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Modelling gear and fishers size-selection for escapees, discards and landings: a case study in Mediterranean trawl fisheries

Authors:

Chryssi Mytilineou[1], Bent Herrmann[2], Danai Mantopoulou-Palouka[1], Antonello Sala[3] and Persefoni Megalofonou[4]

Authors' Affiliation:

[1] Hellenic Centre for Marine Research (HCMR), Institute of Marine Biological Resources & Inland Waters (IMBRIW), P.O. Box 712, Anavyssos 19013, Attica, Greece

[2] SINTEF, Fisheries and Aquaculture, Fishing Gear Technology, Willemoesvej 2, 9850 Hirtshals, Denmark; University of Tomsø, Norway

[3] Italian National Research Council (CNR), Institute of Marine Science(ISMAR), Ancona (Italy)

[4] Faculty of Biology, Department of Zoology-Marine Biology, National and Kapodistrian University of Athens (NKUA), Panepistimioupolis, Ilissia, 15784 Athens, Greece

Authors' E-mail address:

Chryssi Mytilineou: chryssi@hcmr.gr
Bent Hermann: Bent.Herrmann@sintef.no

Danai Mantopoulou Palouka: danaim@hcmr.gr
Antonello Sala: a.sala@ismar.cnr.it
Persefoni Megalofonou: pmegalo@biol.uoa.gr

Corresponding author:

Mytilineou Chryssi

E-mail: chryssi@hcmr.gr

tel.:+30. 210. 9856706

fax: +30. 210. 9811713

Postal address: Hellenic Centre for Marine Research, Institute of Marine Biological Resources & Inland Waters, 46.7 km Athens-Sounio Av., P.O. Box 712, Anavyssos 19013, Attica, Greece

ABSTRACT

Gear selectivity and discards are important issues related to fisheries management but separately modelled. The present work examine for first time the overall size-selection pattern on the total amount of individuals of a species entering the trawl codend. An innovative approach was used based on modelling the escapement through the codend in the sea and the subsequently selection process by the fisher on the deck of the fishing vessel resulting into the discards and landings. Three different trawl codends and three species were used in the case study conducted. A dual sequential model accounting for both gear size-selectivity and the subsequent fisher-size-selectivity was applied, under the hypothesis that a fish entering the codend can follow a multinomial distribution with three probabilities, the escape, the discard and the landing probability, respectively. The model described the escape probability through the gear and the landing probability by the fisher as S-shaped curves leading to a bell-shaped curve for the discard probability affected by both gear and fisher selection. The model described well the experimental data in all cases. Sampling scheme of three compartments proved adequate. The model provides at the same time selectivity and discard parameters useful in fisheries management.

Key words: fishers selectivity, escape pattern, discards, landings, trawl, codend mesh, hake, horse mackerel, four-spot megrim, Mediterranean

Introduction

Knowledge on gear selectivity is important in fisheries management and stock sustainability (e.g. Pope. 1975, Armstrong *et al*., 1990; MacLennan, 1992; Wileman *et al*., 1996; Valdemarsen and Suuronen, 2001; Krag, 2009; Vasilakopoulos *et al*., 2011; 2015; Madsen et al., 2015; Stepputtis *et al*., 2015). The ecosystem approach to fisheries management, by incorporating both stock and ecosystem sustainability, triggered many discussions and debates on the need for more sophisticated management schemes and alternative selectivity concepts (Hall *et al*., 2000; Zhou *et al*., 2010; Rochet et al., 2011; Garcia *et al*., 2012). The echo of all these was the recently proposed Common Fisheries Policy reform that set out the gradual elimination of discards by establishing a discard ban and the landing obligation of all catches by 2019 (Regulation (EU) 1380/2013).

Discarding is globally an important and complex issue related to fisheries management (Hall *et al*., 2000; Kelleher, 2005). Annual global discarding has been estimated 7.3 million tonnes (Kelleher, 2005). A rough estimate of discards in the Mediterranean was around 230.000 t or 18.6% of the catch (Tsagarakis *et al.,* 2014). Several studies, debates and regulations have been focused on discards aiming to their elimination and management. However, solving the discard problem is notoriously difficult since many intricate drivers contribute to this phenomenon including species, fishing gear, catch composition, fishing tactics, fishers themselves, market, fish damages, regulations, community and environmental conditions (Tsagarakis *et al.*, 2014 and references therein; Catchpole *et al*., 2014 and references therein; Rochet *et al*., 2014 and references therein).

Bottom trawling is a fishing practice producing high quantities of discards (e.g. Hall *et al*., 2000; Tsagarakis *et al*., 2014; Bellido *et al*., 2014). Management measures for trawl fishery have been focused on improving the gear size-selectivity, although this has been proven difficult for multispecies fisheries (Valdemarsen and Suuronen, 2001).Trawl selectivity is traditionally expressed by trawl codend selectivity, where a simple size-selection process occurs represented by an S-shape size selection curve (Wileman *et al*., 1996). Historically, trawl selectivity studies were always focused on modelling only the gear selectivity occurring in the sea. However, the size selection in the sea by the gear is followed by a fisher selection process on the vessel resulting in that only a proportion of the catch reaching the deck on the fishing vessel will be landed in the harbor. The fishers sort the catch on the deck of the fishing vessels into the amount of landings as well as the amount of discards. The total size selection process from when the fish enter the gear in the sea to the fish is landed in the harbor can therefore be considered as a dual sequential process. Despite the growing number of studies on discards and the improvement of our knowledge on this issue, few works have been done on modelling discard probability by length based on data collected by observers and assuming that this probability is described by a logistic function (Rochet *et al*., 2002; Pálsson, 2003; Machias *et al*., 2004; Borges et al., 2006; Damalas and Vassilopoulou, 2013) or a nonlinear isotonic curve (Stratoudakis *et al*., 1998). These works focused on the discard probability related to the codend catch only. No research is known to date confronting the overall size-selectivity process and modeling both the gear and the following fishers size-selection processes.

Mediterranean bottom trawl fishery is a multispecies fishery characterized by many commercial and non commercial species as well as undersized individuals of the target species; the last two constituting part of the discards. Establishment of a minimum landing size (MLS) for many commercial species in the Mediterranean and several technical measures related to the mesh size of the trawl body, twine thickness, codend circumference and codend mesh size are tools included in the European Common Fisheries Policy for the sustainability of the stocks, the protection of juveniles and discards mitigation (EC Regulation 1967/2006). Mediterranean bottom trawl fishery in the past used small diamond meshes in the codend retaining almost all specimens (Petrakis and Stergiou, 1997; Mytilineou et al., 1998; Stewart, 2002), which resulted in high quantities of discards (Tsagarakis *et al*., 2014). EC Regulation 1967/2006 imposed the use of 40 mm square mesh size in the trawl codend or 50 mm diamond in particular cases. The use of 40 mm square mesh showed reduction of discards and improvement of the selectivity in most research studies in the Mediterranean Sea (e.g. Petrakis & Stergiou, 1997; Stergiou *et al*., 1997; Tokaç *et al*., 1998; 2010; Bahamon *et al*., 2006; Guijarro & Massuti, 2006; Luccheti, 2008; Ordines *et al*., 2006; Tosunoğlu *et al*., 2009; Aydin & Tosunoğlu, 2010; Sala *et al*., 2015). However, important quantities of discards still exist in the Mediterranean bottom trawl fishery particularly for horse mackerel (*Trachurus trachurus*), anglefish (*Lophius spp*.), pandoras (*Pagellus erythrinus*) and hake (*Merluccius merluccius*) (e.g. Damalas & Vassilopoulou, 2013; Bellido *et al*., 2014) and selectivity parameters still remain low for some species (e.g. Sala *et al*., 2008 and references therein; 2015; Deval *et al*., 2016).

