described in Virgili et al. (2018).

Data Analysis

Bottom Trawl

For each haul, the catch was divided into four categories: Commercial species (fish retained and sold), Discards (e.g., fish without commercial value, below the minimum legal size, damaged, skinned, etc.), and debris, which included anthropogenic material (marine litter) and natural material (shells, wood, stones, etc.), PET (Protected, Endangered and Threatened species, including *C. caretta*).

Catches were standardized as:

$$CPUE_W = W / (60' / \text{Tow Duration})$$

where $CPUE_W$ is the catch per unit effort expressed in terms of weight (Kg) per hour of trawling, W is the weight of the catch of each single haul and the Tow Duration is the time the net fished in each single haul expressed in minutes. A One Way ANOVA was applied to compare the commercial, discards and debris $CPUE_W$ among TEDs and control net.

For commercial species, the total length for fish (TL) and the carapace length for crustaceans (CL) were measured on-board the vessels to the nearest 0.5 cm below. To assess the influence of the TED on the size of the species caught, the length frequency distributions (LFD) for the commercial species representing more than 5% of the total catch in weight were analyzed. The generalized linear mixed model – GLMM (with haul as random intercept) was successfully used to fit curves for the expected proportions of the total catch and thus to assess the catch efficiency (at length) of TED relative to CTRL, as suggested by Holst and Revill (2009). The probability of a fish being retained by TED follows from:

$$\begin{aligned} & \Pr\{\text{TED}/(\text{TED} + \text{CTRL})\} \\ &= 1 / \left(1 + e^{-(\beta_0 + \beta_1 \times \text{length} + \beta_2 \times \text{length}^2 + \beta_3 \times \text{length}^3)} \right) \end{aligned}$$

A binomial error distribution was used to calculate the probability of the number of fish caught in the TED gear given they enter both gears by 1-cm size class (1-mm for crustaceans). A probability of 0.5 corresponds to equal catches in both gears. The analyses proceeded as recommended by Holst and Revill (2009), by fitting third order polynomials followed by subsequent reductions until all terms showed significance; this would be adequate for most cases, although in some instances a first or second order would be enough. As suggested by Holst and Revill (2009), the best model is the minimal degree polynomial curve that captures the main trends indicated by the observed proportions. The best model describing the retention probability was decided based on the lowest value of AIC. The species selected correspond to the most important commercial species during the study period: *S. mantis*, *Merlangius merlangus*, and *S. solea*.

Fishing hauls were performed following the fishermen decisions dealing with target species, fishing grounds, tow duration, etc., in order to operate in a commercial situation. According to the fishing practices the Supershooter was used in shallower waters (16 m of depth) than Flexgrid (26 m of depth). Taking into consideration the different fishing grounds, the statistical analysis enabled to directly compare the control net used in coastal waters (TC) against the Supershooter (SS), and the control net used in deeper waters (TO) against the Flexgrid (FG).

All the analyses were performed using the free software R (R Core Team, 2016) and the R packages nlme (Pinheiro et al., 2018) and lme4 (Bates et al., 2015).

The sea turtles eventually caught (as well as other bycatch species) were measured (curved carapace length, CCL, in cm) and

weighed, and then rescued as laid down by Italian Ministry of Environment guidelines (Mo et al., 2013).

Set Nets

In each trial, netting panels fitted with UV-LED lamps (*Test* nets) were compared with panels without illumination (*Control* nets). The netting panels with and without the lamps were randomly distributed along the gang, to avoid introducing additional variables. An escape area of about 15 m was left between illuminated and non-illuminated panels, to maximize their separation. The nets were set at sunset and retrieved at sunrise, providing for an average soak time of 10–16 h.

After the net was hauled on board, the catch of the *Test* and *Control* nets was analyzed separately. The catch was sorted into commercial species, discards and PET (including species as *C. caretta*, *Pteroplatytrygon violacea*, *Myliobatis aquila*, *Dasyatis pastinaca*, *Prionace glauca*, *Carcharhinus plumbeus*). Commercial, discard, and PET species were classified to the lowest possible taxonomic level, and their number and weight standardized as number and weight per 1000 m of net and 12 h of soak time, as follows:

$$CPUE_N = N_c / [(\text{Net Length}/1000 \text{ m}) \times (\text{Net Soak Time}/12\text{h})] \quad (1)$$

$$CPUE_W = W_c / [(\text{Net Length}/1000 \text{ m}) \times (\text{Net Soak Time}/12\text{h})] \quad (2)$$

where $CPUE_N$ is the catch per unit effort expressed as number of individuals and $CPUE_W$ is the catch per unit effort in terms of weight (kg); N_c and W_c are respectively the number and weight of captured individuals.

