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Estimation of selectivity parameters for target and bycatch fishes of the trammel net fisheries in the northern Aegean Sea (eastern Mediterranean Sea)

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Abstract

The size selectivity of trammel nets was investigated in the northern Aegean Sea using 10 different inner-panel mesh sizes ranging from 16 to 70 mm nominal mesh size (bar length). Selectivity estimates were made for the eight most abundant target and bycatch fish species, namely black scorpionfish, *Scorpaena porcus* Linnaeus, 1758; annular seabream, *Diplodus annularis* (Linnaeus, 1758); red mullet, *Mullus barbatus* Linnaeus, 1758; surmullet, *Mullus surmuletus* Linnaeus, 1758; round sardinella, *Sardinella aurita* Valenciennes, 1847; European hake, *Merluccius merluccius* (Linnaeus, 1758); greater weever, *Trachinus draco* Linnaeus, 1758; and blotched picarel, *Spicara flexuosum* Rafinesque, 1810, which accounted for 51.5% by number and 42.7% by weight of the fish caught with trammel nets in the sea trials. The SELECT method was used to estimate the selectivity parameters. Five different selectivity functions (i.e., normal scale, normal location, gamma, log-normal, and bi-normal) were applied with the bi-normal function providing the best fit as it had the lowest deviance value for all species and the lowest values for the dispersion parameter (D/df). The mesh size of 16 mm in most of the cases retained specimens below the size at first maturity (L_m). The mesh size of 19 mm seems more appropriate for red mullet, surmullet, and blotched picarel, the mesh size of 22 mm for annular seabream and round sardinella, while for European hake and black scorpionfish, the mesh size larger than 26 mm would be more appropriate.

Keywords

bycatch, Mediterranean Sea, SELECT, size-selectivity, small-scale fisheries, trammel nets

Introduction

Over the past 40 years, population growth, economic and technological development, and dietary diversification have increased the demand for fish products, putting pressure on fish stocks (FAO 2022). Patterns of exploitation have expanded and a global trend towards overexploitation of fisheries resources has emerged. The proportion of global fisheries stocks within biologically sustainable levels was 64.6% in 2019 (FAO 2022), while in European waters, recent assessments show that 69% of stocks are subject to persistent overfishing and half of them are outside safe biological limits (Froese et al. 2018). In the Mediterranean and the Black Sea, 83% of assessed stocks were classified as overfished (Froese et al. 2018). It should be noted that the above figures do not take into account stocks of non-target species of low commercial value which are fished as bycatch and are often not assessed because their catch data are generally lacking (Tsikliras et al. 2021).

Although their effect is often overlooked, small-scale fisheries (SSF) contribute to the stock exploitation status, as they provide more than a quarter of the global marine fisheries catch and supply almost half of the landings intended for human consumption (FAO 2022). Nevertheless, the social, economic, and cultural importance of SSF to coastal communities is disproportionately higher than its impact on fish and invertebrate stocks (Jacquet and Pauly 2008; Palmer et al. 2017), since they employ 90% of the fisheries workforce globally, either directly on-board vessels or in parallel inshore activities. In the Mediterranean Sea, SSF mainly consist of small-sized vessels (usually < 12 m) that undertake short fishing trips (1–3 days), have a crew of 1–3 people, family-owned capital, and a small investment in vessel equipment and fishing gears (Gil et al. 2018; Liontakis et al. 2020). In Greece, SSF provide income and employment to the local communities in coastal areas and several remote islands, while being recognized as part of local cultural heritage and are closely linked to local traditions (Liontakis et al. 2020; Tzanatos et al. 2020).

The Mediterranean SSF are characterized by their multispecies and multi-gear nature (Stergiou et al. 2016). Different species are targeted seasonally and locally according to market demand, resource availability, and possible local restrictions, leading to the use of many different fishing gears and techniques (Maynou et al. 2011; Palmer et al. 2017). Among the variety of fishing gears used in Mediterranean SSF, set nets (trammel nets and gillnets) are the most popular (García-Rodríguez et al. 2006; Lucchetti et al. 2020). This is also true for Greek SSF as trammel nets and gillnets are used throughout the country and constitute the main component of the most common *métiers*, namely those targeting red mullets (*Mullus* spp.), cuttlefish (*Sepia officinalis*), common sole (*Solea solea* (Linnaeus, 1758)) and caramote prawn (*Penaeus kerathurus*) (Adamidou 2007).

Although the fishing gears employed in SSF (mostly passive gears) are considered to be more size and species selective, have a moderate to low discard rate (Kelleher 2005), and are less damaging to stocks and habitats than the towed gears used in large-scale fisheries (Huse et al. 2000; Stergiou et al. 2002), the total amount of discards they produce should not be ignored, considering a large number of vessels in the sector (Bellido et al. 2011; Sartor et al. 2018). Fish retained by fishing gear is usually an unknown proportion of the various size classes available in the exploited population. The probability of catching and retaining a given size of fish with a given mesh size (or hook) is defined as selectivity (Kitahara 1971) and is represented by a selectivity curve. The selectivity of a fishing gear describes the catching capacity and efficiency of the gear. It can be used to minimize the likelihood of catching non-targeted unwanted species or species of certain age groups by modifying the selective characteristics of fishing gears. Apart from that, it is also used to estimate population length frequency distribution, as well as length at age (Millar and Fryer 1999).

The most important aspect of gear selectivity is that it is directly associated with fisheries management since fishing regulations based on allowable mesh sizes require precise knowledge of gear selectivity. Up to now, the majority of fisheries in the Mediterranean Sea are managed by controlling the fishing effort and by technical measures (closed areas and seasons, minimum landing size, minimum mesh sizes) (Lucchetti et al. 2020). The latest reform of the Common Fisheries Policy (CFP) intends to reduce overfishing, enable the transition to low-impact fisheries and create strong incentives for fishers to move to more selective fishing practices by modifying their traditional fishing gears to improve their size and species selection (EU Regulation 1380/2013). Through that, the main goals are to restore and maintain populations of all commercial fish stocks above the biomass level that allows maximum sustainable yield (MSY) (Article 2, point 2 of EU Regulation 1380/2013), and to eliminate discards and reduce unwanted catches through the landing obligation of all catches of species subject to the minimum conservation reference size (MCRS), previously known as minimum landing size (Article 15 of EU Reg.1380/2013).

In the Mediterranean Sea, several studies have investigated the selectivity of fishing gears with the aim of reducing bycatch of undersized species, both commercial and non-commercial. The vast majority of the studies (>70%) concerned the bottom trawls targeting finfish (Sala and Lucchetti 2011; Özbilgin et al. 2012) or crustaceans (Guijarro and Massutí 2006; Kaykaç et al. 2009). Studies on the selectivity of SSF gears were mainly related to gillnets and investigated the effects of different mesh sizes (Petrakis and Stergiou 1995; Sbrana et al. 2007) and twine thickness/material (Ayaz et al. 2011). Few studies compared the selectivity of gillnets and trammel nets (Fabi et al. 2002; Karakulak and Erk 2008), while an overview of gill net and trammel net size selectivity in the Mediterranean has been published (Lucchetti et al. 2020). Regarding trammel nets, although they are the most important fishing gears of the Mediterranean small-scale fisheries (Lucchetti et al. 2020), there are very few studies that refer to their size selectivity and most assess the impact of selectivity on target species (Erzini et al. 2006; Kalaycı and Yeşilçiçek 2012; Bolat and Tan 2017); thus, information on bycatch remains scarce.

The objective of this study is to assess the impact of trammel net size selectivity on both target and bycatch species in SSF of the northern Aegean Sea. The selectivity parameters for the most abundant target and bycatch species were calculated and compared for different mesh sizes aiming to propose the most appropriate mesh size on a species basis that will ensure the sustainability of key *métiers* of SSF and minimize their negative effects on fish stocks.

Materials and methods

Experimental nets and fishing operation. The sea trials were conducted seasonally, from April 2016 to February 2017, for 5 successive days each season (20 sea trials in total), on board a chartered commercial SSF fleet vessel (8.5 m in length, 4.3 GT, 45 HP). The study area was Strymonikos Gulf in the western part of the northern Aegean Sea (Fig. 1).

The data were collected during a trammel net selectivity survey. The technical characteristics and the structure of trammel nets are described in the literature (He et al. 2021) as well as their dominant catching mechanism, the pocketing (Fabi et al. 2002), and the other ways in which a fish can be caught in a net, namely gilled, wedged, or entangled (Ricker 1975 and references therein).