The objectives of the present work are two fold: i) to determine a model expressing the complete selection process on the total amount of individuals of a species entering the trawl codend and ii) to assess the probability of escapees, discards and landings by size and identify helpful tools for fisheries management A case study has been conducted for the above purposes using three different codends (made by 40 mm diamond, 40 mm square or 50 mm diamond meshes), and for three species (European hake-*Merluccius merluccius*, Atlantic horse mackerel-*Trachurus trachurus* and four spot megrim-*Lepidorhombus boscii*).

Material and Methods

Experimental design

Experimental fishing survey was carried out on important commercial fishing grounds for the Greek trawl fishery in the area of south Aegean Sea (E. Mediterranean) (Figure 1). The survey was conducted between 27th May and 18th June of 2015. A total number of 84 hauls in 28 locations (one haul with each studied codend per location: 28x3=84) was performed targeting several commercial species; few hauls were not considered valid because of damaged net or bad net performance. Gear good performance was followed during the fishing operation in all hauls using a SCANMAR system. The average measured horizontal and vertical opening of the trawl was 17.9±1.8 m and 2.1± 0.3 m, respectively. Each haul lasted always 1 hour during daytime and the vessel towing speed was around 2.8 knots. The substarte type was sand or mud and the fishing depth ranged from 50 to 310 m, the common depth range of Mediterranean trawl fishery targeting hake (*M. merluccius*), red mullets (*Mullus barbatus, Mullus surmuletus*), rose shrimp (*Parapenaeus longirostris*) and other commercial species of the continental shelf. In order to achieve as much as possible the real conditions of the commercial trawl fishery, a hired professional trawler (357 KW, 29 m LOA, 160.81 GT) was used equipped with two typical type otterboards ("portuguese type": 330 kg each) and a typical commercial trawl used in the Greek trawl fishery and made according to the EC Regulation 1967/2006; the design of the gear shown in Figure 2. Trawl main body and codend were made by nylon (polyamid-PA).

Three different codends were used to study the overall selection process: i) a codend made by 40 mm nominal size diamond meshes (40D) used in the past but not allowed now, ii) a codend made by 40 mm nominal size square meshes (40S), actually in use according to the EC Regulation 1967/2006 and iii) a codend of 50 mm nominal size diamond meshes (50D), that according to the same regulation can be used if proved more selective than that of 40S. Although the questions addressed in our study refer mainly to the last two meshes, 40D was also included in this study for comparison purposes and because it has not been studied for the Greek trawl fishery in the past, before the application of the EC Regulation 1967/2006 and fishers always were wondering about the advantages of the change from 40D to 40S. The codend mesh sizes (100 meshes for each codend type) were measured using an ICES mesh gauge (ICES, 1962) with 4 kg tension while the nettings were wet. The actual mesh sizes of the three tested codends were: 43.2±0.6 mm for the 40 mm diamond- and square-mesh codend (40D and 40S), and 51.1±0.7 mm for the 50 mm diamond-mesh (50D) (Table 1). The three knotless codends were made by monofilament nylon (PA) and the nominal twine thickness was always 3 mm (in line with EC Regulation 1967/2006). The number of meshes in the codend length and circumference was selected (as proposed by Sala *et al.*, 2015) to obtain in all cases similar measurements for the codend length (~5.6 m) and the codend circumference (~4.3 m during fishing operations, since according to EC Regulation 1967/2006 the codend circumference should be 2 or 4 times less than the extension circumference). The number of meshes of each codend are given in Table 1.

A case study has been carried out focused on the examination of the overall selection of three species with different characteristics; *Merluccius merluccius*-European hake, a species of high commercial value with MLS at 20 cm total length (TL); *Trachurus trachurus*-Atlantic horse mackerel, an abundant but of low commercial value species with MLS at 15 cm (TL); *Lepidorhombus boscii*-four spot megrim, a species without legislated MLS, of medium but more constant commercial value because of a lower abundance. The first two species are rounded shaped fish, whereas the latter is a flatfish for which selectivity may not be improved by 40 mm square mesh codend (Sala et al., 2008).

To estimate the individual (gear, fisher) and overall selectivity process for each species, it was necessary to use a three-compartment sampling design to directly quantify fish escaping through the trawl codend, fish retained in the codend being discarded and fish retained in the codend being landed. For the first compartment, we used an experimental design as in the scheme published by Sala *et al*. (2015) based on the cover-codend method (Wileman *et al*., 1996) to collect trawl size-selectivity data. For each haul, the catch of each species from the cover was managed separately from that of the codend. In order to achieve the information for the other two compartments, the vessel crew was asked to sort the codend catch of each species in two fractions according to the market demands as usually have experienced, the commercial (potential landings if fishing was carried out during professional conditions) and that non commercial (potential discards).

Data collection

Data were collected during the experimental fishing survey. Data for European hake (namely hake from now on), Atlantic horse mackerel (namely horse mackerel) and four spot megrim (namely megrim) were collected from 16, 17 and 7 sampling locations, respectively. In each location, the three compartments -escapees, discards and landings- were recorded from each haul conducted with the three different codends (40D, 40S, 50D). Total length (TL, mm) of hake, horse mackerel and megrim individuals were measured to the nearest 1.0 mm. Measurements took place from all individuals of the catch of each compartment (separately for cover-escapees, codend-discards, codend-landings) of each studied species or in randomly selected sub-samples when the catch of each component consisted of numerous individuals. In the latter case, 200 measurements were recorded, number sufficient for a 5% uncertainty in selectivity parameters estimations (Herrmann *et al.*, 2016). In some cases, a lower number of measurements than the expected was obtained due to damaged fish or bad weather conditions. Because of the three compartment sampling design, in each haul and each length class l, our data included the number of measured fish in the cover, the number of measured fish in the codend being discarded and the number of measured fish in the codend being landed.

Modelling the overall size-selection process

For a fish of length l entering the codend during fishing to end up being landed in the harbor two conditions needs to be fulfilled: i) it needs to be retained in the codend during the trawl haul; ii) it needs to be selected for landing by the fisher when the catch is sorted on the vessel. The first condition is modelled by the fishing gear size selection curve with retention probability $r_{gear}(l,\mathbf{v}_{gear})$ and the second by the fisher size selection curve with retention probability $r_{fisher}(l,\mathbf{v}_{fisher})$. The vectors $\mathbf{v}_{gear}$ and $\mathbf{v}_{fisher}$ represents the parameters of the two parametric selection models describing respectively the gear size selection in the sea and the fisher size selection on the deck of the fishing vessel. The two selection processes are distinguished, based on a different amount of fish, and can be examined independently as two separate selection steps. However, these two sequential processes, could describe the overall selectivity (gear and fisher) on the total amount of fish entering the trawl codend resulting into three different outcomes: the escapees, the discards and the landings. Thus, a fish entering the codend during the towing of the gear in the sea will end up following a multinomial distribution with one of three fates (probabilities) as consequence of the fishing activity: i) escaping through the meshes of the codend described by the probability $p_{esc}(l,\mathbf{v}_{gear})$; ii) being discarded by the fisher, given that it had been retained in the trawl codend, and described by the probability $p_{disc}(l, \mathbf{v}_{gear}, \mathbf{v}_{fisher})$ iii) being landed in the harbor, given that it had been retained in the trawl codend, and described by the probability $p_{land}(l, \mathbf{v}_{gear}, \mathbf{v}_{fisher})$. Based on the two and sequential size selection processes, the three fate probabilities can be described by:

$$\begin{aligned} p_{esc}(l,\boldsymbol{v}_{gear}) &= 1.0 - r_{gear}(l,\boldsymbol{v}_{gear}) \\ p_{disc}(l,\boldsymbol{v}_{gear},\boldsymbol{v}_{fisher}) &= \left(1.0 - r_{fisher}(l,\boldsymbol{v}_{fisher})\right) \times r_{gear}(l,\boldsymbol{v}_{gear}) \\ p_{land}(l,\boldsymbol{v}_{gear},\boldsymbol{v}_{fisher}) &= r_{gear}(l,\boldsymbol{v}_{gear}) \times r_{fisher}(l,\boldsymbol{v}_{fisher}) \end{aligned} \quad (1)$$