For commercial species, the total length (TL) of each specimen was measured to the nearest 0.5 cm below. Any sea turtles found in the nets were disentangled after recording their position in the gillnet, measured (curved carapace length, CCL, in cm), weighed, and rescued as above described. Those in good physical condition were released after a period of rest on board (>2 h). The CPUEs of the different categories found in the *Test* and *Control* nets were analyzed using the One Way ANOVA.

Length-frequency distributions (LFD) were analyzed for the target species (*S. solea*). The catch-comparison analysis described for TED vs. Traditional trawl (above described) was applied to assess the influence of LED on the size of common sole caught. The polynomial regression GLMM (with haul as random intercept) was successfully used to fit curves for the expected proportions of the total catch and thus to assess the catch efficiency (at length) of LED relative to CTRL. The probability of a fish being retained by LED follows from:

$$\begin{aligned} & \Pr\{\text{LED}/(\text{LED} + \text{CTRL})\} \\ &= 1 / \left(1 + e^{-(\beta_0 + \beta_1 \times \text{length} + \beta_2 \times \text{length}^2 + \beta_3 \times \text{length}^3)} \right) \end{aligned}$$

A probability of 0.5 means no difference between the gears.

RESULTS

TEDs in Bottom Trawling

The general details of each haul and the mean catch per gear, categories and species are summarized in the **Supplementary Annex SI**. The two TEDs performed in accordance with their objectives: on average, comparing TC vs. SS and TO vs. FG the discards were reduced and the debris (anthropic litter, shells, stones, etc.) was usually excluded by the escaping window (**Figure 3** and **Table 1**). However, in some hauls both discards and debris showed a great variability, so that the standard deviation was high and the differences were not statistically significant except for the debris excluded by the Supershooter and the discards reduced by the Flexgrid (**Table 1**). The results showed that both TEDs can be used in commercial conditions without negatively affect the commercial catch (**Table 1**).

Constant, Linear, and quadratic models fit catch comparisons for different species (**Table 2**), however, in general, the catch-comparison analysis showed a similar catch performance of TEDs and control nets, because the ratio TED/(TED + CTRL) is almost near the value 0.5 indicating that both nets caught similar number of fishes (**Figure 4**). From the species listed in **Supplementary Annex SII** it is clear there were no differences in the species composition.

During nine hauls performed in coastal waters to assess the performance of Supershooter TED, 10 sea turtles were caught in the control net only. These were juveniles and sub-adults with a carapace length ranging from 33 to 82 cm see **Supplementary Figures S3, S4**. No turtles were observed in the catch of sea trials performed at deeper depth.

UV LEDs in Set Nets

A total of 20 sets (*Test* and *Control* nets) were carried out during June and November 2018. Total net length ranged from 1.2 to

1.8 km (mean 1.53 ± 0.3 km; hereafter mean \pm standard error, SE). The mean length of the net portions without and with illumination was 0.76 ± 0.15 km. Mean soak time was 12 ± 1.6 h and mean fishing depth was about 8–10 m.

The mean CPUE_N of the three catch fractions (commercial, discard, and bycatch) neither mean CPUE_W were not significantly different between *Control* and *Test* nets (**Table 3**). Further analysis of the catch of the target species showed that the CPUE was highest for the two target species, *S. solea* and *S. mantis* (**Table 3**), which accounted respectively for 28 and 20% of the catch in terms of number of individuals and for 17 and 9% in terms of weight. Also in this case, the mean CPUEs for the two target species were not significantly different between the nets.

Two loggerheads were caught during the study period (see **Supplementary Figures S1, S2**), both were released in good condition after a period of rest on board. Individuals were juveniles and subadults; their CCL was 23 and 40 cm and weight were 1.4 and 8 kg, respectively. Turtles were caught by the *Control* nets. The mean CPUE_N was 0.14 ± 0.10 and the mean CPUE_W was 0.57 ± 0.45 kg.