Thirty bottom-set trammel nets were used, all newly made for the study. Ten different combinations of inner and outer panel mesh sizes were used as follows: 16/100 mm, 19/100 mm, 22/110 mm, 26/130 mm, 30/150 mm, 36/160 mm, 42/180 mm, 50/200 mm, 60/240 mm, 70/265 mm (bar length of inner/outer sheets of trammel nets). Mesh size increased following a geometric order, depending on the commercial availability. All nets were made with the same net type and twine diameter. Multifilament nylon (PA) twine, of 0.23 mm thickness was used for the inner sheets of the trammel nets, whereas for the outer sheets, the twine thickness ranged from 0.36 mm to 0.45 mm depending on mesh size. All nets had almost the same length (100 m stretched/50 m mounted) and depth (1.5 m stretched), therefore the fishing effort was considered the same for all mesh sizes. Also, the inner sheets of the trammel nets were of the same depth for all mesh sizes, greater than that of outer panels, in order to have the same slack with the outer panels (Holst et al. 1998) (see Suppl. material 1). The float lines were made of 5 mm diameter braided rope and were approximately 50 m long. Floats of expanded polystyrene were used giving a buoyancy of 34.3 g/m. The lead lines were made of 4 mm diameter braided rope, with leads inside weighing 80 g/m. The lead lines were about 1.15% longer than the float lines. The hanging ratio was 0.50 on the headline and 0.51 on the lead line.

The nets were rigged in 3 fleets of 10 nets each with different mesh sizes. The position of each net in the fleet was determined randomly and no net had the same

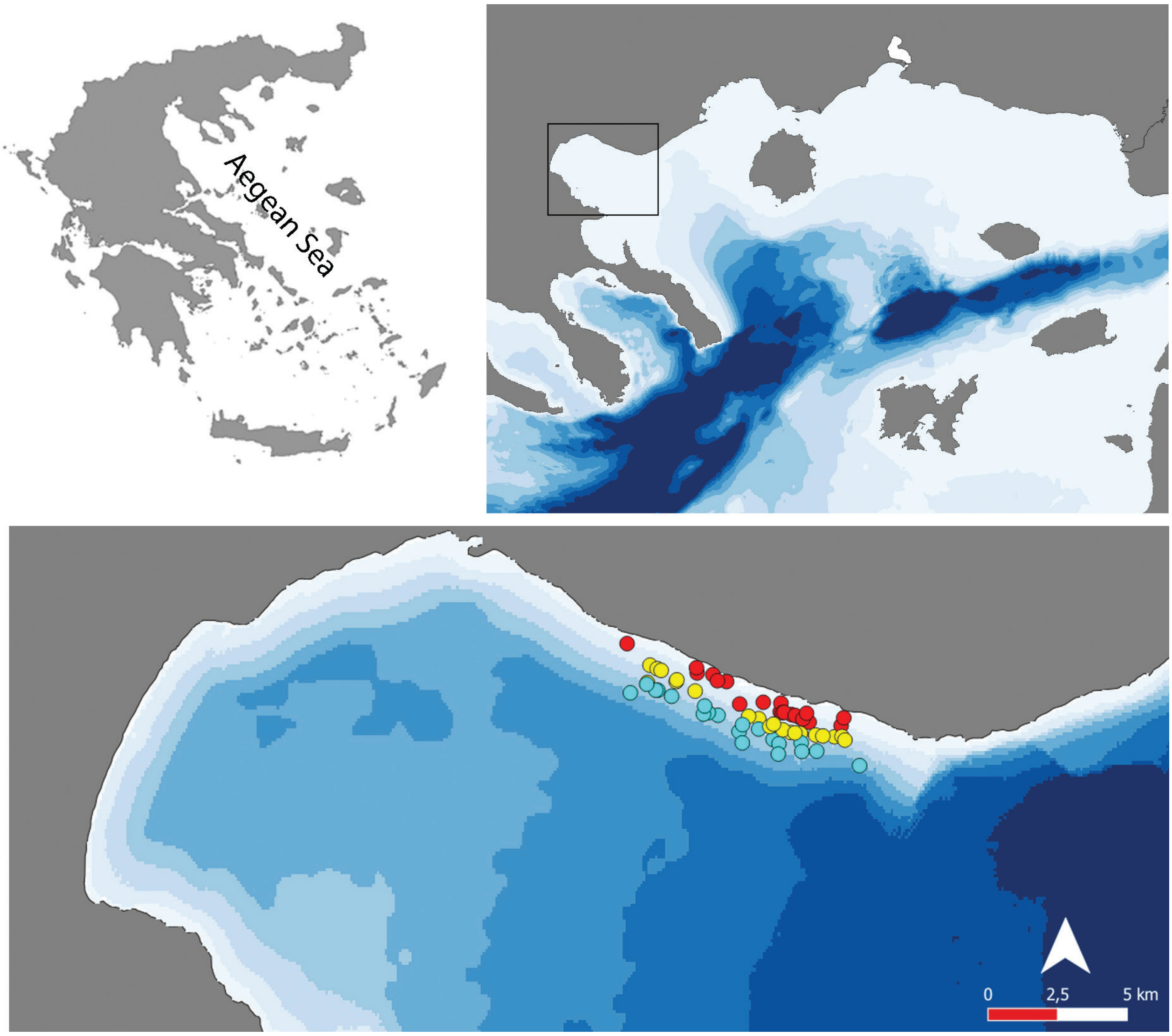

Figure 1. Map of the study area showing also the haul positions during the fishing trials. The different colors correspond to different depth zones (red: 0–20 m, yellow: 20–40 m, turquoise: 40–60 m).

position in the three fleets, to reduce possible interaction between nets of different efficiency (Millar 1992). Also, the end positions of the fleets were occupied by all types of different mesh sizes (as possible). There were escape areas of 1.5 m between the adjacent nets to avoid any guiding effect from one net to the next (Holst et al. 1998). The nets were deployed from the coastline to a depth of 60 m, as coastal fisheries in the area typically exploit these depths, in three depth zones (0–20 m, 20–40 m, and 40–60 m), one fleet in each depth zone, to investigate any possible effect of depth in net selectivity. The fleets were deployed simultaneously, set late in the afternoon (17:00–19:00), and hauled the following morning (05:00–07:00) according to commercial practices, with an average soaking time of 12 h.

Upon retrieval, the entire catch was sorted according to the fleet, net type, and mesh size, and marine organisms were classified to the species level. An additional sorting into target and bycatch fraction was done by the fisher, with no interference from researchers on board. The method of capture was recorded as far as it was possible. Given that several target and bycatch species were caught in the experimental sea trials, it was not practically possible to record the method of capture of each fish. In addition, some species (e.g., greater weever) were still very mobile even after capture, which caused the net to rotate around their body, making it difficult to determine the method of capture. For other species (e.g., black scorpionfish) which appeared to be gilled or enmeshed, the net was also collected in the spines and rays, so it was also difficult to determine the method of capture.

Total weight and number were recorded for the catch of each species per fleet, and mesh size while specific measurements for each individual were recorded in the laboratory. The total length (TL, cm) and body girth (G, cm) for fishes and dorsal mantle length (DML, cm) for cephalopods were measured to the nearest 0.1 cm and the carapace length (CL, cm) for crustaceans to the nearest 0.01 cm, the individual total weight (W, g) was measured to nearest 0.01 g. The taxonomy and nomenclature of the species are according to FishBase (Froese and Pauly 2022).

Data analysis. Due to the small sample per species, a temporal (by season) or spatial (by depth stratum) stratified selectivity analysis was not possible; thus, data from all sampling periods and depth strata were pooled together into a single dataset per species. Length frequency distributions (LFDs) were estimated for all species (1 cm size classes or 2 cm size classes for species with a wide length range) per mesh size. In order to use the proper parametric (ANOVA) or non-parametric test (Kruskal–Wallis) for the comparison of the mean/median TL among different mesh sizes the normality of the TL data per species was tested with a Shapiro–Wilk normality test. Based on the outcome either one-way analysis of variance (ANOVA) or the non-parametric Kruskal–Wallis test was applied. Additionally, paired Kolmogorov–Smirnov (K–S) test with a significance level of ±95% ($\alpha = 0.05$) was applied to compare the LFDs by different mesh sizes per species. The proportion of fish below the minimum conservation reference size (MCRS, according to EU regulation and the national legislation) and the length at first maturity (L_m) obtained from the literature, were also calculated for each species and mesh size. As mentioned above, fish are caught in trammel nets in four different ways. Two of them (gilling and wedging) are related to their body size, while the other two (entanglement and entrapment) are independent of it. When estimating selectivity, it is important to know whether fish were gilled/wedged or entangled/entrapped. Therefore, the ratio of gill (GG/MP) and maximum girth (MG/MP) to mesh perimeter were calculated for all species and mesh sizes to investigate the method of capture of each species at different mesh sizes and to confirm the observed method of capture.

Selectivity estimation. When the length distribution of the fished population is known, a direct estimation of the selectivity can be applied (Hamley 1975). This is possible for towed gears by collecting the individuals that escape from the codend to the codend cover. In passive gears (nets, longlines) it is impossible to collect escaping fish to estimate the actual size of the population on the fishing ground, and therefore an indirect estimation is most frequently used (Millar 1992; Madsen et al. 1999). This process usually involves deploying several nets/longlines, all of the same size, and different mesh/hook sizes in random order, fishing simultaneously on the same population with equal effort. The selectivity is then estimated by comparing the observed catch frequencies across the several meshes/hooks used (Millar 1992). This procedure was followed in the presently reported experimental survey.

