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Effects of Turtle Excluder Devices on bycatch and discard reduction in the demersal fisheries of Mediterranean Sea

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Abstract – The Central Mediterranean provides important neritic habitats for loggerhead turtles (*Caretta caretta*), but Mediterranean bottom trawlers catch an estimated 30 000 turtles a year, with 25% mortality. Mortality by trawling is mainly due to enforced apnoea during towing activity. In order to reduce the submergence time and consequent turtle mortality, a specific technical modification was developed in the early 1980s: the Turtle Excluder Device (TED). In this paper, we field-tested a typical *Supershooter* TED and three new types of low-cost TED, built with different designs and materials, incorporating aspects of US and Australian TEDs, as well as design features to improve handling and catch rates. The performance of the TEDs was investigated under commercial fishing conditions in diverse trawling grounds in the Adriatic Sea (Mediterranean). All TEDs were easy to operate and did not require changes to normal fishing operations. Due to lack of entry of turtles it was not possible to evaluate the ability of the different TEDs to release turtles, but one large loggerhead turtle (*C. caretta*) was captured during the experimental tows and was successfully excluded by the *Supershooter*. The TEDs reduced anthropogenic debris and, consequently, sorting operations on board. Among the four TEDs tested, both the semi-rigid TED and the *Supershooter* performed in accordance with the design objectives: total discards were reduced but total commercial catches were not significantly reduced. With the *Supershooter*, all European hake (*Merluccius merluccius*) individuals equal to or above 16 cm were found in the codend and 10–15% of those between 5.0 and 15.5 cm were released. In general, the total discard rate of the TED-equipped nets was reduced to around 20–60%. Since the Council Regulation (EC) No. 1967/2006 called for a discard reduction policy in waters under the jurisdiction of the European Union, TEDs may have some broader value in this context.

Key words: Bycatch-reduction device / TED / Demersal trawl / Generalised linear mixed model (GLMM) / *Caretta caretta* / Mediterranean Sea

1 Introduction

Bycatch, the capture of undesired species, is a recognized problem with all fishing methods (Watson et al. 2005; Sala et al. 2006, 2007, 2008; Kot et al. 2010). Bycatch can include species that may be targeted in other fisheries, undersized fish in the target fishery and accidentally captured endangered or protected species such as whales, turtles and seabirds.

Hall's (1996) definition of bycatch as *"all non-target fish whether retained and sold or discarded"* may not be appropriate enough for multispecies Mediterranean fisheries. The source of the problem is mainly in the description of "target" species. Undersized individuals (e.g. below the Minimum Landing Size, MLS) or juveniles are illegal but are very often sold and therefore targeted. In some cases, they are the main target. Therefore, *"retained"* and *"discarded"* are much more realistic catch components for Mediterranean trawl fisheries.

In the Mediterranean, interactions of sea turtles with fishing gears, including trawl nets, are still insufficiently studied (Casale et al. 2004; Lucchetti and Sala 2010).

The loggerhead sea turtle (*Caretta caretta*) is the most abundant turtle species in the Mediterranean Sea. Three main ecological phases characterize the life of these turtles: the pelagic phase, the demersal phase, and finally an intermediate neritic phase (Lucchetti and Sala 2010). Bottom trawling activity has a strong impact on turtles in the demersal phase, as they are found at highest densities in shallow waters (<100 m). Mediterranean bottom trawlers are estimated to catch approximately 30 000 loggerheads a year, with 25% mortality (Lucchetti and Sala 2010). Moreover, as the same individual turtle can be captured more than once, Casale (2008) estimated more than 40 000 "capture events" in Italian waters alone. Mortality due to trawling is mainly caused by enforced apnoea during towing activity. Therefore, towing time is one of the main factors affecting mortality rate (Henwood and Stuntz 1987), especially in bottom trawl fisheries, although additional factors may influence mortality in this fishery (Stabenau et al. 1991).

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Turtle excluder devices (TEDs) were proposed in the early 1980s to reduce turtle submergence and mortality. A TED is a grid-like device that diverts large objects (including turtles) towards an exit positioned before the codend (Mitchell et al. 1995; Epperly 2003). Some authors report that the currently available TEDs are probably not a realistic solution for reducing turtle bycatch in the Mediterranean because they are designed for the shrimp trawl fishery and would exclude larger commercial fish (Laurent and Lescure 1994; Laurent et al. 1996; Casale et al. 2004). However, Atabey and Taskavak (2001) found promising results in the Turkish fishery because their modified *Supershooter* TED excluded both loggerhead and green sea turtles (*Chelonia mydas*), as well as unwanted incidental catches such as jellyfish, sharks, and rays.

In this paper, we sea-tested a typical *Supershooter* and three new types of low-cost TEDs made using different designs and materials. The performance of the TEDs was investigated under commercial fishing conditions in diverse trawl grounds in the Adriatic Sea (Mediterranean). Our first objective was to compare catch rates of retained species, discarded species and debris components in each TED-equipped net. We also investigated the effect of each TED on catch at the species level. Our second objective was to analyse length data of European hake (*Merluccius merluccius*), the main commercial species in Mediterranean trawl fisheries, in the TED-equipped nets. A length-based analysis could provide more insight into the relative performance of the TEDs tested. Furthermore, catch ratios were modelled as a function of length as a means of estimating the relative size selection of TED-equipped nets.