Logit model has been commonly used in selectivity studies, however, other s-shaped models can also be used to describe gear size-selectivity $r_{gear}(l,\mathbf{v}_{gear})$ (Millar, 1993; Wileman *et al*., 1996). Discard probability by length has been described in the past by a nonparametric isotonic curve by Stratoudakis *et al*. (1998) and as logistic function ogives by Rochet *et al*. (2002), Pálsson (2003), Machias *et al*. (2004), Borges *et al*. (2006) and Damalas and Vassilopoulou (2013). In the present work, to describe the above mentioned probabilities, four models, Logit, Probit, Gompertz and Richard (see Supplement and Wileman et al., 1996 for more details on these models), were examined for each selection process in the sequential selection model. The selection parameters characterizing the curves of these models are: L_{50} (the length of fish having 50% probability of being retained by codend) and *SR (*the selection range = L_{75} - L_{25}) and for Richard model as well the additional parameter 1/δ (which expresses the amount of asymmetry of the curve with δ>1 or 0<δ<1 giving longer tail to the left or right of L_{50} respectively and δ=1 giving the symmetric logistic curve). According to that the parameters in the present work are denoted as:

$$\boldsymbol{v_{gear}} = \left(L50_{gear}\,, SR_{gear}\,, \left(1/\delta_{gear}\right)\right)$$
$$\boldsymbol{v_{fisher}} = \left(L50_{fisher}\,, SR_{fisher}\,, \left(1/\delta_{fisher}\right)\right)$$

Data analysis and parameter estimation

Using each of the four basic s-shaped size selection models in each of the two processes in (1) lead to a total of 16 potential models for the total selectivity process. Evaluation of each model performance to describe the data was based on the calculation of p-value, which expresses the likelihood of obtaining at least as large a deviation between the experimental data and the applied model by coincidence. Model deviance (D) compared to the number of degrees of freedom (DOF) can be used to help judge the ability of a model to describe the experimental data; in general model D should not exceed DOF (Madsen et al., 2012). Detailed information on the selectivity models evaluation is included in Wileman et al. (1996). AIC criterion (Akaike, 1974) should then be examined to select the best one of the models; the lowest value indicating the best model.

For the estimation of the selection parameters of the dual sequential model (1), the maximum log-likelihood function (that can be minimized as equivalent to maximize) was used , accounting in the present work the sub-sampling ratios, as follows:

$$-\sum_l \sum_{i=1}^{h} \left\{ \frac{nco_{li}}{qco_i} \times ln\left(p_{esc}(l, \boldsymbol{v}_{gear})\right) + \frac{nd_{li}}{qd_i} \times ln\left(p_{disc}(l, \boldsymbol{v}_{gear}, \boldsymbol{v}_{fisher})\right) + \frac{ncm_{li}}{qcm_i} \times ln\left(p_{land}(l, \boldsymbol{v}_{gear}, \boldsymbol{v}_{fisher})\right) \right\} \quad (2)$$

where (nco_{li}): the number of measured fish in the cover in length class l-escapees; (nd_{li}): the number of measured fish in the codend being discarded in length class l-discards; (ncm_{li}): the number of measured fish in the codend to be landed in length class l-landings; qco_i, qd_i and qcm_i: the corresponding sub-sampling ratios for the cover, discarded and landed compartment in each haul, respectively, and calculated by dividing the weight of each sub-sample by the total weight of the catch of each component. The subscript *i* refers to the specific fishing haul. The outer summation is over the length classes *l* and the inner over the *h* fishing hauls included in the analysis.

Besides the selection parameters $\boldsymbol{v}_{gear}$ and $\boldsymbol{v}_{fisher}$ for the two size selection processes, we calculated based on the estimated curve for the length dependent landing probability $p_{land}(l, \boldsymbol{v}_{gear}, \boldsymbol{v}_{fisher})$ the parameters $L50_{land}$ and SR_{land}, which quantify the length of a fish with 50% probability for end up being landed (conditioned it enters the codend during the fishing haul) and the corresponding selection range ($L75_{land} - L25_{land}$), respectively. Simply, following the technique described in Sistiaga et al. (2010), we numerically solved the equation $p_{land}(l, \boldsymbol{v}_{gear}, \boldsymbol{v}_{fisher})=0.5$ with respect to l to obtain the value for $L50_{land}$. SR_{land} was obtained by the same technique by first solving for $L25_{land}$ and $L75_{land}$ for the landing probability fixed at respectively 0.25 and 0.75.

In addition, since discards is an issue of main importance in fisheries management, parameters related to discard probability curve, were examined. The following parameters describing the discards were calculated based on the discard curve by a numerical technique; $DR_{0.05}$, $DR_{0.25}$, $DR_{0.5}$, $DR_{0.75}$ and $DR_{0.95}$: the difference between the two sizes of the bell-shape curve with probability 0.05, 0.25, 0.5, 0.75 and 0.95, respectively (expressed in cm); Dp_{max}: the maximum discard probability; LDp_{max}: the length at the maximum discard probability (in cm); $DA_{0.05}$: the surface of the discard bell-shape curve when probability is $\geq$0.05. Figure 3 shows these parameters on a plot. The aim for the discard parameters is to obtain values close to zero, that is interpreted as negligible discards.

Traditionally, the estimation of mean selectivity from a set of hauls is based on individual hauls selectivity (Fryer, 1991). In the present study, in some individual hauls, the numbers of the studied species was very low in some length classes. Moreover, some of the hauls presented only escapees or only retained individuals. As a result, the size selection would not be possible to be estimated haul by haul. To overcome this problem, "average" selectivity parameters were obtained by pooling the data for all hauls based on fitting a single "average" curve, as proposed by Millar (1993) if fisheries issues are of primary interest and not between haul variation. Moreover, in order to incorporate the within and between haul variation in our selectivity estimates, the double bootstrapping method was used (Efron, 1982); an outer bootstrap resample with replacement from the group of hauls for between-haul variation and an inner bootstrap resample with replacement for the data of each length class within each resampled haul, for within-haul variation (Millar, 1993). Bootstrap involved pooling the raised data for all hauls per compartment and resulted in a pooled set of data, which then was analysed using (1) and (2). The inner bootstrap was performed prior to the raising of the data to avoid overestimation of the within-haul variation. For each case 1000 bootstrap repetitions were conducted to estimate the *"Efron percentile" 95% confidence limits* (95% CI) of the selectivity curve (Efron, 1982). This approach avoids underestimation of the uncertainty and consequently of the 95% confidence intervals of the "average" selection curves, which according to

Fryer (1991), would occur from simply estimating them from pooled data. The method has been applied in several published works (e.g. Sistiaga *et al*., 2010; Herrmann *et al*., 2012; 2013a,b; Eigaard *et al*., 2012; Madsen *et al*., 2012; Sala *et al*., 2015; Brčić *et al*., 2015; 2016; Özbilgin *et al*., 2015; Alzorriz *et al*., 2016; Larsen *et al*., 2017).