The trammel net selectivity was estimated using the SELECT (Share Each Length's Catch Total) method, initially developed for trawling (Millar 1992) and then extended to set nets and hooks (Millar and Holst 1997), by which the expected catch proportions are fitted to the observed catch proportions using maximum likelihood which also allows the between-haul variability to be taken into account (Millar and Fryer 1999). SELECT method is described by the equation

$$n_{lj} \sim Po(p_j \cdot \lambda_l \cdot r_j(l)) \text{ and the log-likelihood of } n_{lj} \text{ is}$$

$$\sum_l \cdot \sum_j \{n_l \log_e [(p_j \cdot \lambda_l \cdot r_j(l)) - (p_j \cdot \lambda_l \cdot r_j(l))]\}$$

where n_{lj}: the number of fish of length l caught in mesh size j; λ_l the abundance of length l fish contacting the gear; p_j: the relative fishing intensity of the net of mesh size j; $r_j(l)$: the retention probability of length l fish in the mesh size j.

Five different patterns of selectivity were applied and tested to the data, corresponding to five functions, four unimodal: the normal location (modal length proportional to mesh size, spread fixed), normal scale, gamma and lognormal, and one bimodal (Bi-normal):

$$\text{Normal location } (k, \sigma) \exp\left(-\frac{(l - k \cdot m_j)^2}{2\sigma^2}\right)$$

$$\text{Normal scale } (k_1, k_2) \exp\left(-\frac{(l - k_1 \cdot m_j)^2}{2k_2 \cdot m_j^2}\right)$$

Log normal (μ, σ)

$$\frac{1}{l}\exp\left(\mu_1 + \log\left(\frac{m_j}{m_1}\right) - \frac{\sigma^2}{2}\quad \frac{\left(\log(l) - \mu_1 - \log\left(\frac{m_j}{m_1}\right)\right)^2}{2\sigma^2}\right)$$

$$\text{Gamma } (\alpha, k) \left(\frac{l}{(\alpha - 1)k \cdot m_j}\right)^{\alpha - 1} \exp\left(\alpha - 1 - \frac{l}{k \cdot m_j}\right)$$

Bi-normal (k_1, k_2, k_3, k_4, c)

$$\exp\left(-\frac{(l - k_1 \cdot m_j)^2}{2k_2^2 \cdot m_j^2}\right) + c.\exp\left(-\frac{(l - k_3 \cdot m_j)^2}{2k_4^2 \cdot m_j^2}\right)$$

where m_j is the mesh size j, μ is the mean size (modal length) of fish caught, σ is the standard deviation of the size of fish (spread), and k, k_1, k_2, k_3, k_4, and c, are selection parameters or constants.

For the selectivity curves, it was assumed that the number of fish of length class l encountering the gear was Poisson distributed; each net was equally efficient at catching fish of optimum/modal length, and hence the selectivity curves are all of the same height; the selection curve follows Baranov's principle of geometrical similarity according to which modal length and spread (SD) of the fish caught increase proportionally to mesh size (Ricker 1975 and references therein). This assumption was not followed only when a normal location function, which assumes a fixed spread, was applied.

For the estimation of the selectivity curves, species with a sufficient number of individuals are needed. Therefore, species with a low number of captured specimens ($n \leq 70$) or low representation in mesh sizes (present in less than 3 different mesh sizes) were excluded from the analysis (Millar and Fryer 1999). For the validation of the goodness of fit, the model deviance (D) was calculated using all length classes with nonzero catch and the mesh sizes for which selectivity curves could be estimated ($n > 5$). The degrees of freedom (df) were also computed automatically. The best-fitting model was the one with the lowest value of deviance and dispersion parameter i.e., ratio D/df ≤ 1 (Holst et al. 1998). Model fitting was also evaluated based on visual inspection of model diagnostics, such as the residual deviance plots. All estimations were performed within an R programming environment (R Core Team 2022) through the function "*select_Millar*" from TropFishR package (Mildenberger et al. 2017).

Results

Length frequency distributions. During the experimental trials, a total of 3233 specimens (235.9 kg) of 94 species (84 fishes, 4 crustaceans, and 6 cephalopods) were caught in trammel nets. Despite the large number of species caught, the catch was dominated by a few species whose numbers of individuals were sufficient for further statistical analysis and which also met the criteria for estimating the selectivity curves. Analyses were therefore carried out for the eight most abundant fish species, which accounted for 51.5% by number and 42.7% by weight of the fish caught with trammel nets. These fish species were the black scorpionfish, *Scorpaena porcus* Linnaeus, 1758; annular seabream, *Diplodus annularis* (Linnaeus, 1758); red mullet, *Mullus barbatus* Linnaeus, 1758; surmullet, *Mullus surmuletus* Linnaeus, 1758; round sardinella, *Sardinella aurita* Valenciennes, 1847; European hake, *Merluccius merluccius* (Linnaeus, 1758); greater weever, *Trachinus draco* Linnaeus, 1758; and blotched picarel, *Spicara flexuosum* Rafinesque, 1810.

Their relative abundance in number (N) and total weight (TW) were as follows: black scorpionfish (13.9% N, 8.8% TW); annular seabream (13.1% N, 7.8% TW); red mullet (6.7% N, 5% TW); surmullet (5.3% N, 5% TW); round sardinella (5.5% N, 4.8% TW); European hake (2.1% N, 6.4% TW); greater weever (2.8% N, 3.8% TW) and blotched picarel (2% N, 1.1% TW) (Table 1). Red mullet and surmullet are the main target species for the trammel net fishery and the rest are bycatch species.

The length frequency distributions (LFDs) of the eight species studied, by mesh size, and from data pooled across all mesh sizes, are shown in Fig. 2. The majority of LFDs were skewed to the right, the shape of the LFD curve from pooled data appears to be bimodal for annular seabream, red mullet, and blotched picarel, unimodal for surmullet, round sardinella and black scorpionfish while for European hake and greater weever, the variability in numbers per length class seems to have hidden the modality pattern. In all cases, the LFDs of the different mesh sizes were overlapping to a greater or lesser extent depending on the species. The Kolmogorov–Smirnov (K–S) test for the mesh size paired comparisons on the LFDs per species, showed that the distributions were significantly different ($P < 0.05$) for surmullet (100%), black scorpionfish (80%; 8 of 10 combinations), round sardinella and blotched picarel (66.7%; 2 of 3 combinations, for both species), annular seabream and red mullet (60%; 9 of 15 and 6 of 10 combinations respectively), while were not significantly different ($P > 0.05$) for European hake (73.3%; 11 of 15 combinations) and greater weever (93.3%; 13 of 14 combinations) (see Suppl. material 2).

For the majority of the species, the abundance in number decreased with increasing mesh size, hence, four smaller mesh sizes (i.e., 16, 19, 22, and 26 mm bar length) were the most efficient in abundance and biomass catch rates (Table 1). The mean and median length and the mean weight of fish increased with mesh size

Table 1. Descriptive statistics of total length and weight for the eight most abundant species fished with trammel nets from April 2016 to February 2017 in the northern Aegean Sea, proportion of fish below MCRS and L_m and ratios of gill (GG/MP) and maximum girth (MG/MP) to mesh perimeter.