2 Materials and methods

2.1 Research vessel and trawl gear

Field tests were conducted on RV *"G. Dallaporta"*, an Italian Research Vessel of 810 kW at 1650 rpm, 35.30 m full length, and 285 gross tonnage. The gear employed in the sea trials was a four-sided net of the type used by professional fishermen in different Mediterranean areas. The main body and wings of the net were made of knotted polyethylene (PE) netting, while the codend was of a typical knotless polyamide (PA) netting (Fig. 1). The codend mesh opening (40 mm, Fig. 1) was measured in wet conditions with the OMEGA mesh gauge (Fonteyne 2005). All rigging components of the gear and trawling speed were identical to those commonly practiced in commercial Mediterranean demersal trawl fisheries (Fig. 1). All TEDs tested were located immediately in front of the codend of the trawl net. An escape gap in the bottom of the net was covered by a clear, weighted sheet of small-mesh netting. This escape gap cover was designed to allow the exclusion of large objects, while preventing the loss of smaller commercial species (i.e., hake, red mullet, shrimp, etc.). A bottom-opening TED was used as it is important to exclude debris, such as grass, sticks, shell and sponge, from commercial catch in Adriatic demersal fisheries. Water flow and gravity can force debris and unwanted bycatch (jellyfish, sharks, and rays) down the grid face and out of the exit hole. In order to direct fish away from the TED exit hole and through the bars of the TED, we installed an accelerator funnel as recommended by Mitchell et al. (1995). A TED cover was attached under the TED opening to collect any escapees. During the first sea trials, 40 cm^2 plastic containers were released by the vessel stern during the tows in order to test whether they were excluded through the TED escape gap.

2.2 Sea trials and gear behaviour performance

Sea trials were carried out in the North Adriatic Sea. This area, with its shallow waters and rich benthic communities, is considered one of the most important feeding habitats in the Mediterranean, especially for the loggerhead population nesting in Greece (Margaritoulis 1988; Lazar et al. 2000, 2004). Three different subareas were surveyed from 3 to 13 March 2008 at about 21 m, 32 m and 71 m water depth in order to determine the general effect of TED insertion on fishing gear behaviour. Gear performance (i.e., door spread, horizontal and vertical net openings) was measured on all hauls using the SCANBAS SGM-15 system (SCANMAR, Norway). A laptop, with customized software, automatically controlled data acquisition and provided real-time information about the correct functioning of the system (Prat et al. 2008; Sala et al. 2009). The main goal of these measurements was to obtain detailed real time data on gear performance for each haul, in order to determine possible influences of the TED on net behaviour and to calculate vessel speed and tow duration. Towing duration was considered as the time between the achievement of optimal gear opening and the moment when speed was reduced to recover the warps.

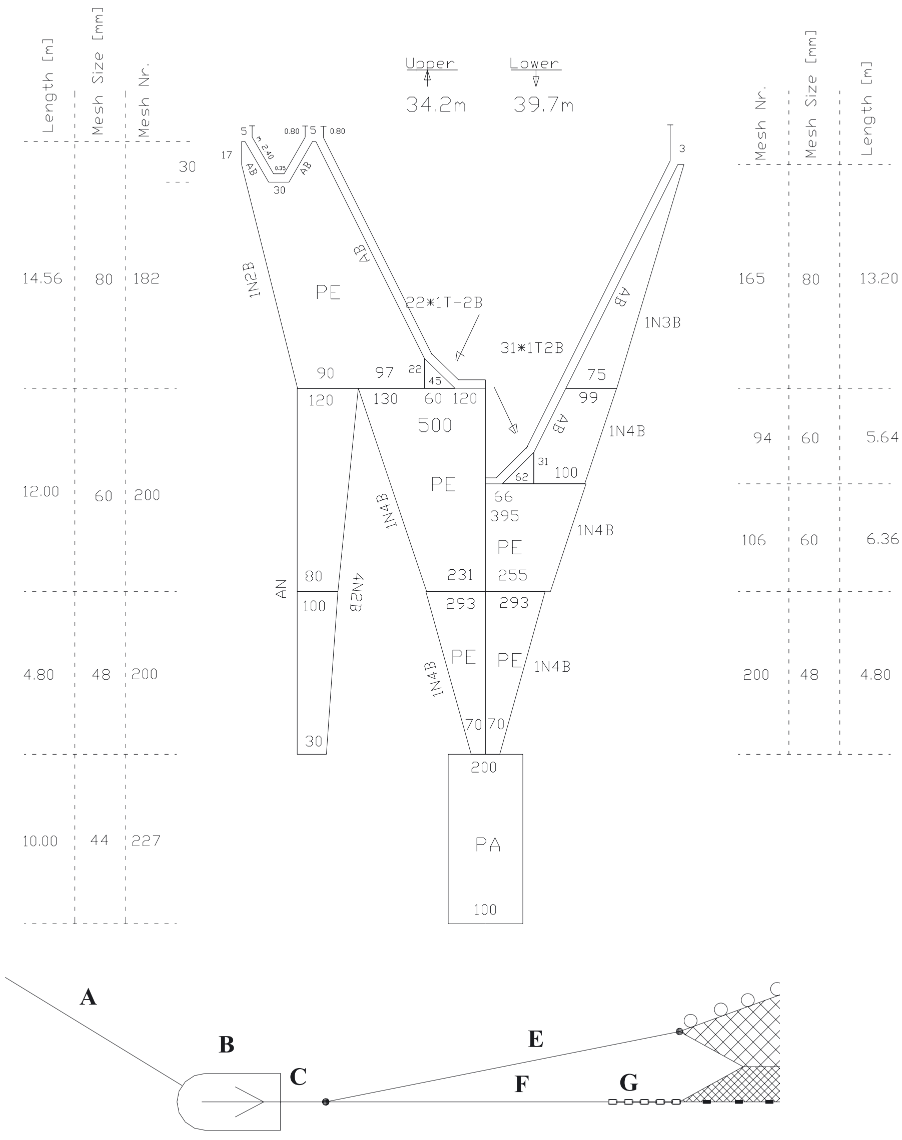
2.3 TED specifications and design details