Catch-comparison analysis highlights there were no differences by size in the catch performance of net equipped with LEDs and nets in the control configuration; the ratio LED/(LED+CTRL) is almost near the value 0.5 (Intercept: 0.499; **Figure 5**) and a constant model fits the catch comparison for this species (parameter $\beta_0 = -0.065 \pm 0.267$). The list of species reported in the **Supplementary Annex SIII** clearly demonstrates there were no appreciable differences in the species composition.

DISCUSSION

Given the fishermen's reluctance to change their traditional gear, a key aim of this study was to determine the optimal BRDs configuration that would minimize both the loss of commercial

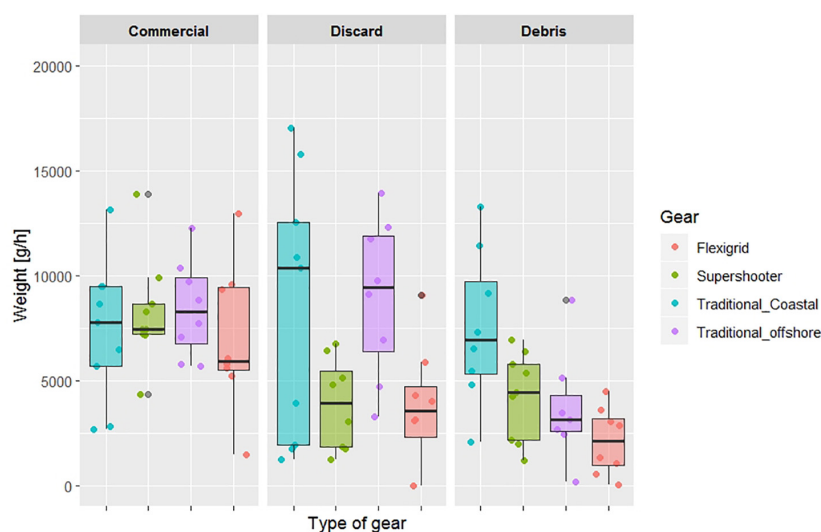


FIGURE 3 | Box plot of the mean catches ($\text{g} \cdot \text{h}^{-1}$) and standard deviations of the different categories (Commercial, Debris, and Discards) obtained with the different tested nets.

TABLE 1 | Standardized catch ($g \cdot h^{-1}$) and summary of the One-way ANOVA applied to categories: Commercial, debris, and discard to assess the difference between two types of nets (with and without TED).

Category/Gear	Mean	Ds	ANOVA	Variance component	Sum of squares	df	Mean square	F	p-value
Commercial									
TC	807.3	1882.8	TC vs. SS	Between net type	3,615,155	1	3,615,155	0.403	0.534
SS	884.1	2166.1		Within net type	143,514,600	16	8,969,663		
Debris									
TC	1484.5	2176.8	TC vs. SS	Between net type	111,304,929	1	111,304,929	5.165	0.037*
SS	673.2	959.5		Within net type	344,780,751	16	21,548,797		
Discard									
TC	633.7	1450.8	TC vs. SS	Between net type	1,100,113	1	1,100,113	0.008	0.929
SS	570.4	2989.7		Within net type	2,152,522,760	16	134,532,673		
Commercial									
TO	687.9	1462.6	TO vs. FG	Between net type	8,255,783	1	8,255,783	0.936	0.350
FG	601.3	1413.6		Within net type	123,484,567	14	8,820,326		
Debris									
TO	888.2	1966.8	TO vs. FG	Between net type	60,099,065	1	60,099,065	2.344	0.148
FG	484.3	643.6		Within net type	358,925,460	14	25,637,533		
Discard									
TO	544.0	938.8	TO vs. FG	Between net type	112,392,037	1	112,392,037	9.809	0.007**
FG	330.4	569.7		Within net type	160,407,840	14	11,457,703		

TC, traditional net used in coastal waters; SS, net equipped with Supershooter; TO, traditional net used in deeper waters; FG, net equipped with Flexgrid. * $p < 0.05$; ** $p < 0.01$.

catch and turtle captures. In the present study, we compared the performance of a rigid Supershooter TED and a flexible TED (Flexgrid) in the Mediterranean bottom twin-trawling. In more detail, we assessed the performances in terms of possible commercial losses and reduction of bycatch, discards, and debris.