Species	MS [mm]	*n*	RF%	TL [cm] mean ± SD	TL [cm] median	TL [cm] min–max	% <MCRS	% <L_m	TW [kg]	% TW	*W* [g] mean ± SD	GG/MP	MG/MP
Annular seabream, *Diplodus annularis*	16	120	28.3	12.6 ± 2.29	13.1	8.3–18.1	32	24	4.4	23.9	36.7 ± 20.6	1.32	1.54
	19	101	23.8	13.4 ± 1.54	13.4	9.1–16.7	20	1	4.2	22.7	41.4 ± 17.0	1.17	1.37
	22	100	23.6	13.5 ± 1.32	13.3	10.0–17.3	7	1	4.2	22.6	42.2 ± 16.4	1.00	1.18
	26	89	21.0	14.7 ± 0.88	14.5	13.2–18.0	0	0	4.8	25.8	53.6 ± 12.0	0.96	1.12
	30	7	1.7	16.0 ± 1.18	16.5	13.7–16.9	0	0	0.5	2.9	75.9 ± 16.4	0.91	1.07
	36	5	1.2	14.7 ± 1.72	13.8	13.1–17.1	0	0	0.3	1.5	54.8 ± 22.5	0.69	0.80
	42	2	0.5	14.7 ± 1.63	14.7	13.5–15.8	0	0	0.1	0.6	55.4 ± 22.4	0.60	0.69
European hake, *Merluccius merluccius*	16	21	30.0	28.6 ± 5.13	27.5	17.8–38.5	5	62	4.0	26.3	198.4 ± 100.0	1.81	1.92
	19	9	12.9	27.4 ± 4.46	26.8	21.3–33.2	0	67	1.5	9.7	162.6 ± 85.2	1.37	1.47
	22	11	15.7	28.4 ± 6.01	26.5	22.2–41.3	0	73	2.1	13.9	190.0 ± 152.7	1.27	1.35
	26	19	27.1	32.0 ± 3.10	32.0	26.7–39.0	0	37	4.7	31.4	248.6 ± 85.3	1.21	1.27
	30	5	7.1	34.6 ± 3.57	36.1	28.3–37.0	0	20	1.6	10.8	325.1 ± 80.5	1.09	1.19
	36	3	4.3	33.9 ± 4.63	34.5	29.0–38.2	0	33	0.9	6.2	309.3 ± 123.5	0.96	1.00
	42	1	1.4	26.0	26.0		0	100	0.1	0.8	116.0	0.55	0.57
	50	1	1.4	27.8	27.8		0	100	0.1	1.0	146.7	0.50	0.55
Red mullet, *Mullus barbatus*	16	139	63.5	15.8 ± 2.01	15.1	12.5–22.0	0	1	6.0	51.7	43.7 ± 20.9	1.19	1.30
	19	36	16.4	18.3 ± 1.66	18.5	15.3–23.9	0	0	2.5	21.1	70.3 ± 23.8	1.18	1.30
	22	31	14.2	18.1 ± 1.72	18.2	12.0–21.0	0	3	2.1	17.8	66.8 ± 16.5	1.02	1.10
	26	10	4.6	20.2 ± 2.64	20.8	14.6–22.7	0	0	0.9	7.9	91.9 ± 29.7	0.96	1.02
	30	3	1.4	16.9 ± 2.93	18.1	13.6–19.1	0	0	0.2	1.5	58.0 ± 24.5	0.69	0.75
Surmullet, *Mullus surmuletus*	16	82	47.7	16.9 ± 2.34	17.2	11.7–22.5	0	31	4.8	41.5	59.0 ± 26.4	1.33	1.43
	19	45	26.2	17.7 ± 1.61	17.8	15.2–22.0	0	4	3.0	26.1	67.5 ± 21.7	1.15	1.27
	22	38	22.1	18.8 ± 1.68	18.6	16.2–22.5	0	0	3.1	26.2	82.4 ± 23.6	1.08	1.18
	26	5	2.9	21.4 ± 0.65	21.6	20.4–22.0	0	0	0.6	5.2	122.3 ± 15.9	1.03	1.14
	30	1	0.6	17.1	17.1		0	0	0.1	0.5	63.1	0.75	0.84
	36	1	0.6	15.8	15.8		0	0	0.0	0.4	49.7	0.58	0.63
Round sardinella, *Sardinella aurita*	16	63	35.6	19.9 ± 1.25	20.0	16.9–22.4	0	0	3.6	32.4	58.1 ± 12.3	1.22	1.36
	19	58	32.8	20.3 ± 0.96	20.2	18.8–23.1	0	0	3.4	30.7	59.9 ± 8.5	1.04	1.13
	22	56	31.6	21.5 ± 0.96	21.4	19.5–23.8	0	0	4.1	36.9	75.9 ± 8.7	0.95	1.09
Black scorpionfish, *Scorpaena porcus*	16	112	24.8	12.6 ± 1.55	12.5	8.5–16.5	0	96	4.3	20.8	38.9 ± 14.5	1.36	1.47
	19	148	32.8	12.7 ± 1.54	12.5	9.9–18.6	0	95	5.9	28.8	40.0 ± 16.1	1.13	1.23
	22	139	30.8	13.6 ± 1.52	13.4	9.3–10.7	0	90	6.7	32.6	48.3 ± 20.4	1.04	1.13
	26	40	8.9	15.1 ± 1.82	14.7	12.1–20.0	0	70	2.6	12.8	67.6 ± 28.2	1.00	1.07
	30	10	2.2	15.6 ± 3.40	16.4	10.4–20.1	0	30	0.8	3.8	77.3 ± 41.4	0.91	0.97
	42	2	0.4	18.6 ± 4.60	18.6	21.8–37.1	0	0	0.3	1.3	136.5 ± 102.9	0.77	0.83
Blotched picarel, *Spicara flexuosum*	16	43	61.4	14.7 ± 1.55	15.0	11.5–17.8	0	0	1.4	55.4	32.5 ± 10.2	1.07	1.23
	19	23	32.9	16.2 ± 0.77	15.9	14.6–17.8	0	0	0.9	37.0	42.5 ± 5.6	1.00	1.13
	22	4	5.7	16.8 ± 0.45	16.9	16.1–17.1	0	0	0.2	7.6	47.8 ± 4.0	0.95	1.05
Greater weever, *Trachinus draco*	16	9	9.8	21.6 ± 3.87	20.5	15.5–27.8	0	11	0.7	7.6	78.1 ± 37.7	1.29	1.45
	19	46	50.0	23.5 ± 3.88	23.6	15.3–31.4	0	11	4.4	57.2	95.3 ± 48.4	1.17	1.29
	22	8	8.7	23.8 ± 3.07	23.1	19.7–28.7	0	0	0.8	8.4	97.5 ± 35.9	1.01	1.11
	26	8	8.7	27.2 ± 3.29	27.8	23.2–31.5	0	0	1.2	12.6	146.6 ± 65.0	0.98	1.07
	30	8	8.7	23.7 ± 7.27	26.0	14.5–32.7	0	38	1.0	11.1	129.1 ± 99.2	0.76	0.87
	36	9	9.8	21.9 ± 5.07	20.4	13.4–30.0	0	11	0.7	7.6	78.4 ± 54.4	0.57	0.63
	42	1	1.1	26.2	26.2		0	0	0.1	1.3	123.3	0.60	0.62
	50	1	1.1	19.5	19.5		0	0	0.0	0.4	41.3	0.36	0.37
	60	2	2.2	28.2 ± 0.71	28.2	27.7–28.7	0	0	0.4	3.8	175.2 ± 50.1	0.47	0.54

MS = mesh size (bar length), *n* = number of fish, RF% = relative frequency, TL = total length, SD = standard deviation, MCRS = minimum conservation reference size, L_m = length at maturity, TW = total weight, *W* = individual weight, GG = gill girth, MG = maximum girth; MP = mesh perimeter).

for round sardinella, black scorpionfish, and blotched picarel and with slight variations for annular seabream, red mullet, and surmullet (Table 1). For European hake, a wide range of sizes was caught with few individuals per length class for each mesh size; the mean length of hake tended to increase with increasing mesh size, however, there was no clear relation between mesh size and fish length (Table 1). For greater weever, the larger proportion of catch was collected in one mesh size (19 mm) while similar proportions were caught in the remaining mesh sizes with no clear relation between mesh size and fish size. The mean length tended to increase with increasing mesh size only for the four smaller mesh sizes (Table 1). A statistically significant difference among the mean fish length of the different mesh sizes was observed for European hake (ANOVA: $F = 2.58$, $P = 0.02$), surmullet (ANOVA: $F = 8.83$, $P = 0.00$), round sardinella (ANOVA: $F = 37.78$, $P = 0.00$) and among the median fish length for annular seabream (Kruskal–Wallis: $H = 85.38$, $P = 0.00$), red mullet