Four different types of TEDs were designed, manufactured and tested at sea. The tested TEDs differed in their material, shape, size and bar spacing and would, therefore, be expected to behave differently, which justifies the testing and performance comparison that are the main objectives of the current study. Features from US and Australian TEDs (Mitchell et al. 1995; Tucker et al. 1997; Robins and McGilvray 1998) were incorporated and novel materials used to produce bycatch reduction systems that avoid reduced catch of commercial species. The first grid type (TED1) was a light and rigid grid made of aluminium (Fig. 2). The bars of TED1 were removable so that the space between them could be adjusted. Unfortunately, after the first haul, TED1 broke down due to the large quantity of debris that was not discharged from the exit hole and, thus, got trapped in the TED, causing a rupture (Fig. 2).

The second grid type (TED2) was a flexible grid made of mixed cable (steel inside and polyethylene outside). This flexible grid was designed so that the TED position could adjust according to the net movements during tow (Fig. 2b).

The third grid type (TED3) was a semi-rigid and resistant grid. This grid was made of steel and rubber to combine the flexibility of rubber and the resistance of steel (Fig. 2c).

TED4 was a classic aluminium *Supershooter* grid, commonly used in shrimp fisheries in several countries. The *Supershooter* is usually designed to reduce the accumulation of



A	**Warp Ø 16 mm**	
B	**Doors (1800 mm x 1150 mm) - 280 kg**	
C	**Combination rope Ø 22 mm**	
E	**Wire Ø 10 mm**	
F	**Combination rope Ø 32 mm**	
G	**Chain**	

Fig. 1. Design and gear rigging of the trawl used during the samplings at sea. The trawl is a 4-faced bottom trawl, recently introduced in the Adriatic Sea. Apart the polyamide codend it is entirely made of knotted polyethylene (PE) netting.

debris on the TED deflector bars, which can prevent fish from passing through the TED and into the codend. By taking into account the complex composition of Adriatic fishing (crustaceans, molluscs and fishes together), we kept the space between reflector bars greater than in standard models. In all the TEDs tested, we set the TED angle to 45–48 degrees (Fig. 2d), which is an important factor in preventing commercial losses during the tow (Mitchell et al. 1995).

2.4 Data analysis

Only species that were caught regularly and abundantly were considered in the analysis. Catch rates (kg km^{-2}) were evaluated with a method for comparison of fishing powers, using natural logarithm transformed data (Cochran 1977; FAO 1999). For each haul, the weight of each species, both in the TED cover and codend, were converted into kilograms per