The whole procedure was implemented using the computer software SELNET (SELection in trawl NETting). SELNET is a flexible software tool developed to acquire, analyze and simulate size selectivity which enables the analysis of data for experimental designs involving multiple compartments (Herrmann *et al*., 2012; 2013a).

In the present study, the analysis of data was conducted separately by species and codend mesh. Overlapping of the 95% CI of the parameters was used to compare the parameters among the three codends (as proposed by Frandsen *et al*., 2010). Moreover, comparison of the fisher selection among the three gears was based on the 95% CI of the entire curves. Frandsen et al. (2009) mentioned that by checking for overlap of the approximate 95% confidence bands for the different selection curves we could compare the selectivities for all length classes.

Results

Data from experimental design

Tables 2, 3 and 4 list the number of individuals of hake, horse mackerel and megrim, respectively, measured in each compartment (cover-escapees, codend-discards, codend-landings) and their percentage to the total catch of each species in each compartment. For each species, one haul performed with 50D codend was not considered valid because of damaged net (Table 2, 3 and 4). In total, for 40D, 40S and

50D codends, 2955, 3285 and 3476 hake were measured (71.35%, 36.90% and 60.99% of the total entering the trawl net population) with lengths ranging between 4-63 cm, 5-58 cm and 5-69 cm, respectively. The total amount of horse mackerel measured was 1812 (31.14%), 1881 (33.72%) and 1837 (26.32%) individuals for 40D, 40S and 50D, respectively; length span between 5-36 cm, 5-39 cm and 4-37 cm for the same codends, respectively. Similarly, the total number of megrim measured was 521 (53.44%), 1096 (94.81%) and 797 (84.07%) for 40D, 40S and 50D, respectively; lengths ranging between 4-38 cm, 3-36 cm and 4-37 cm. Hake was very abundant in many hauls providing a strong sample for our analysis. This was not the case for the other two species since the sampling design followed hauls of the commercial bottom trawl fishery, targeting mainly hake, mullet, rose shrimp and Norway lobster and including megrim and horse mackerel as by-catch. In some hauls the number of individuals in each compartment was <10; these hauls were kept in the analysis first because their inclusion did not affected the results (analysis done with and without them) and second because for comparison purposes, if these were excluded, we had to exclude also the other two hauls performed in the same location with the other two codends.

Modelling the overall size-selection

The overall selection pattern throughout the fishing process was modelled for each species and codend using the formulas (1) and (2) and based on the fish collected in the cover (escapees), the compartment of the codend being discarded and the compartment of the codend being landed.

In total, 16 different models for the overall selection on the population entering the trawl codend, combining size-selectivity of the gear and fisher, were estimated by species for each one of the three codends. Their fit statistics permitted to consider their performance relevant to the data they described in all cases (following the rules: p-values>0.05, Deviance< or close to DOF value). The best model was finally identified based on the AIC-value (Table 5). For each codend and species, the best identified model and its fit statistics, shown in Table 6, clearly described the size-selection data of the present work. Moreover, plots in Figures 4-6 show the graphical representation of the best model by species, codend type and compartment, indicating the good performance of the models to the experimental rates per length class. On the same graphs, confidence intervals (95% CI) of the curves are also in most of cases quite narrow supporting the hypothesis of the proposed model and indicating the strength of the sampling design for the three compartment pattern used for the data analysis. Horse mackerel and megrim showed in few cases wider 95% CI, probably related to the low number of samples analysed, while the strong sampling for hake provided very narrow 95% CI in all cases. Gear size-selectivity for 40S and 50D seemed to be better described by Richard model for all three studied species, whereas 40D presented a variety of models depending on the species.

The plots in Figures 4-6 show always, that escape and landing probability are described by an S-curve, whereas discard probability is fitted by a bell-shaped curve, with zero values in small and large length classes and a peak value among them. This was symmetric (e.g. discard probability in 40D of megrim, Figure 6) or asymmetric with longer tail to the left or right side (e.g. discard probability in 50D of horse mackerel, Figure 5). Discard probability ranged between 0.0 and 1.0 depending on the escape probability of the gear in small sizes and the landing probability from fisher-selection in large sizes. The overall size selection on the population is given finally by the landing probability (sequential retention probability for landings on deck of the fishing vessel).

Escape, Discard and Landing size-dependent probability by species and codend type

Hake

The model describing the overall and the escape, discard and landing pattern for hake fitted very well the datapoints for all the three codend types (40D, 40S and 50D) and the three catch compartments (Figure 4).

The escape probability of hake differed among the three codends, with lower $L50_{gear}$ values for 40D and higher for 40S. The 95% CI of $L50_{gear}$ did not show overlap (Table 6). Escape probability for 40D decreased significantly (<0.3) at lengths >8 cm and tends to be zero when TL≥15 cm. In contrast, for 40S escape likelihood became <0.3 at lengths >15 cm and tends to be zero when TL≥20 cm. In 50D codend, values ranged between those of 40D and 40S codends. Taking into account the hake size structure entering the trawl codend (Figure 4), it was obvious that an important part of young individuals can escape to the sea only when 40S is used.

The discard probability for 40D presented very high values for lengths between 8-14 cm TL, corresponding to a big part of the total amount of hake entering the gear that has low probability to escape through this net (Figure 4). Table 7 summarizes the information on the discard probability of hake. The 40S codend showed the best discard parameters compared with the other two codends. Discard range ($DR_{0.05\text{-}0.95}$) presented the narrowest values for 40S decreasing to zero before the probability 0.5, whereas for 40D and 50D it was always >0. The maximum discard probability Dp_{max}

for 40S was 0.43 at 15.23 cm TL; that for 50D and 40D was 0.75 at 13.51 cm TL and 0.98 at 11.62 cm TL, respectively. The discard surface *($DA_{0.05}$)* for probability ≥0.05 was significantly lower for 40S without overlapping with the 95% CI of the other two codends (Table 7).

It is worth mentioning that landing probability of hake and the related parameters $L50_{land}$ and SR_{land} were almost identical among the three codend types (Figure 4, Table 6), indicating that fishers behaviour for the selection of hake landings is quite constant. This was also obvious in Figure 7, where the curves of fisher selection and their 95% CI for the case of 40D, 40S and 50D demonstrate overlapping among them. In fact, for all codends landing probability started at 12-13 cm and became 0.5 at 15-16 cm, reaching top at lengths ~20 cm TL that is the minimum landing size (MLS) of the species (Figures 4 and 7).

Horse Mackerel

The model describing the overall and the escape, discard and landing pattern for horse mackerel fitted well the experimental data in all cases, although 50D codend showed wider 95% CI for escape and discard probability in small sizes, because of some small individuals in the codend (TL: 7 cm) (Figure 5).

The escape probability of horse mackerel differed among 40D and the other two codends, with lower $L50_{gear}$ for 40D. Overlap among 40S and 50D was found for the 95% CI of $L50_{gear}$ (Table 6). Escape probability for 40D decreased significantly (<0.3) at lengths >11 cm and became almost null between 13-19 cm TL. In contrast, for the other studied codends escape likelihood became <0.3 at lengths >15 cm and null when TL≥17 or 20 cm for 40S and 50D, respectively.