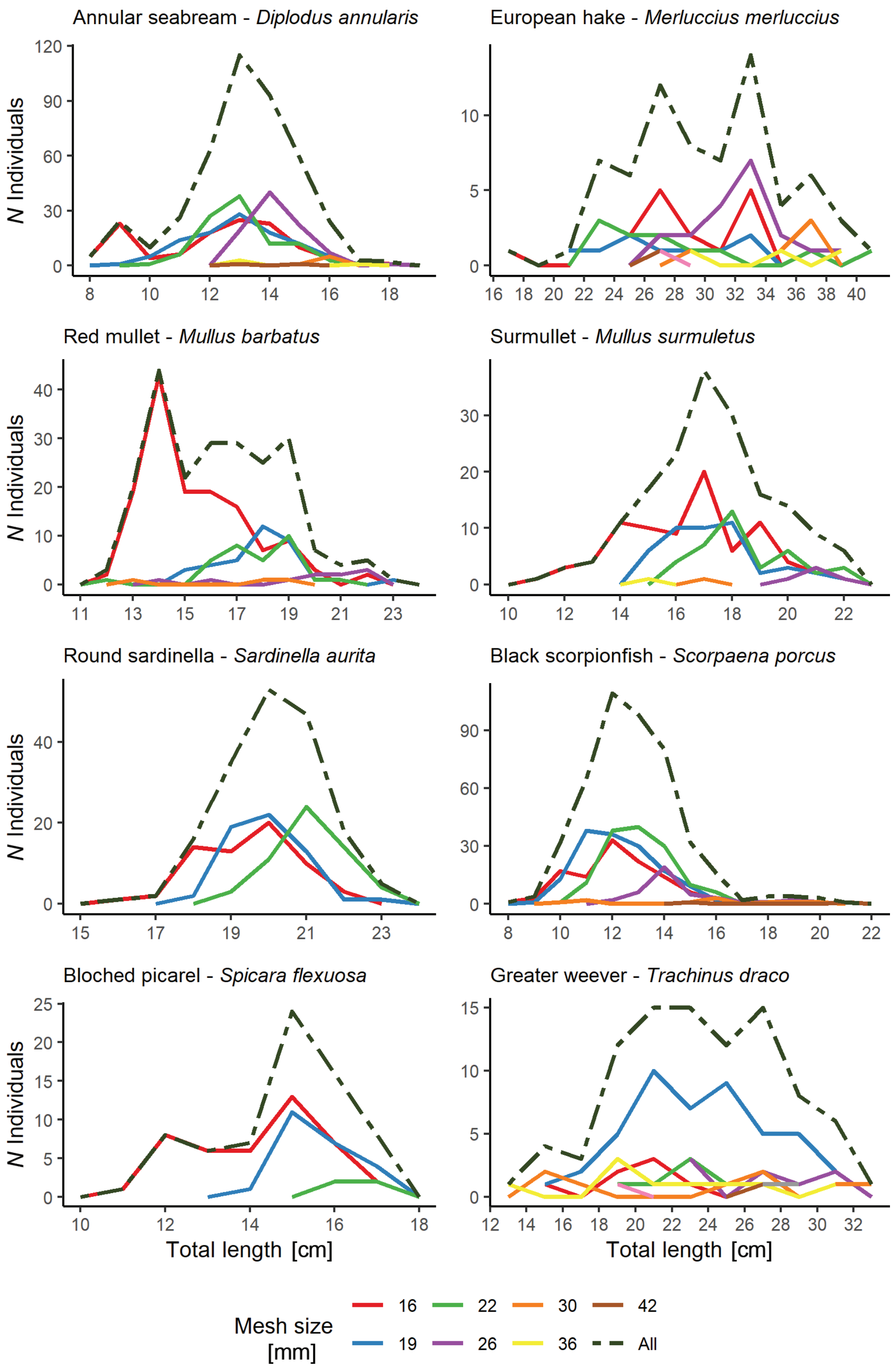

Figure 2. Length frequency distributions per mesh size and from pooled data across all mesh sizes for the eight most abundant species fished in trammel nets from April 2016 to February 2017 in the northern Aegean Sea (eastern Mediterranean Sea).

(Kruskal–Wallis: H = 68.63, P = 0.00), black scorpionfish (Kruskal–Wallis: H = 83.18, P = 0.00), blotched picarel (Kruskal–Wallis: H = 21.35, P = 0.00). No statistically significant difference was observed for greater weever (ANOVA: F = 1.58, P = 0.14).

The GG/MP and MG/MP ratios indicated that in some cases fishes were caught in mesh sizes larger than expected (e.g., annular seabream in 36 and 42 mm mesh sizes, red mullet in 30 mm mesh, and surmullet in 30 and 36 mm mesh sizes) or smaller than expected (e.g., annular seabream, red mullet, surmullet, in 16 and 19 mm mesh sizes and round sardinella, black scorpionfish in 16 mm mesh size) (Table 1), which indicate that a certain number of individuals of these species were caught entangled by maxillaries and teeth or entrapped/pocketed. For European hake and greater weever, the GG/MP and MG/MP ratios indicate that both fishes were caught in mesh sizes larger than expected (European hake in 42 and

50 mm mesh size and greater weever in 30, 36, 42, 50, 60 mm mesh sizes) and smaller than expected (European hake in 16 and 19 mm mesh size and greater weever in 16 mm mesh size) (Table 1) confirming capture in nets other than gilled or wedged.

Only some individuals of annular seabream (30%, 20%, and 7% at mesh sizes 16, 19, and 22 mm respectively) and to a lesser extent European hake (5% at mesh size 16 mm) were recorded below the minimum conservation reference size (MCRS) (Table 1). However, when examining the fish size in relation to size at first maturity (L_m), the entire catch was above L_m only for round sardinella and blotched picarel and most of the catch for red mullet. For European hake and black scorpionfish, most of the catch was below the L_m, for annular seabream and surmullet a considerable part of the catch was below the L_m at the smaller mesh size, and for greater weever different proportions were below the L_m at different mesh sizes (Table 1).

Estimation of the selectivity parameters. The selectivity parameters were estimated per species for each of the tested selectivity functions (Table 2). The bimodal function provided the best fit having the lowest deviance value for all species and the lowest values for dispersion parameter (D/df) for all species except greater weever. Over-dispersion was observed for red mullet, round sardinella, and greater weever. The fitted selectivity curves and the corresponding deviance residuals are shown in Fig. 3. The first mode of the selectivity curves corresponds to fish that were gilled or wedged, while the second mode describes the selectivity associated with fish that are entangled or entrapped/pocketed. The residual plots reveal that for annular seabream the fishing power of the mesh size 36 mm was greater (positive residuals) while that of the mesh size 30 mm was lower (negative residuals) than modeled. For red mullet the fishing power of mesh sizes 22 mm (for the smaller length classes) and 26 mm (for the larger length classes) were great-

Table 2. Selectivity parameters estimates resulting from the use of four uni-modal and one bi-modal models, with the corresponding deviances, degrees of freedom, and the mesh sizes whose catch was used in estimating the selectivity parameters for the eight most abundant species fished with trammel nets from April 2016 to February 2017 in the northern Aegean Sea (eastern Mediterranean Sea).

Species	Model	Parameters	Deviance	df	D/df	Mesh sizes
Annular seabream, *Diplodus annularis*	Normal location	$(k, \sigma) = (0.686, 3.366)$	166.41	53	3.14	16, 19, 22, 26, 30, 36
	Normal scale	$(k_1, k_2) = (0.743, 0.022)$	206.62	53	3.90	
	Log normal	$(\mu, \sigma) = (2.476, 0.211)$	162.87	53	3.07	
	Gamma	$(\alpha, k) = (22.533, 0.033)$	174.83	53	3.30	
	Bi-modal	$(k_1, k_2, k_3, k_4, c) = (0.582, 0.035, 0.861, 0.167, 0.601)$	**60.82**	50	1.22	
European hake, *Merluccius merluccius*	Normal location	$(k, \sigma) = (1.463, 9.173)$	51.11	46	1.24	16, 19, 22, 26, 30
	Normal scale	$(k_1, k_2) = (1.668, 0.261)$	62.85	46	1.37	
	Log normal	$(\mu, \sigma) = (3.302, 0.313)$	52.15	46	1.26	
	Gamma	$(\alpha, k) = (10.889, 0.158)$	59.67	46	1.30	
	Bi-modal	$(k_1, k_2, k_3, k_4, c) = (1.219, 0.123, 2.017, 0.395, 0.521)$	**46.25**	43	1.08	
Red mullet, *Mullus barbatus*	Normal location	$(k, \sigma) = (1.053, 3.446)$	105.51	34	3.10	16, 19, 22, 26
	Normal scale	$(k_1, k_2) = (1.079, 0.024)$	90.30	34	2.66	
	Log normal	$(\mu, \sigma) = (2.873, 0.174)$	87.19	34	2.56	
	Gamma	$(\alpha, k) = (38.979, 0.028)$	87.26	34	2.57	
	Bi-modal	$(k_1, k_2, k_3, k_4, c) = (0.965, 0.092, 1.412, 0.262, 0.448)$	**75.10**	31	2.42	
Surmullet, *Mullus surmuletus*	Normal location	$(k, \sigma) = (1.036, 3.465)$	50.33	34	1.48	16, 19, 22, 26
	Normal scale	$(k_1, k_2) = (1.080, 0.030)$	59.69	34	1.76	
	Log normal	$(\mu, \sigma) = (2.857, 0.178)$	49.52	34	1.46	
	Gamma	$(\alpha, k) = (34.738, 0.032)$	52.43	34	1.54	
	Bi-modal	$(k_1, k_2, k_3, k_4, c) = (0.833, 0.066, 1.193, 0.151, 0.425)$	**31.63**	31	1.02	
Round sardinella, *Sardinella aurita*	Normal location	$(k, \sigma) = (1.093, 2.816)$	40.10	14	2.86	16, 19, 22
	Normal scale	$(k_1, k_2) = (1.127, 0.025)$	44.12	14	3.15	
	Log normal	$(\mu, \sigma) = (2.896, 0.138)$	40.33	14	2.88	
	Gamma	$(\alpha, k) = (53.227, 0.021)$	41.54	14	2.97	
	Bi-modal	$(k_1, k_2, k_3, k_4, c) = (1.027, 0.037, 1.252, 0.105, 0.598)$	**26.94**	11	2.45	
Black scorpionfish, *Scorpaena porcus*	Normal location	$(k, \sigma) = (0.692, 2.807)$	83.19	54	1.54	16, 19, 22, 26, 30
	Normal scale	$(k_1, k_2) = (0.726, 0.017)$	120.32	54	2.23	
	Log normal	$(\mu, \sigma) = (2.453, 0.193)$	94.78	54	1.76	
	Gamma	$(\alpha, k) = (29.045, 0.025)$	101.13	54	1.87	
	Bi-modal	$(k_1, k_2, k_3, k_4, c) = (0.608, 0.047, 0.814, 0.142, 0.539)$	**46.85**	47	1.00	
Blotched picarel, *Spicara flexuosum*	Normal location	$(k, \sigma) = (0.919, 1.760)$	5.36	12	0.45	16, 19, 22
	Normal scale	$(k_1, k_2) = (0.934, 0.009)$	6.83	12	0.57	
	Log normal	$(\mu, \sigma) = (2.706, 0.106)$	4.65	12	0.39	
	Gamma	$(\alpha, k) = (94.074, 0.010)$	5.27	12	0.44	
	Bi-modal	$(k_1, k_2, k_3, k_4, c) = (0.829, 0.041, 0.980, 0.082, 0.406)$	**1.58**	9	0.18	
Greater weever, *Trachinus draco*	Normal location	$(k, \sigma) = (1.270, 2.574)$	55.07	31	1.78	16, 19, 22, 26
	Normal scale	$(k_1, k_2) = (3.305, 0.068)$	56.75	31	1.83	
	Log normal	$(\mu, \sigma) = (3.050, 0.221)$	55.98	31	1.81	
	Gamma	$(\alpha, k) = (22.746, 0.059)$	56.05	31	1.81	
	Bi-modal	$(k_1, k_2, k_3, k_4, c) = (1.222, 0.207, 1.604, 0.081, 0.569)$	**54.10**	22	2.46	