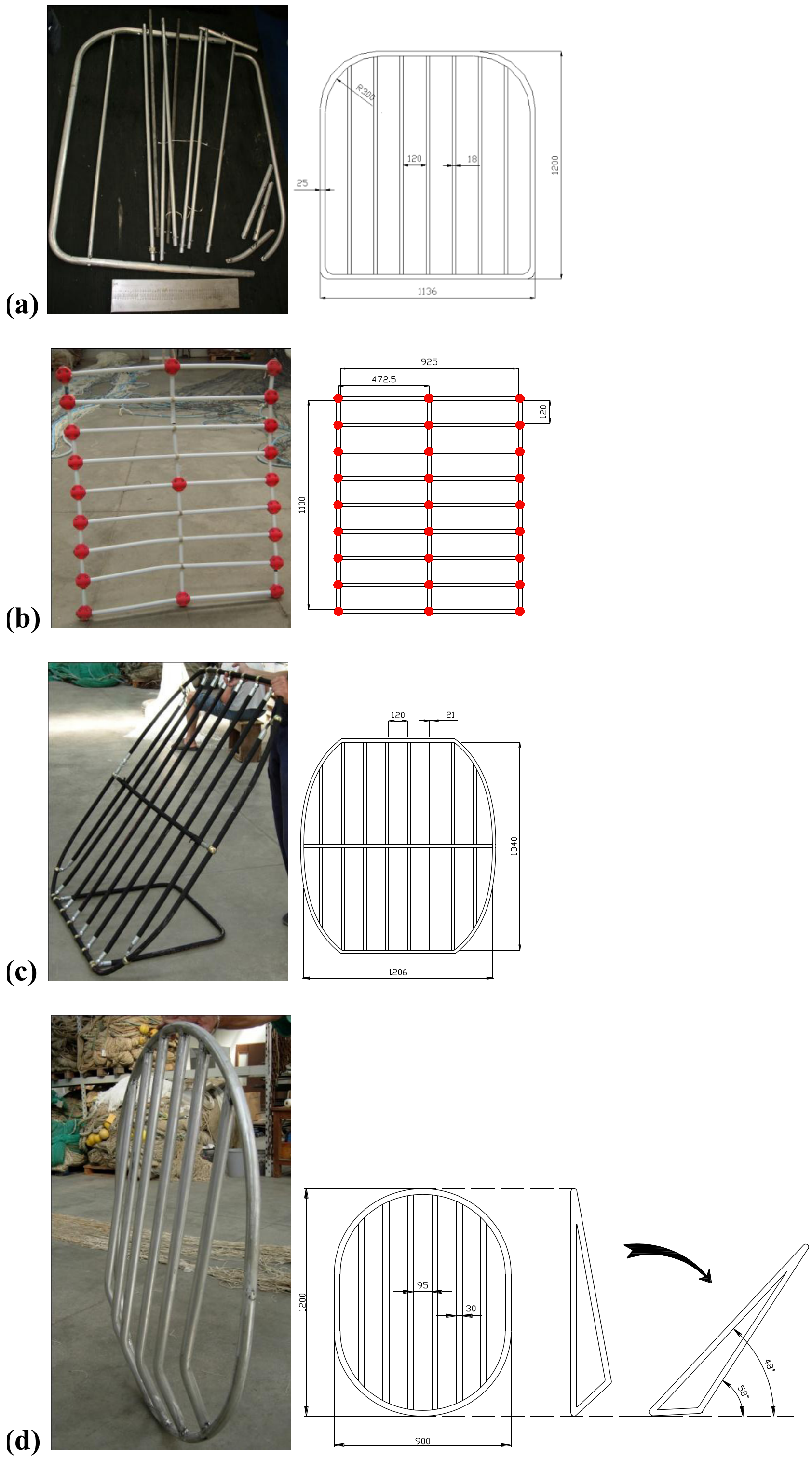


Fig. 2. Dimensions (mm) of the Turtle Excluder Devices (TED): (a) TED1, made of aluminium. The bars were removable to enable the adjustment of the space between them. TED1 broke down because of the large quantity of debris. (b) TED2, made of a flexible grid of mixed cable (steel inside and polyethylene outside). TED2 was installed with the aim of making the TED position capable of adjusting according to net movements during tow. (c) TED3, made of a semi-rigid and resistant grid of steel and rubber, with the aim of combining the flexibility of rubber and the resistance of steel. (d) TED4, the *Supershooter* grid made of classic aluminium. TED4 is commonly used in prawn fisheries in several countries. To take into account the complex fishing composition (crustaceans, molluscs and fishes together), we kept the space between reflector bars larger than in the standard models.

km^2, based on horizontal net opening (measured by the Scanmar system), vessel speed, and tow duration. Tow duration was the time between the achievement of optimal gear opening and the moment of speed reduction to recover the warp. The method was modified so that catch rates were adjusted to catch per standard haul (kg tow^{-1}), derived from the standardisation of hauls. Because the mean of the original (non-transformed) data may be oversensitive to extreme values and confidence intervals are large, McConnaughey and Conquest (1993) suggested the use of the geometric mean as an estimator with more desirable statistical properties. This estimator was computed by exponentiating the mean of the *log*-transformed data and subtracting one (Sala et al. 2004). This estimator is reported in the tables and was used for all comparisons. The fishing power (FPOW) of each TED-equipped net (*test*) relative to a *"control"* was then calculated. Since we did not tow any unmodified nets (without TEDs), we pooled catches from the TED cover and codend in the test tow to calculate total catch of a *"control"*. For each species, FPOW was computed as the ratio between the mean catch of the *test* (codend) and the *control* (codend + TED cover). This was calculated by subtracting the two means of the log-transformed data and then calculating the exponent of the result (Finney 1971). Fishing power is a proportional value; hence, if there were no differences between the trawls, fishing power would be 1.00. Balanced one-way analysis of variance (ANOVA) and Tukey's post-hoc tests were conducted on log-transformed data of FPOW with TED-type as the factor. The statistical tests were performed using the SPSS software package. Normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test) of FPOW data were verified before applying the ANOVA test.

Catch comparison experiments generate binomial data, it is, therefore, interesting to estimate the expected proportions of each length class in the total catch in the codend. For a single haul, the curve may be fitted with a generalised linear model (GLM). For a cruise (i.e., a collection of related hauls), the mean curve may exhibit random variation between hauls in addition to the variation accounted for by fixed effect covariates (Fryer 1991). For such data, Holst and Revill (2009) showed that generalised linear mixed models (GLMM) can be used to obtain a reliable curve for the expected proportions-at-length and to avoid making unrealistic variance estimates by modelling the sampling structure. Tools for GLMM analyses have been recently standardised by Holst and Revill (2009), and we used, as these previous authors, the same glmm-PQL function implemented in the MASS package of the *R* statistical software (R Development Core Team 2009). This method implements the penalised quasi likelihood function (Breslow and Clayton 1993), where insignificant terms are removed based on the Wald's test. The TED-equipped net and *control* being compared are indexed *t* (test) and *c* (control), respectively. Essentially, the selection properties can be described by logistic curves. The *logit* of the expected proportion (p_k) of the catch caught in the *test* can be approximated by *k*th order polynomial in ℓ

$$p_k(\ell;\beta) = \log(q_t/q_c) + \beta_0 + \beta_1 \cdot \ell + \ldots \beta_k \cdot \ell^k.$$