Turtle excluder devices are usually designed to reduce sea turtle bycatch but, in the current study, we verified they also reduce the accumulation of debris on the codend, which negatively affects the fish quality by damaging and spoiling fish, crushing crustaceans, etc. Moreover, the presence of a turtle in the

codend catch can crush the fish already caught compromising the quality of the catch. In particular, the Supershooter successfully operates by expelling sea turtles from the net and reducing the debris. Innovations of fishing gears can be easily accepted by professional fishermen only if the economic losses are negligible and if the new gears or devices do not involve changes to the on-board procedures. The results show that both tested TEDs reduce debris and discards while keeping the commercial part of the catch unchanged. Discards reduction was statistically significant in the Flexgrid; this is of paramount importance on the light of European Regulation (Ec) 1380/2013 (2013), that introduced a legal framework for discards reduction in the Mediterranean. Present findings confirm the results obtained in the Mediterranean in other studies with Supershooter (Sala et al., 2011) and Flexgrid (Lucchetti et al., 2016b). Atabey and Taskavak (2001) found promising results in the Turkish fishery because their modified Supershooter excluded both loggerhead and green sea turtles (*Chelonia mydas*), as well as unwanted incidental catches such as jellyfish, sharks, and rays.

The selective performance of the net was unchanged with the addition of the TEDs. In fact, there was not any appreciable difference in the size frequency distributions of the fish caught nor in the species composition. Even if with slight differences, the catch-comparison analysis showed that the ratio TED/(TED + CTRL) was almost near the value 0.5, indicating that both nets (control net and net with TED) caught similar number of fishes. The results clearly show that the TEDs designed and tested in the current study can be successfully used in coastal trawling, where the most important commercial species have small sizes. Furthermore, the use of TED would lead to a reduction in debris in the codend in an area (the north-western

TABLE 2 | Generalized linear mixed model (GLMM) estimates of the Catch-Comparison.

Species	Test gear	Model	Parameter	Estimate	SE	p
<i>Squilla mantis</i>	SS	Linear	β_0	2.557	0.649	<0.001**
			β_1	-0.083	0.023	<0.001**
<i>Squilla mantis</i>	FG	Quadratic	β_0	14.605	4.397	<0.001**
			β_1	-1.053	0.306	<0.001**
			β_2	0.018	0.018	<0.001**
<i>Merlangius merlangus</i>	SS	Constant	β_0	0.209	0.207	0.311
			<i>Merlangius merlangus</i>	FG	Quadratic	β_0
β_1	1.291	0.613				0.035*
β_2	-0.028	0.014				0.051
<i>Solea solea</i>	SS	Constant	β_0	-0.189	0.254	0.457
<i>Solea solea</i>	FG	Constant	β_0	-0.128	0.223	0.568

SS, net equipped with Supershooter; FG, net equipped with Flexgrid. * $p < 0.05$; ** $p < 0.01$.