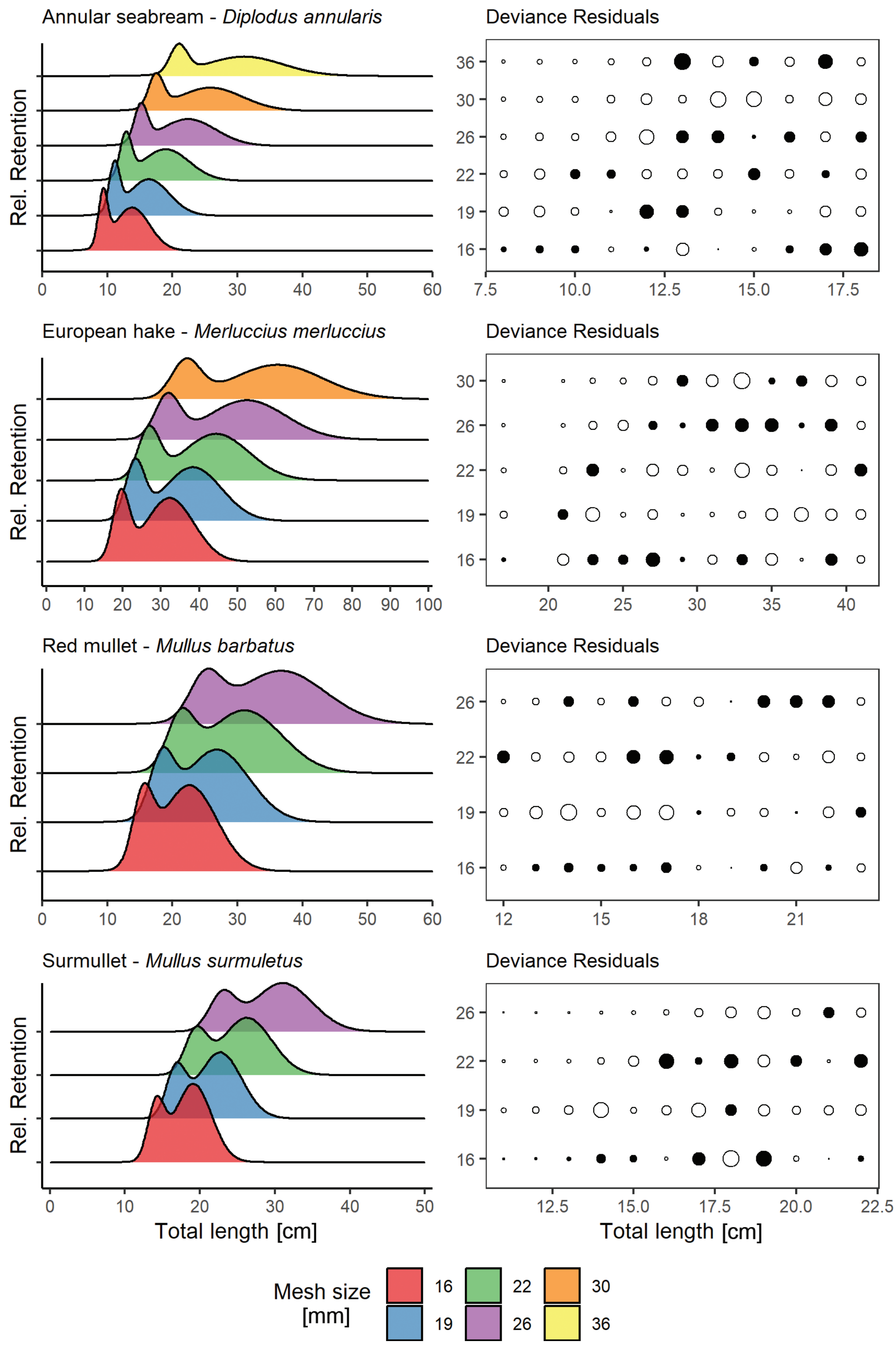

Figure 3. Selectivity curves for the eight most abundant species fished from April 2016 to February 2017 in trammel nets in the northern Aegean Sea (eastern Mediterranean Sea), and the respective deviance residual plots. Full circle indicates a positive residual and open circle a negative residual. Bubble size proportional to the residual value. [Figure continues on next page.]

er than expected (positive residuals), while that of the mesh size 19 mm (for the smaller length classes) lower than expected (negative residuals). For round sardinella the fishing power of the mesh size 19 mm was lower than modeled (negative residuals). For greater weever, the residuals had a non-random pattern, especially for mesh size 19 mm. The estimated modal lengths and spreads of the eight species studied, by mesh size, for the best-fit model are shown in Table 3. Modal length increased with mesh size as well as spread, following Baranov's principle (Ricker 1975) of geometrical similarity, but varied by species.

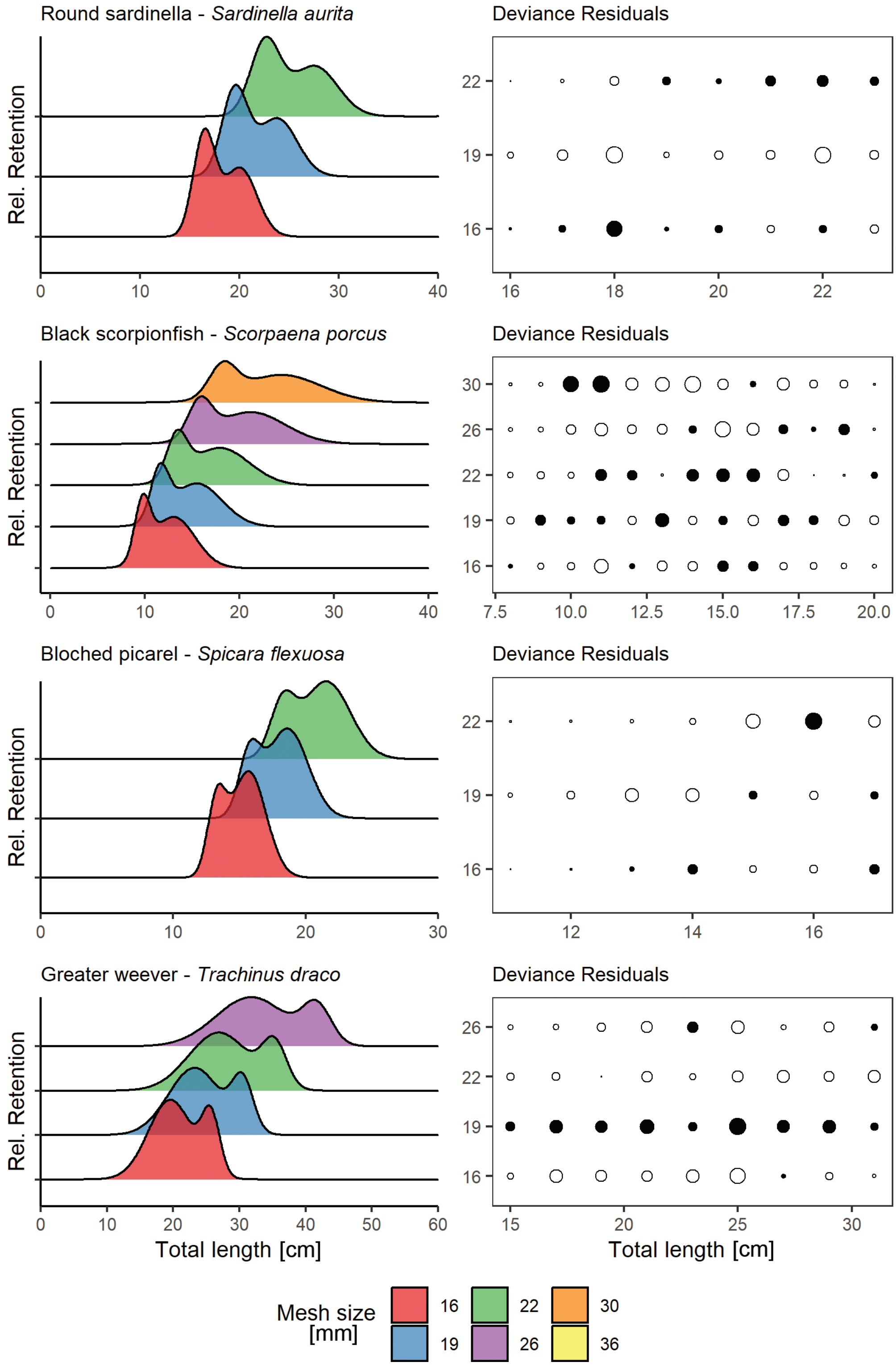

Figure 3 (Continuation). Selectivity curves for the eight most abundant species fished from April 2016 to February 2017 in trammel nets in the northern Aegean Sea (eastern Mediterranean Sea), and the respective deviance residual plots. Full circle indicates a positive residual and open circle a negative residual. Bubble size proportional to the residual value.