Catches are often sub-sampled, so let q_t and q_c be the sub-sampling ratios of fish taken out for measurements from the catch bulk of the *test* and *control*, respectively. When data are collected in, say, *H* hauls, a mixed effects model approach may be used to account for the variability between the hauls (Holst and Revill 2009). For a random intercept model the polynomial associated with haul *h* becomes:

$$p_k^{(h)}(\ell;\beta) = \log\left(q_t^{(h)}/q_c^{(h)}\right) + \beta_0 + \beta_1 \cdot \ell + \ldots \beta_k \cdot \ell^k + b_n$$

with $q_t^{(h)}$ and $q_c^{(h)}$ being sub-sampling ratios for haul *h*, for test and control, respectively, and where $b_h \sim N(0, s^2)$. For further details see Holst and Revill (2009).

3 Results

3.1 Sea trials

Data were collected from 42 hauls, with a mean duration of 48 ± 12 min: 11 with TED2, 15 with TED3 and 15 with TED4. There was no evidence that the TEDs were more likely to be damaged than other parts of the trawl. Due to lack of entry of turtles, it was not possible to evaluate the ability of the different TEDs to release turtles, but one large loggerhead turtle was captured during the experimental tows, and was successfully excluded by the *Supershooter* (TED4).

3.2 Effect on catch rates

All TED systems performed in accordance with their objectives: total discards were reduced and bulky objects such as anthropogenic debris were usually excluded by the escape gap and found in the TED cover. Preliminary simulations with plastic containers released by the vessel stern during the tows revealed that all TEDs successfully excluded all of the containers and diverted them into the TED cover.

Significant reductions in discards were observed during the tests of all the TEDs, but these were sometimes associated with a different degree of reduction in the total catch retained (Table 1). When trawling operations moved into areas where anthropogenic debris was abundant, species/materials tended to clog up the bars of both TED2 and TED3, which resulted in greater losses of retained species (Table 1). TED4 had the best performance, with only 2% of losses (FPOW = 0.975) in retained and saleable total catch. Furthermore, TED4 had the highest reduction in total discards (FPOW = 0.415) and anthropogenic debris (FPOW = 0.514). TED2 was equivalent to TED4 in reduction of discarded catch (FPOW = 0.443), but had the lowest total catch rate of retained species (FPOW = 0.642). Subsets of means that do not differ from one another are indicated in Table 1. For retained species, TED2 was significantly different from the other two TEDs ($p < 0.001$). For discards, however, the mean of TED3 differed significantly from the others ($p < 0.003$). Only one subset of means was identified for anthropogenic debris, meaning that debris did not significantly differ among the TEDs according to ANOVA ($p = 0.431$) and Tukey's post-hoc tests.

Twenty-one main species were identified in the catches (Table 2), eleven species in the retained catch and ten species of discards. A summary of the mean catch per tow (kg/tow)

Table 1. Analysis of fishing power for all the TED-equipped nets. The fishing power (in bold, SD in parenthesis) of each TED-equipped-net (Test) relative to a Control (codend + TED cover) was calculated for each catch category (retained, discards and anthropogenic debris), as the ratio between the mean catch of the Test and Control (kg/tow, SD in parenthesis). Balanced one-way analysis of variance (*ANOVA*) and Tukey's post-hoc tests were conducted for each category on log-transformed data of fishing power with TED-type as factor. Means are given for groups in homogeneous subsets (HS).

		RETAINED		DISCARDS		DEBRIS	
TED2	Test	13.29	(1.30)	11.64	(2.26)	5.52	(2.04)
	Control	20.77	(1.34)	27.91	(2.18)	6.76	(2.18)
	Fishing power	**0.642**	(0.05)	**0.443**	(0.14)	**0.825**	(0.09)
TED3	Test	17.45	(1.78)	21.11	(1.88)	10.71	(5.15)
	Control	20.35	(1.90)	27.25	(1.89)	14.50	(3.78)
	Fishing power	**0.865**	(0.08)	**0.778**	(0.07)	**0.623**	(0.35)
TED4	Test	19.71	(1.83)	8.88	(4.23)	1.59	(3.68)
	Control	20.24	(1.85)	24.60	(5.09)	3.52	(3.94)
	Fishing power	**0.975**	(0.03)	**0.415**	(0.31)	**0.514**	(0.35)
ANOVA	Signif.*p*	0.000**		0.003**		0.431	
HS	1	TED2		TED2,4		TED2,3,4	
	2	TED3,4		TED3			

and fishing power (FPOW) for each species is presented in Table 2. From the retained catch, *Melicertus kerathurus*, *Eledone* spp., *Merluccius merluccius*, *Mullus barbatus*, *Sepia officinalis* and *Squilla mantis* were generally the most important commercial species. The effect of TEDs on discarded species was more variable, as indicated in the large range of catch rates (Table 2). The trawl fitted with TED2 had the worst performance with the highest losses of all retained species (Table 2). Among the retained species (except for *M. kerathurus*, *M. barbatus* and *Trachurus* spp.), the catch rate of TED4 was always highest, but it was not significantly different from that of TED3 (Table 2). Such a similarity between TED3 and TED4 was also found for *Scomber* spp., *Sepia officinalis* and *Squilla mantis* (Table 2). For European hake (*M. merluccius*) also, the fishing power of TED4 (0.972) was not significantly higher than that of TED3 (FPOW = 0.859), but this pair does show significant pairwise differences from TED2 FPOW (0.632; Table 2).