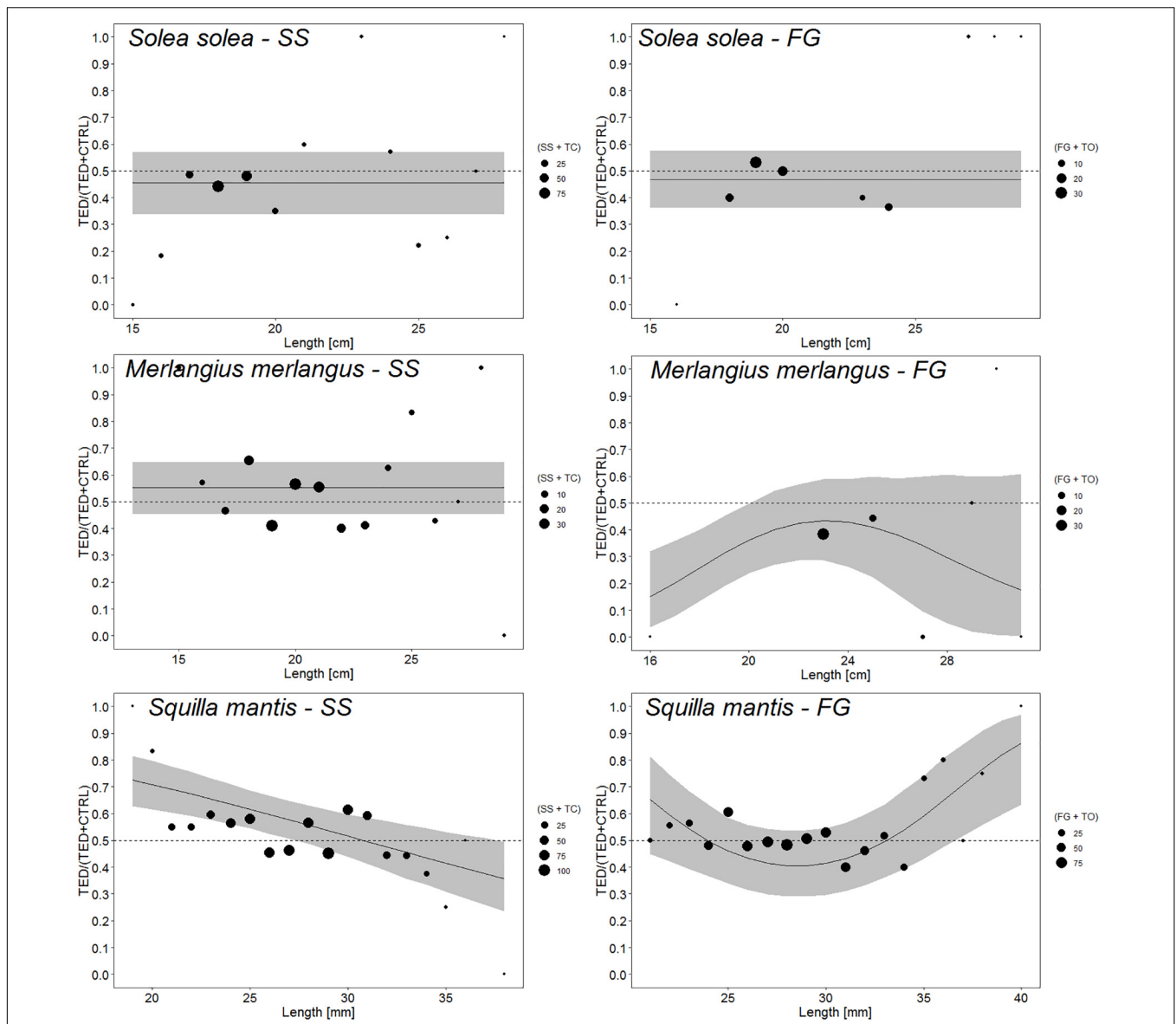


FIGURE 4 | GLMM modeled proportions of the total catches caught by the TEDs. Interpretation: a value of 0.5 indicates an even split between TED and CTRL, whereas a value of 0.25 indicates that the net mounting TED caught 25% of the total fish at that length and 75% were caught in the CTRL net. Shaded area is the 95% confident interval. The size of dots refer to the sum (TED + CTRL) of specimens for each length class.

Adriatic) where the amount of anthropic and natural waste is high due to the massive influx of the Po river (Strafella et al., 2015). Therefore, both TEDs were effective but some logistic and technical aspects could be taken into consideration in choosing the best TED: the Flexgrid was sufficiently stiff to maintain a rigid configuration during towing, and sufficiently flexible for safe winding around a standard net winch. Therefore, it did not require changes to on board procedures and did not induce a loss of time for fishermen during hauling. The Supershooter is made of aluminum and its rigidity would imply a slight change in the procedures on board. On the other hand, two horizontal bars are required in the Flexgrid to maintain the rigidity of the grid during towing; this reduces the space

to allow the fish to pass toward the codend compared to the Supershooter.

Sea turtle migrations are strongly linked with sea water temperature and prey availability (Casale et al., 2018). As a possible result of climate changes, the present study confirms that sea turtles winter in the shallow waters of the Adriatic Sea where temperatures fall below 13°C, thus remaining at northern latitudes rather than migrating south and aggregate in small groups, as reviewed by Luschi and Casale (2014) and in accordance with Hochscheid et al. (2007). This is alarming: although sea turtles may adapt to the increasing temperatures, climatic changes in foraging and overwintering habitats will probably negatively affect loggerhead turtle populations nesting

TABLE 3 | Set net catch rates expressed as mean CPUE_N and CPUE_W and summary of the One-way ANOVA applied to categories: Commercial, discard, PET (Protected, Endangered, and Threatened species), and target species to assess the difference between two types of nets (with and without LEDs; Control = without illumination; Test = with UV-LED lamps).