A big amount of horse mackerel entering the 40D codend has probability of being discarded; particularly individuals with lengths between 9-13 cm TL, that in the case of 40S and 50D have important probability to escape. The worst discard parameters were found for 40D. No important differences were detected among the discard parameters of 40S and 50D as shown by the overlapping of their 95% CI (Table 7); the lower Dp_{max} and higher LDp_{max} values of 50D related to some big individuals found in the cover (TL: 18-20 cm).

The most impressive result for horse mackerel was that, for all codends, individuals with lengths ≥15cm (the MLS of the species-EC Regulation 1967/2006) and ≤19cm TL, either have a low likelihood to escape or mainly are discarded (~0.9). Even individuals of large sizes (19-23 cm), much larger than MLS, presented a probability of being discarded between 0.15-0.95 (Figure 5).

The constant fishers behaviour selecting only the few very big individuals from those entering the trawl codend, resulted in similar landing curves (Figures 5 & 7) and landing selection parameters for horse mackerel for the three studied codends (Table 6).

Megrim

The model for the escape, discard and landing likelihoods for megrim described well the datapoints in all cases, although 50D codend showed wider 95% CI for escape and discard probability in small sizes, because of gaps in some length classes and the presence of small individuals in the codend (Figure 6).

For all the three codends, escape probability concerned a small part of the entering the codend megrims. The biggest amount of them had a probability of being discarded; whereas another small part of being landed. Landing probability became

>0.01 at lengths of 13 cm, and became higher than 0.5 at lengths ≥18 cm TL in all cases (Figure 6 and 7). $L50_{gear}$ values for the three codends did not show important differences with overlap of their 95% CI, although the wide range of CI in 50D do not allow a clear suggestion (Table 6). However, the 50D $L50_{fisher}$ and $L50_{land}$ values differed from those of 40D and 40S, although a small overlap appeared between the upper limit of 50D and the lower of 40S for these parameters (Table 6). Examination of the fisher selection curves showed that the curve of 50D differed significantly from the other two curves without overlap among their 95% CI, except in the case of sizes <17 cm where a small overlap was observed among the three curves (Figure 7). Discard parameters did not show a clear situation because of the overlapping of 95% of CI in many cases, although the average parameters values for 50D seemed a little better than those of the other two nets (Table 7).

Discussion

In the present work, the overall size-selection on the total amount of individuals of a species entering the trawl codend is described and modelled for first time. The model was based on the concept of a multinomial distribution with three size-selection probabilities related to two size-selection processes. For a fish entering the trawl codend, the model describes the escape probability through the gear to the sea and the landing probability by the fisher-selection with S-shaped curves leading to a bell-shaped curve for the discard probability affected by the gear selectivity (first selection and retention in the codend) and the fisher-selection (sequential selection). In contrast to models that have traditionally studied these two processes separately (e.g. Wileman *et al.*, 1996; Stratoudakis *et al.*, 1998; Rochet *et al.*, 2002; Machias et al., 2004; Borges et al., 2006; Damalas and Vassilopoulou, 2013), the present dual sequential model accounts for the fact that these processes are sequential with the second depending on the first one. This kind of models have also been used in various studies (e.g. Zuur et al., 2001; Sistiaga *et al*., 2010; Herrmann *et al*., 2013a; Brčić *et al*., 2015; Larsen *et al*., 2017).

Historically, the logit model has been used to describe the size-selectivity of the trawl gear (Millar et al., 1993; Wileman et al., 1996) and the discard selection pattern (Rochet *et al*., 2002; Pálsson, 2003; Machias *et al*., 2004; Damalas and Vasilopoulou, 2013). The present work has demonstrated that other models can describe better these selection processes. More complicated models can be tested in the future as well as the incorporation of factors affecting the examined probabilities to better interpret the deviance of the double sequential model. However, in the present phase, the simplest possible approach of the initial concept, has been attempted.

The developed model described well the experimental data for all the three studied species and codend types. Sampling scheme of three compartments (escapees, discards, landings) proved adequate for modelling the overall selection process on the total amount of entering the gear fish. As a result, it can be proposed to be used also for other species and codend types. More cases can be tested in the future that is also in the purpose of the authors.

The described model permits to designate the overall length-dependent selection as well as the individual selection processes (gear or fishers). Several selection parameters (e.g. $L50_{gear}$, $L50_{fisher}$,$L50_{land}$) can be estimated at the same time. Discard parameters such as $DR_{0.05}$, Dp_{max}, LDp_{max} and $DA_{0.05}$, that can be used as a kind of discard indicators, can also be available. These are useful tools in fisheries management. In addition, the developed model demonstrates the image of the overall exploitation pattern and therefore the overall impact on the total amount of a fish entering the trawl codend. This is important in assessment studies for the estimation of mortality in exploited stocks (Wileman et al., 1996) and seems to support more the Environmental Approach to Fisheries Management by studying in a more holistic way factors affecting stock sustainability. It can also be useful to understand discards patterns and their relation to gear selectivity and to fishers behaviour. As a result, different scenarios can be proposed, based on experiments or simulations for changes in gear selection, fishers selection or both processes, useful for alternative exploitation patterns. Recently, different exploitation patterns have been studied for trawl size-selectivity by Stepputtis *et al.* (2016). Similar attempts could be examined for discard and landing selection patterns for useful alternative scenarios in discards management. Alternative concepts in fisheries management have been debated to date (Hall *et al*., 2000; Zhou *et al*., 2010; Rochet et al., 2011; Garcia *et al*., 2012), thus investigation should be focused on how to bring all new findings into practice. Furthermore, the useful tools that the present model can offer to fisheries management are provided by many different studies to date consuming big budgets and time. The advantage of combining selectivity and discards studies may reduce funding necessities.

In the present work, hake escape probability through bottom trawl codend was generally low for the species population structure in the fishing grounds examined, where commercial trawl fishery is practiced. More escapees were found for 40S, although even in this case, $L50_{gear}$ was below the minimum landing size (MLS) of the species nominated at 20 cm (EC Regulation 1967/2006) and much more lower than the length at first maturity (LFM) of hake in the area (~30 cm, Tsikliras and Stergiou, 2013). This has also been found by Pertakis and Stergiou (1997), Aydin and Tosunoğlu (2010), Tokaç *et al.* (2010) and Özbilgin *et al*. (2012) for hake in the

Aegean Sea. The square net showed also less discards. Thus, among the three codends, 40S presented the lowest impact on hake population. Fishers behaviour remained constant regarding selection probability for landings among the three codends with high likelihood (0.4-0.9) to keep undersized hake between 15-19 cm for marketable purposes. This probability was higher in 40D and lower in 40S. Thus, the use of 40S net triggers fishers to include less illegal sizes in landings and therefore act with more compliance to the existing regulations. Machias et al. (2004), Damalas and Vassilopoulou (2013) and Keskin et al. (2014), based on onboard observations, found also undersized hake in landings as in our case. Moreover, Tsagarakis *et al*. (2017) mentioned that among various Mediterranean countries hake size at which 50% is discarded (or retained) ranges between 10-17 cm. All the above results are in accordance and support the findings of the present model and its usability.