3.3 Catch comparison analysis

The GLMM method was applied to catches of European hake, the most abundant species, which represented an average 15% of the total retained catch weight. The sizes of hake were in the ranges 8–38 cm, 10–36 cm and 6–38 cm for the TED2-, TED3- and TED4-equipped nets, respectively. The catches of fish (measured to nearest 0.5 cm below) from *test* (codend of the TED-equipped net) and *control* (codend + TED cover) were compared. The polynomial regression GLMM (with haul as random intercept) was successfully used to fit curves for the expected proportions of the total catch. The analyses were conducted as recommended by Holst and Revill (2009), by fitting third order polynomials followed by subsequent reductions until all terms showed significance. As suggested by Holst and Revill (2009), the best model was the minimal degree polynomial curve that captured the main trends indicated by the observed proportions. Parameter estimates with standard errors of the final fits are detailed in Table 3. The best polynomial curve for all TEDs was the *logit*-linear curve (Table 3), indicating that fish length was a significant factor in the curve fit.

Extra variability induced by sampling over multiple hauls is appropriately handled within the framework of GLMM. The numbers of hake in the catches with TED2 were significantly reduced by 20–50% (Fig. 3). With TED2, significant reductions of hake were observed across the entire length range caught (8–38 cm), with higher releases for larger hake. With both TED3 and TED4, larger hake were released to a lesser extent than smaller hake (Fig. 3).

4 Discussion

Commercial Mediterranean fishermen are very interested in testing TEDs because these devices can reduce debris and bycatch in the trawl, which can potentially reduce damage to fish, and speed up the sorting time on deck (Lucchetti and Sala 2010). The economic consequences of introducing gear modifications are possibly the single most important constraint. This further emphasizes the need for a close partnership with industry in the introduction of any BRDs (*Bycatch Reducer Devices*) or more selective gears in a gradual and adaptive manner. To be acceptable in any fishery, TEDs, for example, must reduce bycatch and discards, while maintaining safety, ease of operation and profitability.

Among the four TEDs tested, both the semi-rigid TED (TED3) and the *Supershooter* (TED4) performed in accordance with the design objectives: total discards were reduced, and commercial catches were not significantly reduced. Both the TED3 and the *Supershooter* were easy to operate and did not require changes to normal fishing operations. No noticeable increase in drag or twisting of the codend was detected in the trawls fitted with the TEDs. The low weight of the *Supershooter* ensured that there was no increase in safety risks to the crew on the work deck.

In the current assessment, as only one loggerhead turtle was captured and successfully excluded by the *Supershooter* (TED4), it should perhaps not be used to draw general conclusions on comparative TED performance. However, we

Table 2. Mean catch per tow (kg/tow, SD in parenthesis) and fishing power for each species caught by all the TED-equipped nets. Balanced one-way analysis of variance (ANOVA) and Tukey's post-hoc tests were conducted for each category on log-transformed data of fishing power with TED-type as factor. The fishing power of each TED-equipped-net (test) relative to a control (codend + TED cover) was calculated for each species as the ratio between the mean catch of the test and control. Means are given for groups in homogeneous subsets (HS).