	Category/Gear	Mean	Ds	ANOVA	Variance component	Sum of squares	df	Mean square	F	p-value	
CPUE _N	Commercial										
	Control	74.2	96.00	Control vs. Test	Between net type	406.5	1	406.5	0.061	0.806	
	Test	67.8	64.00		Within net type	253,066	38	6659.63			
	Discard	Control	4.73	14.00	Control vs. Test	Between net type	0.07	1	0.07	0.0003	0.986
		Test	4.81	15.43		Within net type	8281.4	38	217.9		
	PET	Control	2.21	3.22	Control vs. Test	Between net type	5.12	1	5.12	0.56	0.459
Test		1.5	2.77	Within net type		347.44	38	9.14			
CPUE _W	Commercial										
	Control	5.98	6.42	Control vs. Test	Between net type	196,516	1	196,516	0.067	0.798	
	Test	6.42	5		Within net type	112,156,000	38	2,951,470			
	Discard	Control	0.44	0.67	Control vs. Test	Between net type	54767.7	1	54767.7	0.129	0.722
		Test	0.36	0.58		Within net type	1,618,750	38	425,986		
	PET	Control	4.29	5.77	Control vs. Test	Between net type	1,682,750	1	1,682,750	0.526	0.473
		Test	2.99	5.5		Within net type	121,573,000	38	3,199,290		
	Solea solea	Control	17.37	25.49	Control vs. Test	Between net type	366.6	1	366.6	0.324	0.573
		Test	26.93	42.8		Within net type	42989.5	38	1131.3		
	CPUE _W	Control	1.77	2.91	Control vs. Test	Between net type	2595.43	1	2595.43	0.0004	0.984
		Test	1.76	1.97		Within net type	23,714,000	38	624,054		
	Squilla mantis	Control	16.35	23.43	Control vs. Test	Between net type	1.12	1	1.12	0.002	0.966
Test		16.01	25.58	Within net type		22900.3	38	602.64			
CPUE _W	Control	0.8	1.12	Control vs. Test	Between net type	332,357	1	332,357	0.199	0.658	
	Test	1.01	1.48		Within net type	6,354,450	38	167,222			
Other species	Control	40.46	77.67	Control vs. Test	Between net type	1463.33	1	1463.33	0.369	0.547	
	Test	28.37	43.48		Within net type	155,031	38	3961.35			
CPUE _W	Control	3.42	5.2	Control vs. Test	Between net type	767,872	1	767,872	0.035	0.853	
	Test	3.7	4.14		Within net type	83,692,000	38	2,202,420			

in the eastern Mediterranean Basin (Patel et al., 2016). Taking into account the fact that the turtles were only caught in very coastal waters, near mussel farms, these animals are likely to find easy availability of prey near the aquaculture facilities. Lucchetti et al. (2016a) identified the study area as a possible hot spot for bottom trawl-sea turtle interaction, especially at depths shallower than 40 m. In this area, the TEDs tested in the present study were highly efficient. Therefore, the adoption of TED in critical areas and seasons together with other management measures has the potential to provide a substantial contribution to the conservation of *C. caretta* in the whole Mediterranean.

No practical solution to reduce the risk of bycatch due to set nets was available for Mediterranean fisheries until a few years ago, except reducing netting twine thickness or using gillnets instead of trammel nets. The UV-LED lamps tested in the current study did not affect the catch efficiency of the major commercial species. Interestingly, however, they did reduce the interaction with sea turtles, since no loggerheads were found in the illuminated portions of the net. Virgili et al. (2018), tested for