Discussion

The presently reported study analyzed the catch rates, length frequency distributions, and size selectivity of the eight most abundant fish species caught with trammel nets in the northern Aegean Sea (black scorpionfish, *Scorpaena porcus*; annular seabream, *Diplodus annularis*; red mullet, *Mullus barbatus*; surmullet, *Mullus surmuletus*; round sardinella, *Sardinella aurita*; European hake, *Merluccius merluccius*; greater weever, *Trachinus draco*; and blotched picarel, *Spicara flexuosum*). An attempt was made to match the technical characteristics

Table 3. Modal length and spread values, by mesh size, for the best-fit model for each of the eight most abundant species fished from April 2016 to February 2017 with trammel nets in the northern Aegean Sea (eastern Mediterranean Sea).

Species	Model	Mesh size (bar length) [mm]	Modal length	Spread
Annular seabream, *Diplodus annularis*	Bi-modal	16	9.31	0.56
		19	11.06	0.67
		22	12.80	0.77
		26	15.13	0.91
		30	17.46	1.05
		36	20.95	1.26
European hake, *Merluccius merluccius*	Bi-modal	16	19.50	1.96
		19	23.16	2.33
		22	26.81	2.70
		26	31.69	3.19
		30	36.56	3.68
Red mullet, *Mullus barbatus*	Bi-modal	16	15.44	1.47
		19	18.33	1.74
		22	21.22	2.02
		26	25.08	2.38
Surmullet, *Mullus surmuletus*	Bi-modal	16	14.14	1.05
		19	16.79	1.25
		22	19.44	1.44
		26	22.97	1.71
Round sardinella, *Sardinella aurita*	Bi-modal	16	16.43	1.07
		19	19.51	1.27
		22	22.59	1.47
Black scorpionfish, *Scorpaena porcus*	Bi-modal	16	9.73	0.75
		19	11.55	0.88
		22	13.37	1.02
		26	15.81	1.21
		30	18.24	1.40
Blotched picarel, *Spicara flexuosum*	Bi-modal	16	13.27	0.66
		19	15.76	0.78
		22	18.24	0.90
Greater weever, *Trachinus draco*	Bi-modal	16	19.56	3.32
		19	23.22	3.94
		22	26.89	4.56
		26	31.78	5.39

of the experimental nets as closely as possible to those used in Greek commercial fisheries in order to achieve compatibility with commercial practice. Therefore, different mesh sizes of the outer panel were used, with the ratio of the mesh sizes of the inner and outer panels corresponding to the local construction of the nets. Previous studies on trammel nets have shown that the mesh size of the outer panel generally had no significant effect on the size selectivity and catch rates of experimental trammel nets (Erzini et al. 2006; Stergiou et al. 2006), which were also considered. For all species except European hake and greater weever, the number of specimens caught decreased with increasing mesh size (Table 1), which can be attributed to intra- and interspecific decreases in abundance and biomass with fish size (Stergiou et al. 2006).

All species appear to have been caught in nets in more than two ways. Apart from gilling and wedging, a certain number of specimens were entangled and entrapped, but in different proportions depending on the species, as indicated by the ratios GG/MP, MG/MP (Table 1). This was also reflected in the shapes of the LFDs (Fig. 2) which were skewed to the right or were bi- or multi-modal, and on the selectivity models as the bi-normal curve gave the best fit for all species (Fig. 3). For red mullet, round sardinella, and greater weever, overdispersion was observed which has little effect on parameter estimates (Millar and Holst 1997), but signifying either a lack of fit of the model or a violation of the Poisson distribution assumption (Millar and Fryer 1999). From visual inspection of the residual deviance plots, it appears that the residuals for red mullet and round sardinella, were randomly distributed without following a pattern, indicative of a good fit. The overdispersion therefore suggests that the species may not have behaved independently, due to the schooling behavior of the fish, which violates the Poisson distribution assumption. For greater weever, where the residuals seem to follow a pattern, we assume a lack of fit of the model and the results should be treated with caution.

The selectivity of the fishing gears should be evaluated in relation to species-specific biological parameters, such as length at first maturity (L_m) and fecundity, to ensure the stock is exploited sustainably (Tsikliras and Stergiou 2014). For that reason, the modal length estimates from the bi-normal function for each species and mesh size were compared with the minimum conservation reference size (MCRS) and the size at first maturity (L_m) of each species. The efficiency of each mesh size during the experimental trials was also taken into account to suggest the most appropriate mesh size for each species for an economically viable fishery (Bellido et al. 2011). The mesh size of the inner panels was only used to estimate size selectivity, as the mesh size of the outer panel generally had no significant effect on the size selectivity and catch rates of the experimental trammel nets (Erzini et al. 2006; Stergiou et al. 2006). The results of the presently reported study were compared with those of previous studies on the selectivity of trammel nets in the Mediterranean and adjacent seas, for the species for which information was available (Table 4). As the methods used to estimate selectivity parameters differed among studies, it was not always easy to distinguish between actual differences in selectivity and different results due to the method used (Fonseca et al. 2005).

The two target species, red mullet and surmullet, constitute one of the more widespread *métiers* in trammel net fishery in Greece. The same nets are used in the commercial fishery for both species ("barbounodicta"), deployed however in different seasons. For red mullet, the mesh size of 16 mm was the most efficient in abundance and biomass catch rates, with no specimen below the MCRS (11 mm for red mullet) and very few below the median L_m of 12.9 mm (ranges between 10.5 and 15.5 mm) in the Mediterranean Sea (Tsikliras and Stergiou 2014 and references therein) (Table 1). The modal length estimates are very similar to those previously reported in the Black Sea for all mesh sizes and nearly coincide for the mesh sizes 16 and 22 mm (Table 4). The operational condition (mesh size range) and the modeling (bi-normal model of SELECT method) were also in agreement (Kalaycı and Yeşilçiçek 2012). Lower values of modal length were re-

Table 4. Comparison of the results of the presently reported study with previous selectivity studies that deal with the same species in Mediterranean and adjacent Seas.

Species	Area	*n*	Length [cm]	Selectivity	Model	MS	Modal	Spread	Reference
Annular seabream, *Diplodus annularis*	N. Aegean Sea (Turkey)	190	7.7–16.8	SELECT	BiM	16	8.82	0.53	Karakulak and Erk 2008
						18	9.93	0.6	
						20	11.03	0.66	
						22	12.13	0.73	
	Adriatic Sea	180	5.5–22.0	Sechin	UniM	22.5	12.1	NA	Fabi et al. 2002
	Ligurian Sea	269	6.5–19.0	Sechin	UniM	22.5	12.1	NA	Fabi et al. 2002
	Cyclades		6.0–18.0	SELECT	BiM	20	11.0	NA	Erzini et al. 2006
						24	12.5	NA	
						28	15.0	NA	
Red mullet, *Mullus barbatus*	Antalya Bay	247	10.8–22.3	SELECT	BiM	20	17.0	1.14	Olguner and Deval 2013
		166	10.8–22.3			22	18.7	1.25	
	E. Black Sea (Turkey)	541	7.4–22.6	SELECT	BiM	16	15.49	2.06	Kalaycı and Yeşilçiçek 2012
						17	16.46	2.18	
						18	17.42	2.31	
						20	19.36	2.57	
						22	21.3	2.83	
	Finike Bay (Turkey)	420	12.1–26.3	HOLT	UniM	22	18.58	NA	Bolat and Tan 2017
						24	20.27	NA	
						26	21.96	NA	
	Adriatic Sea	131	9.0–19.5	Sechin	UniM	22.5	16.7	NA	Fabi et al. 2002
	Ligurian Sea	722	8.5–21.0	Sechin	UniM	22.5	16.7	NA	Fabi et al. 2002
Surmullet, *Mullus surmuletus*	N. Aegean Sea (Turkey)	411	11.3–27.7	SELECT	BiM	16	14.7	1.47	Karakulak and Erk 2008
						18	16.54	1.65	
						20	18.38	1.84	
						22	20.22	2.02	
	Cyclades		8.0–36.0	SELECT	BiM	20	17.5	NA	Erzini et al. 2006
						24	21.5	NA	
						28	25.0	NA	
Black scorpionfish, *Scorpaena porcus*	E. Black Sea (Turkey)	942	8.4–27.9	SELECT	BiM	16	9.17	2.82	Kalaycı and Yeşilçiçek 2012
						17	9.74	3.00	
						18	10.31	3.18	
						20	11.46	3.52	
						22	12.61	3.88	
	Cyclades		8.0–46.0	SELECT	BiM	20	13.0	NA	Erzini et al. 2006
						24	15.0	NA	
						28	17.5	NA	

n = number of fish, MS = mesh size, BiM = Bimodal, UniM =Unimodal.

ported in Antalya Bay, Levantine Sea (Olguner and Deval 2013) in Finike Bay, Levantine Sea (Bolat and Tan 2017), and in the Adriatic and the Ligurian Sea (Fabi et al. 2002) but the difference could be attributed to the different methodology among the studies (Table 4).