SPECIES	Gear	MEAN CATCH PER TOW (kg / tow)			FISHING POWER			Diff. Test Signif. *p*	HS	
			TED2	TED3	TED4	TED2	TED3	TED4		
Alloteuthis media	Test	0.760 (0.023)	0.933 (0.015)	0.688 (0.030)	**0.459**	**0.844**	**0.987**	0.000**	TED2	TED3
	Control	1.540 (0.014)	1.320 (0.042)	0.722 (0.041)						TED4
Aporrhais pespelecani	Test	0.856 (0.027)	1.042 (0.009)	0.606 (0.182)	**0.583**	**0.458**	**0.498**	0.577	–	–
	Control	1.129 (0.082)	1.928 (0.033)	1.006 (0.045)						
Eledone spp.	Test	0.700 (0.173)	0.785 (0.138)	0.797 (0.014)	**0.681**	**0.821**	**1.000**	0.174	–	–
	Control	1.087 (0.066)	0.950 (0.055)	0.797 (0.014)						
Loligo vulgaris	Test	0.584 (0.177)	0.748 (0.121)	0.699 (0.017)	**0.502**	**0.814**	**0.996**	0.044*	TED2	TED3
	Control	1.153 (0.059)	0.810 (0.025)	0.730 (0.028)					TED3	TED4
Sepia officinalis	Test	1.050 (0.010)	0.987 (0.022)	1.039 (0.009)	**0.766**	**1.000**	**1.000**	0.056	–	–
	Control	1.452 (0.042)	0.987 (0.022)	1.039 (0.009)						
Turritella communis	Test	0.694 (0.060)	0.413 (0.223)	0.979 (0.032)	**0.943**	**0.405**	**0.621**	0.029*	TED2	TED3
	Control	0.746 (0.085)	0.842 (0.104)	1.592 (0.038)					TED4	TED4
Liocarcinus depurator	Test	0.869 (0.149)	1.136 (0.038)	0.839 (0.020)	**0.766**	**0.764**	**0.913**	0.383	–	–
	Control	1.684 (0.043)	1.629 (0.094)	1.109 (0.052)						
Melicertus kerathurus	Test	0.423 (0.172)	0.985 (0.014)	1.038 (0.007)	**0.563**	**1.000**	**0.862**	0.076	–	–
	Control	0.656 (0.065)	0.985 (0.014)	1.388 (0.047)						
Squilla mantis	Test	0.523 (0.142)	0.785 (0.118)	1.152 (0.003)	**0.650**	**0.879**	**0.879**	0.212	–	–
	Control	0.766 (0.071)	0.861 (0.042)	1.689 (0.035)						
Arnoglossus laterna	Test	0.925 (0.023)	1.059 (0.009)	0.961 (0.005)	**0.656**	**0.838**	**0.934**	0.021*	TED2	TED3
	Control	1.719 (0.016)	1.587 (0.045)	1.332 (0.031)					TED3	TED4
Boops boops	Test	0.841 (0.028)	0.829 (0.028)	0.788 (0.021)	**0.619**	**0.895**	**0.868**	0.019*	TED2	TED3
	Control	1.334 (0.069)	1.004 (0.063)	0.904 (0.054)						TED4
Cepola macrophthalma	Test	0.772 (0.018)	0.577 (0.020)	0.698 (0.017)	**0.835**	**1.000**	**0.902**	0.102	–	–
	Control	0.978 (0.065)	0.577 (0.020)	0.747 (0.041)						
Engraulis encrasicolus	Test	0.695 (0.142)	1.129 (0.011)	1.007 (0.013)	**0.160**	**0.967**	**0.935**	0.000**	TED2	TED3
	Control	1.562 (0.111)	1.358 (0.043)	1.208 (0.052)						TED4
Gobius niger	Test	0.767 (0.027)	0.788 (0.035)	1.160 (0.008)	**0.781**	**0.803**	**0.951**	0.346	–	–
	Control	1.081 (0.032)	1.083 (0.059)	1.503 (0.045)						
Merluccius merluccius	Test	1.267 (0.006)	1.264 (0.025)	0.916 (0.012)	**0.632**	**0.859**	**0.972**	0.000**	TED2	TED3
	Control	2.447 (0.007)	1.822 (0.071)	0.964 (0.034)						TED4
Mullus barbatus	Test	0.212 (0.201)	0.966 (0.007)	0.810 (0.009)	**0.297**	**0.972**	**0.867**	0.004**	TED2	TED3
	Control	0.634 (0.073)	1.031 (0.044)	0.984 (0.046)						TED4
Pagellus erythrinus	Test	0.692 (0.018)	0.706 (0.030)	0.578 (0.033)	**0.838**	**0.877**	**0.972**	0.519	–	–
	Control	0.898 (0.058)	0.766 (0.032)	0.628 (0.050)						
Sardina pilchardus	Test	0.490 (0.191)	1.127 (0.020)	1.078 (0.013)	**0.417**	**0.937**	**0.936**	0.000**	TED2	TED3
	Control	1.198 (0.080)	1.434 (0.040)	1.407 (0.043)						TED4
Scomber spp.	Test	0.862 (0.028)	0.834 (0.011)	0.772 (0.019)	**0.534**	**1.000**	**1.000**	0.010*	TED2	TED3
	Control	1.522 (0.061)	0.834 (0.011)	0.772 (0.019)						TED4
Spicara spp.	Test	0.590 (0.029)	1.028 (0.033)	0.174 (0.298)	**0.263**	**0.981**	**0.414**	0.000**	TED2	TED3
	Control	1.342 (0.025)	1.337 (0.069)	0.335 (0.009)					TED4	
Trachurus spp.	Test	0.989 (0.009)	0.923 (0.026)	0.541 (0.013)	**0.398**	**0.964**	**0.862**	0.000**	TED2	TED3
	Control	2.040 (0.014)	1.113 (0.063)	0.626 (0.042)						TED4
Anthropogenic debris	Test	1.231 (0.014)	0.542 (0.319)	1.485 (0.003)	**0.825**	**0.477**	**0.959**	0.060	–	–
	Control	1.859 (0.047)	1.264 (0.070)	2.386 (0.013)						

Table 3. Generalised linear mixed model (GLMM) parameters from sea trials with the Turtle Excluder Devices (TED) mounted on a Mediterranean demersal trawl.