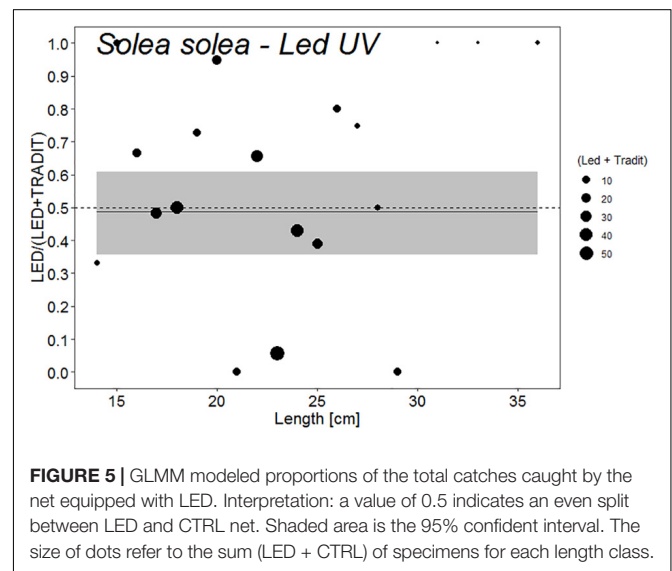


FIGURE 5 | GLMM modeled proportions of the total catches caught by the net equipped with LED. Interpretation: a value of 0.5 indicates an even split between LED and CTRL net. Shaded area is the 95% confident interval. The size of dots refer to the sum (LED + CTRL) of specimens for each length class.

the first time this BRDs applied to gillnets targeting rays in the Adriatic Sea (offshore waters), in an area that has been proven to be a hotspot of sea turtle occurrence (Lucchetti et al., 2017b). The net was illuminated with the same UV-LED lamps used in the present study, which have a longer life and provide greater light intensity than ordinary light-sticks. They obtained the same results, with sea turtle bycatch zeroing and no differences in the commercial catch. Visual deterrents, like chemical light sticks and LED lamps mounted on set nets, have successfully been tested in gillnet fisheries in some areas of the Pacific Ocean, where they have proved effective in reducing the sea turtle bycatch (Wang et al., 2010, 2013; Ortiz et al., 2016). Although further sea trials are needed, UV-LED illumination confirms to be an effective tool to deter sea turtles from approaching set nets in Mediterranean while preserving the commercial catch.

This was a pilot study trying to test the efficacy of TED (in bottom trawl) and lamps (in passive nets) to reduce sea turtle bycatch while keeping unchanged the commercial catch. The study does not claim to be exhaustive and definitive of the problem; however, the results are encouraging and the use of these devices can be replicated efficiently in the main Mediterranean demersal fishing activities that operate with bottom trawls and passive nets. Therefore, before introducing these BRDs in the fisheries mentioned above, it is appropriate to carry out a final distribution of these devices to a reasonable number of vessels.

DATA AVAILABILITY

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

ETHICS STATEMENT

Caretta caretta is a protected species, included in the list of Annex IV of animals requiring close protection under the Habitat Directive and assessed by the International Union of Conservation of Nature and Natural Resources (IUCN) as “vulnerable” at global scale (Casale and Tucker, 2015) and as “least concern” for the Mediterranean Sea (Casale et al., 2015; Lucchetti et al., 2016b). In this study, no manipulations were performed on the turtles and no direct interventions were carried out. We only recorded individual capture events. In case of injured turtles observed in the catch, the procedures of the Italian Ministry of Environment guidelines were applied (“*Linee Guida per il recupero, soccorso, affidamento e gestione delle tartarughe marine ai fini della riabilitazione e per la manipolazione a scopi scientifici*,” Mo et al., 2013) and sea turtles were rescued by Authorized Rescue Centres. All applicable international,

national, and/or institutional guidelines for the care and use of animals were followed, in particular: Mo et al. (2013). This article does not contain any studies with human participants performed by any of the authors.

AUTHOR CONTRIBUTIONS

AL made the analysis and wrote the manuscript. MV, GB, AP, and CV made the data collection. MV wrote some parts of the manuscript. GB, AP, and CV reviewed the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2019.00387/full#supplementary-material>

FIGURE S1 | See turtle disentangled from the gillnet during hauling procedures.

FIGURE S2 | See turtle caught in the gillnet tests.

FIGURE S3 | See turtle caught and released by the TED during trawl tests (1).

FIGURE S4 | See turtle caught and released by the TED during trawl tests (2).

ANNEX SI | Details of the hauls performed during the study. TC: Traditional net used in coastal waters; SS: net equipped with Supershooter; TO: Traditional net used in deeper waters; FG: net equipped with Flexgrid.

ANNEX SII | Details of the mean catch and standard deviation (g/h) by categories and gears obtained during the study. TC: Traditional net used in coastal waters; SS: net equipped with Supershooter; TO: Traditional net used in deeper waters; FG: net equipped with Flexgrid.

ANNEX SIII | Details of the mean catch and standard deviation (g/12h*1000m) by categories and gears obtained during the study. CTRL: Traditional net used and UV-LED: set net equipped with visual deterrents.

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Conflict of Interest Statement: 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.

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