For surmullet, the higher yield was observed also at a mesh size of 16 mm with one-third of the catch being below L_m (median 15.5 mm, ranges between 11.9 mm and 17.8 mm in the Mediterranean Sea according to Tsikliras and Stergiou 2014 and references therein). At the next larger mesh size of 19 mm, all individuals were above MCRS and only 4% were below L_m (Table 1). The modal length estimates are similar for all mesh sizes to those previously reported in the northern Aegean (Karakulak and Erk 2008), using the SELECT method (Table 4). Similar selection curves and similar modal lengths were observed in the Cyclades, central Aegean (Erzini et al. 2006).

According to modal length estimates, the 19 mm mesh size is clearly the more suitable trammel net mesh size for surmullet, while for red mullet the largest amount of catch was recorded at a mesh size of 16 mm. However, larger red mullet individuals of almost double the weight, and therefore of greater commercial value, were caught in the larger mesh size (19 mm), which appears to be more profitable for fishers. Given the heavy exploitation of red mullet by the bottom-trawling fleet and the high number of undersized individuals caught by trawlers, a 19 mm mesh trammel net would be considered a more sustainable *métier*. A minimum mesh size of 18 mm in the red mullet trammel net fishery has been previously proposed in the eastern Mediterranean Sea to promote sustainable fisheries that will ensure profits for the fishers and catch for the future (Karakulak and Erk 2008, Kalaycı and Yeşilçiçek 2012).

Concerning bycatch, annular seabream is a species with a low commercial value for small individuals and slightly higher value for larger individuals that are usually sold mixed with other sparids. The higher catch rates were obtained in mesh sizes from 16 to 26 mm while the rest of the mesh sizes had negligible catch. Mesh size 16 mm was most efficient in terms of catch in numbers and 26 mm in terms of biomass. The modal length estimates are in close agreement with those previously reported in the northern Aegean Sea (Karakulak and Erk 2008), the Cyclades (central Aegean) (Erzini et al. 2006), and the Adriatic and Ligurian seas (Fabi et al. 2002). From a fisheries management perspective, the catch of mesh sizes 22 and 26 mm was above MCRS (12 mm) and L_m (12.2 mm: Koc et al. 2002), and the most appropriate mesh size that will ensure the sustainable exploitation of the species seems to be between these two mesh sizes. Indeed, a mesh size of 22.5 mm has been previously proposed in Italy (Fabi et al. 2002) while an even larger mesh size of 27 mm has been suggested in Turkey (Karakulak and Erk 2008).

One of the main target species in gillnet, longline, and bottom-trawl fisheries (Deniz et al. 2020), European hake is a very valuable bycatch in trammel net fisheries. Most of the catch of the species was fished in mesh sizes from 16 to 26 mm, with mesh sizes 16 and 26 mm being most efficient in terms of abundance and 26 mm in terms of biomass. Nearly no individuals were below MCRS (20 cm), which is considered very low for a large-sized fish such as hake that matures well after 20 cm (Tsikliras and Stergiou 2014). For that reason, a considerable number of individuals (>60%) per mesh size were below L_m (30.5 cm, ranges between 21.5 and 42.5 cm; Tsikliras and Stergiou 2014 and references therein) for mesh sizes 16, 19, 22 mm, and a significant proportion (37%) for mesh size 26 mm (Table 1). Considering the length at first maturity of hake and its heavy exploitation by many gears in the Mediterranean (Cardinale et al. 2017), a mesh size larger than 26 mm would be most adequate for the sustainable exploitation of the species.

Round sardinella and blotched picarel are both bycatch species with low commercial value. They were fished by 16, 19, and 22 mm mesh sizes and all individuals caught were above MCRS (10 cm for round sardinella, 8 cm for blotched picarel according to national legislation) and above L_m (14.7mm ranging from 11.5 to 16.8 cm for round sardinella; 10.1 cm ranging between 9.5 and 10.7 cm for blotched picarel; Tsikliras and Stergiou 2014 and references therein). The mesh size of 22 mm was more efficient in terms of biomass for round sardinella, while for blotched picarel the largest catch was recorded at 16 mm mesh size. However, the higher individual weight of blotched picarel individuals were caught by the 19 mm mesh size which results in a higher commercial value of the catch because of the positive relation between fish size and its market price (Tsikliras and Polymeros 2014).

The most common bycatch species in trammel nets, black scorpionfish is a low commercial value species with only the bigger individuals (>15 cm) being marketed while the smaller ones are discarded (Tsikliras et al. 2021). Most of the catch of the species was fished in three mesh sizes 16, 19, and 22 mm (Table 1), with nearly all individuals being below L_m (15.3 cm ranging from 13.8 to 17.5 cm according to Tsikliras and Stergiou, 2014 and references therein). The results of our study are in agreement with those reported in the Black Sea (Kalaycı and Yeşilçiçek 2012) and in the Cyclades, central Aegean (Erzini et al. 2006). Considering the length at first maturity a mesh size larger than 26 mm seems to be better for the sustainable exploitation of the species.

Greater weever is also a bycatch species in trammel net fisheries, with no commercial value for small sizes and low commercial value for ones larger than 25 cm (Tsikliras et al. 2021). Greater weever was caught by nearly all mesh sizes, with half of the catch obtained with 19 mm mesh. No differences were found between mesh sizes in either LFDs or mean length. All individuals were above the MLS (8 cm, according to national legislation), while, as there is no clear relation between mesh size and fish size, a number of specimens below L_m (18.5 cm, ranging from 12 to 25 cm: Ak and Genç 2013) were recorded in several mesh sizes (Table 1). Because of the lack of fit of the model as shown by the residuals plot, the estimates of the selectivity parameters should be considered with caution and no prediction of the appropriate mesh size was made.

Conclusions

Overall, the higher yield for nearly all species was observed in the smaller mesh size of 16 mm. However, this mesh size retained specimens below size at first maturity (L_m) in most of the cases and below MCRS for some species (Table 1). Biomass rather than abundance is a better indicator of the more appropriate mesh size because small individuals of the species have lower economic value than large ones, which are sold at higher prices and provide greater economic profit to fishers (Colloca et al. 2013; Tsikliras and Polymeros 2014). The mesh size of 19 mm seems to be more efficient for the main target species, red mullet, and surmullet. Regarding bycatch species, since most of them have a low commercial value, the aim was not to determine the mesh sizes that will provide the higher abundance but to determine the mesh sizes that will retain large specimens in order to obtain the highest possible market value (Tsikliras and Polymeros 2014), while allowing the smaller specimens to escape. With this perspective, for the bycatch species, a mesh size of 19 mm is more appropriate for blotched picarel, a mesh size of 22 mm for round sardinella, and annular seabream, while for European hake and black scorpionfish a mesh size over 26 mm would be more appropriate.

Modifying the size selectivity of fishing gears, and thus their capture efficiency, has been widely proposed to mitigate unwanted bycatch and discards (Bellido et al. 2011), to reduce the catch of immature individuals so they can survive to spawn (Vassilakopoulos et al. 2011), and to limit the capture of larger individuals in order to protect the most productive spawners (Hixon et al. 2014). Therefore, a thorough knowledge of fishing gear selection properties is crucial for sustainable fisheries management (Froese et al. 2018). Management actions could leverage this selectivity information to reduce catches of species of concern by modifying minimum and maximum mesh sizes (Sbrana et al. 2007). The length at first maturity (L_m)is a crucial population parameter for maintaining stock biomass; therefore, it should be considered the basis for setting MCRS of exploited stocks and proposing the appropriate mesh sizes (Tsikliras and Stergiou 2014). However, the results of the presently reported study also highlight the difficulties of managing multispecies fisheries based only on mesh size, since the optimal mesh varies considerably among species.

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Supplementary material 1

Technical parameters for the experimental trammel nets

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Data type: table (Excel spreadsheet)

Link: https://doi.org/10.3897/aiep.53.103358.suppl1

Supplementary material 2

Results of the Kolmogorov–Smirnov test used to compare the LFDs of paired mesh sizes at the 95,0% confidence level

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Data type: Statistics (Excel spreadsheet)

Link: https://doi.org/10.3897/aiep.53.103358.suppl2