TED	Model	Parameter	Estimate	SE	DF	*t*-value	*p*-value
TED2	Linear	β_0	1.058	0.291	355	3.636	0.000
		β_1	–0.029	0.017	355	–1.695	0.041
TED3	Quadratic	β_2	0.002	0.001	290	2.546	0.011
TED4	Linear	β_1	0.278	0.057	183	4.907	0.000

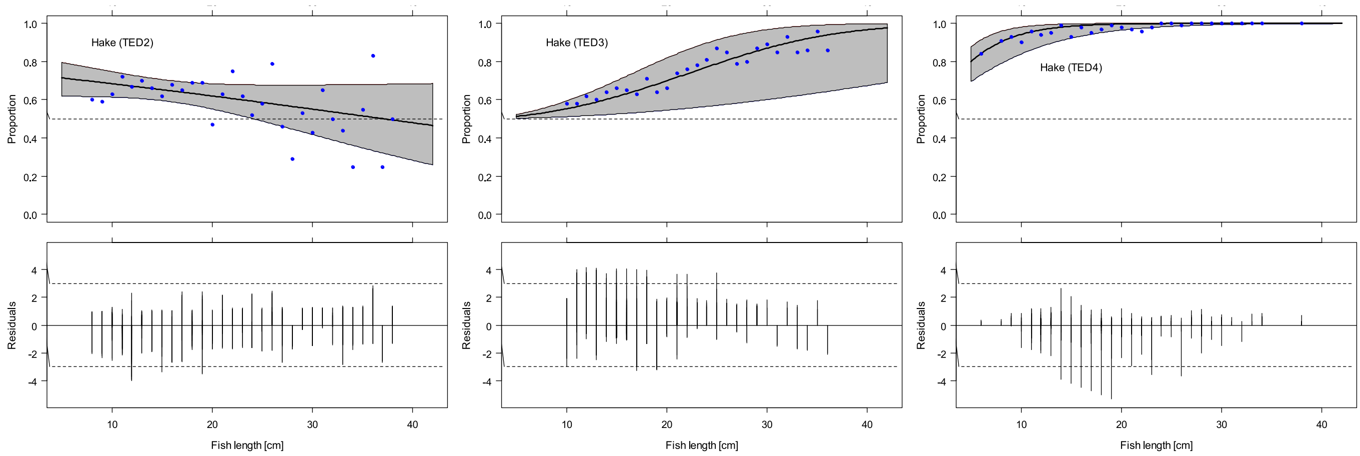


Fig. 3. GLMM modelled proportion of the total catches of European hake (*Merluccius merluccius*) caught in the codend of TED-equipped trawl (Proportion = TED-equipped trawl codend / (TED-equipped trawl codend + TED-cover)). Interpretation: a value of 0.5 indicates an even split between the codend and the TED-cover, whereas a value of 0.75 indicates that 75% of the total fish at that length were caught in the codend of the TED-equipped trawl and 25% were caught in the TED-cover. Circle points are pooled experimental proportions and the shaded areas around the mean curves (bold lines) are the 95% confidence regions.

demonstrated that downward excluding TEDs can be potentially effective at preventing sea turtle capture.

Our results lend further support to the concept that fish of different size behave differently when interacting with a trawl (Dremière et al. 1999; Fiorentini et al. 1999). In particular, we confirmed that smaller hakes tend to go towards the seabed, while larger hakes usually swim towards the upper part of the trawl. All TEDs tested made the best use of this behaviour. Thus, small hakes probably get sucked into the TED escape window when they come up against the lower part of the TED and the largest hakes, able to pass through the grid bars, are retained in the codend.

Notably, with the *Supershooter* (TED4), all individuals of European hake equal to or above 16 cm were found in the codend and around 10–15% of those between 5.0 and 15.5 cm were released (Fig. 3).

In general, the discard rate (by weight) of the TED-equipped net was 30–60% lower for many discarded species (Table 2). Among the retained species (except *M. kerathurus*, *M. barbatus* and *Trachurus* spp.), the catch rate of TED4 was always highest, but it was not significantly different from that of TED3 (Table 2). Such a similarity between TED3 and TED4 was also found for *Scomber* spp., *Sepia officinalis* and *Squilla mantis*. For European hake also, the fishing power of TED4 (0.972) was not significantly higher than that of TED3 (FPOW = 0.859), but this pair did show significant pairwise differences from the TED2 FPOW (0.632; Table 2).

Innovations can only be easily accepted by professional fishermen if the economic losses are negligible. Our study does not provide an economic overview of the TEDs, but reduced catches of commercial species certainly might deter some fishers from using trawls equipped with them. Nevertheless, the emergence and strength of new European "selective catching gears" may be a sufficient incentive for fishermen to use more-selective trawls.

Council Regulation (EC) No. 1967/2006, concerning management measures for sustainable exploitation of fishery resources in the Mediterranean, called for a discard reduction policy in waters under the jurisdiction of the European Union (Sala et al. 2006, 2007, 2008; Lucchetti and Sala 2010; Sala and Lucchetti 2010). TEDs may, therefore have some broader value in this context.

5 Future work

Direct underwater observation of the TEDs might prove generically useful for future development, particularly if it were to identify the strategic components of the trawl equipped with TEDs that most affect fish behaviour. Further experimentation, video observation and modification of TED design to accommodate fish and crustacean behaviour could enhance the performance of TED systems. Although TEDs will require more improvement before they are accepted by the wider fishing industry, extension to commercial conditions would allow fishermen to provide some input on the development of excluder systems suitable for their fishing operations.

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