For horse mackerel, the overall selection pattern revealed that an important part of individuals can escape to the sea from 40S and 50D codends; this was not the case for 40D with much more discards amount than the other two nets. Better selectivity for this species was also found by Aydin and Tosunoğlu (2010) for square than diamond meshes codend in the Aegean Sea. Although 40S showed better $L50_{gear}$ value, none of the codends achieved MLS (15 cm) and certainly not LFM size (~20 cm, Tsikliras and Stergiou, 2013). For all codends, the vast amount of horse mackerel entering the trawl presented very high probability (~0.9) of being discarded at lengths above the MLS (15 cm) and less than 20 cm. A very small part of horse mackerel with size >23 cm (larger than LFM) have mainly probability of being landed. Horse mackerel is a fish of very low commercial value and besides the MLS establishment, it constitutes mainly an unwanted bycatch. This is also in accordance with the findings of Machias *et al*. (2004) and Damalas and Vassilopoulou (2013) from onboard observations on commercial fishing vessels. Tsagarakis *et al*. (2017) certifies this phenomenon for various areas of the Mediterranean, where the mean size of 50% discarding practice for horse mackerel ranges between 18-21 cm, fact that also supports the findings of the present model and its usability.

Megrim selection by the gear and the fisher followed generally a similar pattern among the three codends, with a small part of escapees, a small part of landings and a large amount of discards including many individuals above the LFM (~14 cm, Tsikliras et al., 2013). The better average values of discard parameters for 50D than 40S can be explained by the fact that square meshes do not offer improvement in selection of flatfish as also mentioned by Petrakis and Stergiou (1997), Sala *et al*. (2008) and Özbilgin *et al*. (2012). No MLS exists for megrim and its medium commercial value makes fishers select mainly big sized specimens for landings that can be marketable. $L50_{gear}$ values did not seem to differ among the three codends, fact possibly affected by the large 95% CI of 50D, and these were always lower than LFM of the species. Regarding fisher selection, 50D curve was found to differ from the other two codends for sizes >17 cm. The reason of such a difference, not easily explained, may be attributed to difference in the catch composition and quantity. In fact, a lower amount of megrim arrived on deck in the case of 50D (772 ind.) than in the other two cases (40D: 898 ind., 40S: 1052 ind.), that may has affected fisher selection behaviour. Fisher selection pattern was common for megrims <17 cm, indicating that fisher selection is constant for sizes that are not marketable, but this may be affected by other factors in larger sizes. None of the codends seemed to be adequate and gear selectivity needs improvement since gear fish small sized megrims and fishers land mainly megrim larger than LFM resulting to a large amount of discards.

The application of the model for hake, horse mackerel and megrim indicated that in all cases selectivity parameters were lower than the regulated MLS and much more lower than LFM. The discrepancy between retention sizes and LFM is expected to impede the sustainability of the stocks (Tsagarakis *et al*., 2017 and references therein). Another important observation is that discard and landing selection is affected mainly by the market demands and less by the establishment or not of MLS. Fishers may land undersized catch (as in the case of hake), but also may land much larger fish than the LFM (as in the case of horse mackerel and megrim) depending on the species and their marketability. This was also suggested by Machias *et al*. (2004), Damalas and Vassilopoulou (2013), Keskin *et al*. (2014), Bellido *et al*. (2014) and Tsagarakis *et al*. (2014, 2017) for the Mediterranean fishery. These findings may imply for more compliance to the legislated MLS as in the case of hake. However, they imply also for more surveillance and control of the market and for more community awareness to avoid the demand of small fish. Furthermore, the results of the present work indicate that MLS should be higher in order to be closer to LFM to ensure opportunity for reproduction, and this can be supposed to be easily acceptable by fishers for species that landing sizes are larger than LFM. However, it is doubtful if MLS revision would drive fishers to avoid juveniles or to further black market for undersized individuals (Tsagarakis *et al*., 2017 and references therein). Alternative scenarios for legal sized fish of not being discarded but used for other purposes (cosmetics, fish meat) can also be proposed. Finally, other issues that can arise are related to the effectiveness of the nets used. 40D was found to be a harmful net since it is characterised by low escape and high discard probabilities for all the three species. Therefore the prohibition of this net was a correct measure. 40S codend showed better selectivity than 50D for hake, but this was not so obvious for mackerel and megrim. Square mesh was examined in the past in several studies carried out in the Mediterranean, which showed that in most cases it improves trawl selectivity (e.g. Petrakis and Stergiou. 1997; Bahamon *et al*., 2006; Guijarro & Massuti, 2006; Özbilgin *et al*., 2012; 2015); but see Petrakis and Stergiou (1997), Sala *et al.* (2008; 2015), Tokaç *et al*. (2010), Özbilgin *et al*. (2012). As a result, alternative scenarios have been investigated (e.g. Sardá *et al*, 2004; Tokaç *et al*., 2010; Aydin and Tosunoğlu, 2010; Brčić *et al*., 2015) to find solutions for the case of multispecies Mediterranean bottom trawl fishery. However, a common solution seems difficult because of other important commercially species losses (e.g. Ordines *et al*., 2006; Bahamon *et al*. 2006, Özbilgin *et al*., 2015). Spatiotemporal protection of nursery grounds (e.g. for hake) and more regional solutions could lead to new approaches for this complex issue.

In summary, the proposed in the present study model can be a useful tool in fisheries management since it has been proved efficient to combine selectivity and discards studies and at the same time implying for a cost-benefit approach. Furthermore, it may initiate further debates in terms of trawl gear selectivity, discards management, fishers behaviour, fish market control and consumers habits to offer various alternatives in fisheries management. More studies with more species in various geographical areas and using different trawl gear designs should be examined in the future.

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Figure 3. Plot indicating Discard parameters calculated in the present study.

Figure 4. Size selectivity plots for hake. Left column plots represent size selectivity of the codend with 40 mm diamond meshes (40D), middle column plots represent the codend with 40 mm square meshes (40S) and right column plots represent size selectivity of codend with 50 mm meshes (50D). First row plots correspond to gear escape size selectivity (p_{esc}), second row plots correspond to discard probability (p_{disc}) and last row plots correspond to landing probability (p_{land}). Black lines represent selectivity curves and grey lines represent the size structure of the population entering the trawl codend. Circles correspond to experimental ratios and grey areas to 95% confidence intervals. Dashed vertical line indicates MLS.

Figure 5. Size selectivity plots for horse mackerel. Left column plots represent size selectivity of the codend with 40 mm diamond meshes (40D), middle column plots represent the codend with 40 mm square meshes (40S) and right column plots represent size selectivity of codend with 50 mm meshes (50D). First row plots correspond to gear escape size selectivity (p_{esc}), second row plots correspond to discard probability (p_{disc}) and last row plots correspond to landing probability (p_{land}). Black lines represent selectivity curves and grey lines represent the size structure of the population entering the trawl codend. Circles correspond to experimental ratios and grey areas to 95% confidence intervals. Dashed vertical line indicates MLS.

Figure 6. Size selectivity plots for megrim. Left column plots represent size selectivity of the codend with 40 mm diamond meshes (40D), middle column plots

represent the codend with 40 mm square meshes (40S) and right column plots represent size selectivity of codend with 50 mm meshes (50D). First row plots correspond to gear escape size selectivity (p_{esc}), second row plots correspond to discard probability (p_{disc}) and last row plots correspond to landing probability (p_{land}). Black lines represent selectivity curves and grey lines represent the size structure of the population entering the trawl codend. Circles correspond to experimental ratios and grey areas to 95% confidence intervals.

Figure 7. Fisher selection curves by species for the three studied codends (40D: continuous line; 40S: dashed line; 50D: dot line; light grey areas: 95% CI of each curve, dark grey areas: overlap of 95% CI of the curves).

Table 1. Characteristics of the three codends with 40 mm diamond (40D), 40 mm square (40S) and 50 mm diamond (50D) meshes used in the present study.

Codend	**40D**	**40S**	**50D**
Nominal mesh size (mm)	40	40	50
Measured mesh size (mm)	43.2±0.6	43.2±0.6	51.09±0.7
Nominal twine thickness (mm)	3	3	3
Measured twine thickness (mm)	2.8±0.1	2.8±0.1	2.8±0.1
Number of meshes in codend circumference	400	200	340
Codend Circumference at sea (mm)	4.32	4.32	4.34
Number of meshes in codend length	130	260	110
Codend longitudinal length (m)	5.616	5.616	5.619

Table 2. Number of hake (*Merluccius merluccius*) with measured total length and their percentage (in parenthesis) to the total catch of the species in the three compartments (C: cover, D: discards, L: landings) of each haul carried out in each sampling location with one of the three codends (40D: 40 mm diamond mesh, 40S: 40 mm square mesh, 50D: 50 mm diamond mesh).

CODEND	**40D**			**40S**			**50D**		
Sampling location	**C**	**D**	**L**	**C**	**D**	**L**	**C**	**D**	**L**
1	23 (100%)	143 (100%)	164 (100%)	84 (93.33%)	19 (95.0%)	126 (100%)	82 (100%)	50 (100%)	125 (100%)
2	16 (94.12%)	200 (35.71%)	427 (100%)	200 (23.57%)	200 (43.96)	295 (100%)	200 (98.04%)	208 (29.30%)	404 (100%)
3	43 (100%)	200 (100%)	325 (100%)	146 (8.47%)	200 (44.44%)	306 (100%)	270 (79.18%)	199 (35.28%)	331 (100%)
4	0 (100%)	4 (80%)	21 (100%)	0 (100%)	0 (100%)	14 (100%)	0 (100%)	0 (100%)	15 (100%)
5	20 (100%)	78 (92.86%)	77 (100%)	200 (74.07%)	15 (100%)	130 (100%)	99 (100%)	107 (91.45%)	103 (100%)
6	0 (100%)	1 (100%)	30 (100%)	2 (100%)	3 (100%)	17 (100%)	not valid haul		
7	0 (100%)	2 (100%)	27 (100%)	1 (100%)	0 (100%)	40 (100%)	3 (100%)	0 (100%)	14 (100%)
8	0 (100%)	0 (100%)	12 (100%)	0 (100%)	1 (100%)	12 (100%)	0 (100%)	0 (100%)	13 (100%)
9	1 (100%)	34 (100%)	136 (100%)	20 (95.24%)	5 (100%)	62 (100%)	32 (100%)	58 (100%)	137 (100%)
10	5 (100%)	86 (100%)	158 (100%)	11 (91.67%)	5 (100%)	118 (100%)	22 (100%)	53 (100%)	148 (100%)
11	90 (100%)	64 (7.30%)	61 (100%)	200 (7.65%)	143 (26.88%)	121 (100%)	178 (18.18%)	174 (27.29%)	107 (100%)
12	1 (100%)	75 (98.68%)	34 (100%)	28 (100%)	14 (100%)	41 (100%)	11 (100%)	17 (85%)	20 (100%)
13	4 (100%)	50 (100%)	56 (100%)	76 (98.70%)	63 (100%)	66 (100%)	4 (100%)	33 (91.67%)	38 (100%)
14	2 (100%)	104 (95.41%)	43 (100%)	79 (98.75%)	30 (100%)	21 (100%)	36 (100%)	73 (97.33%)	35 (100%)
15	2 (100%)	35 (100%)	36 (100%)	61 (100%)	27 (100%)	33 (100%)	2 (100%)	7 (100%)	9 (100%)
16	4 (100%)	12 (100%)	49 (100%)	10 (100%)	3 (61.07%)	37 (100%)	10 (90.91%)	8 (88.89%)	41 (100%)
TOTAL	**211** (99.50%)	**1088** (47.85%)	**1656** (100%)	**1118** (19.15%)	**728** (44.80%)	**1439** (99.93%)	**949** (51.97%)	**987** (42.31%)	**1540** (100%)

Table 3. Number of horse mackerels (*Trachurus trachurus*) with measured total length and their percentage (in parenthesis) to the total catch of the species in the three compartments (C: cover, D: discards, L: landings) of each haul carried out in each sampling location with one of the three codends (40D: 40 mm diamond mesh, 40S: 40 mm square mesh, 50D: 50 mm diamond mesh).

CODEND		**40D**			**40S**			**50D**	
Sampling location	**C**	**D**	**L**	**C**	**D**	**L**	**C**	**D**	**L**
1	200 (60.98%)	103 (88.03%)	0 (100%)	200 (66.04%)	179 (100%)	0 (100%)	21 (100%)	104 (100%)	0 (100%)
2	12 (100%)	3 (100%)	22 (100%)	0 (100%)	2 (100%)	19 (100%)	6 (100%)	5 (100%)	2 (100%)
3	3 (100%)	9 (100%)	0 (100%)	3 (100%)	1 (100%)	0 (100%)	24 (100%)	2 (100%)	1 (100%)
4	12 (100%)	22 (100%)	0 (100%)	14 (100%)	0 (100%)	2 (100%)	7 (100%)	2 (95.58%)	0 (100%)
5	3 (100%)	0 (100%)	0 (100%)	10 (100%)	0 (100%)	0 (100%)	23 (100%)	53 (98.15%)	0 (100%)
6	3 (100%)	3 (100%)	0 (100%)	21 (100%)	11 (100%)	1 (100%)	27 (100%)	11 (100%)	4 (100%)
7	2 (100%)	5 (100%)	5 (100%)	23 (95.83%)	0 (100%)	3 (100%)	16 (100%)	0 (100%)	0 (100%)
8	97 (90.65%)	16 (100%)	0 (100%)	200 (52.91%)	23 (61.03%)	0 (100%)	165 (96.49%)	0 (100%)	0 (100%)
9	0 (100%)	200 (86.96%)	4 (100%)	18 (100%)	24 (100%)	0 (100%)	10 (100%)	50 (100%)	14 (100%)
10	122 (31.28%)	200 (9.48%)	2 (100%)	200 (7.74%)	190 (16.67%)	0 (100%)	200 (17.61%)	200 (11.25%)	3 (100%)
11	200 (44.0%)	200 (19.04%)	0 (100%)	200 (74.91%)	63 (100%)	0 (100%)	200 (10.37%)	200 (19.72%)	2 (100%)
12	0 (100%)	34 (20.0%)	16 (100%)	1 (100%)	116 (100%)	36 (100%)	46 (100%)	104 (100%)	19 (100%)
13	6 (100%)	200 (39.06%)	6 (100%)	23 (100%)	184 (100%)	4 (100%)	81 (100%)	200 (71.94%)	3 (100%)
14	2 (100%)	2 (100%)	26 (96.30%)	0 (100%)	0 (100%)	63 (100%)	1 (100%)	1 (100%)	2 (100%)
15	1 (100%)	7 (100%)	3 (100%)	2 (100%)	1 (100%)	0 (100%)	3 (100%)	4 (100%)	0 (100%)
16	0 (100%)	0 (100%)	15 (100%)	0 (100%)	0 (100%)	23 (100%)	0 (100%)	0 (100%)	21 (100%)
17	0 (100%)	35 (27.03%)	11 (100%)	0 (100%)	19 (100%)	2 (100%)		not valid haul	
TOTAL	**663** (50.10%)	**1039** (23.70%)	**90** (99.10%)	**915** (25.08%)	**813** (45.73%)	**153** (100%)	**830** (23.71%)	**936** (27.47%)	**71** (100%)

Table 4. Number of four spot megrims (*Lepidorhombus boscii*) measured and their percentage (in parenthesis) to the total catch of the species in the three compartments (C: cover, D: discards, L: landings) of each haul carried out in each sampling location with one of the three codends (40D: 40 mm diamond mesh, 40S: 40 mm square mesh, 50D: 50 mm diamond mesh).

CODEND	**40D**			**40S**			**50D**		
Sampling location	**C**	**D**	**L**	**C**	**D**	**L**	**C**	**D**	**L**
1	6 (100%)	40 (100%)	3 (100%)	8 (100%)	170 (100%)	72 (100%)	12 (100%)	54 (100%)	5 (100%)
2	1 (100%)	40 (100%)	8 (100%)	2 (100%)	90 (100%)	29 (100%)	17 (100%)	57 (100%)	47 (100%)
3	21 (100%)	40 (20.00%)	24 (100%)	38 (100%)	200 (76.91%)	52 (100%)	124 (100%)	200 (52.77%)	82 (100%)
4	0 (100%)	23 (100%)	2 (100%)	0 (100%)	23 (100%)	1 (100%)	1 (100%)	30 (100%)	15 (100%)
5	19 (100%)	82 (100%)	0 (100%)	21 (100%)	125 (100%)	29 (100%)	50 (100%)	69 (100%)	6 (100%)
6	30 (100%)	109 (27.03%)	54 (100%)	35 (100%)	164 (100%)	30 (100%)	not valid haul		
7	0 (100%)	0 (100%)	19 (100%)	0 (100%)	3 (100%)	4 (100%)	0 (100%)	0 (100%)	28 (100%)
TOTAL	**77** (100%)	**334** (42.39%)	**110** (100%)	**104** (100%)	**775** (92,81%)	**217** (100%)	**204** (100%)	**410** (69.61%)	**183** (100%)

Table 5. AIC (Akaike, 1979) values obtained for the sixteen different models fitted to the experimental selectivity data of hake (HAK), horse mackerel (HOM) and four spot megrim (MEG). Models with the lowest AIC value are denoted by bold italics.

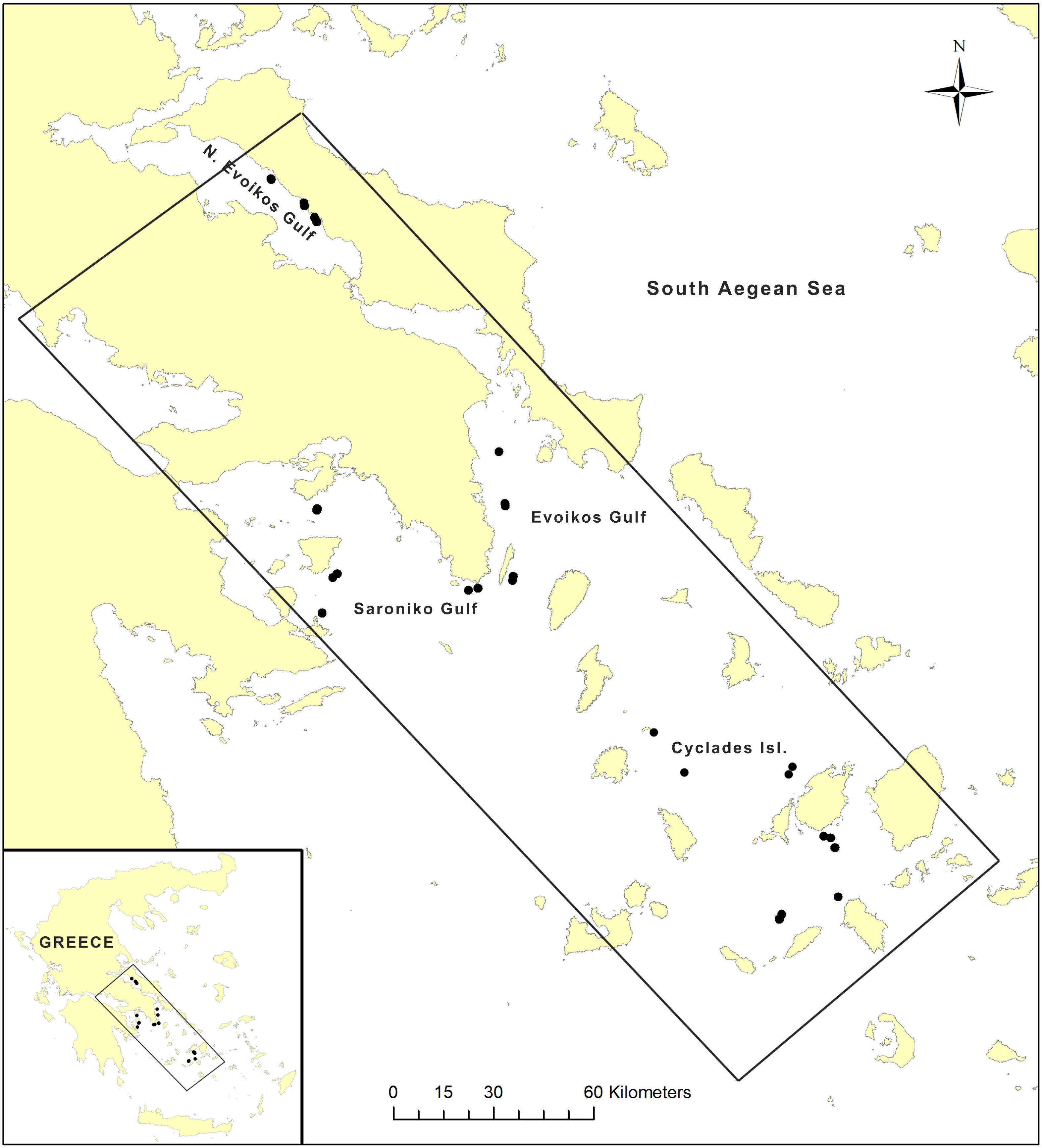
Codend	Gear Selectivity Model	Fisher Selection Model	AIC		
			HAK	HOM	MEG
40D	Logit	Logit	2616.09	**3719.89**	508.77
		Probit	2647.84	3729.21	505.33
		Gompertz	2641.73	3760.67	507.54
		Richard	2603.78	3721.54	508.63
	Probit	Logit	2636.62	3747.92	504.76
		Probit	2668.38	3757.24	**501.31**
		Gompertz	2662.26	3788.70	503.52
		Richard	2624.32	3749.57	504.61
	Gompertz	Logit	2612.00	3753.19	507.88
		Probit	2643.76	3762.51	504.43
		Gompertz	2637.64	3793.98	506.64
		Richard	**2599.70**	3754.84	507.73
	Richard	Logit	2613.60	3721.85	509.88
		Probit	2645.36	3731.17	506.43
		Gompertz	2639.24	3762.63	508.64
		Richard	2601.30	3723.50	509.74
40S	Logit	Logit	8686.78	4117.09	547.68
		Probit	8720.13	4122.84	548.43
		Gompertz	8667.05	4149.42	569.54
		Richard	8663.53	4117.12	549.66
	Probit	Logit	8725.43	4145.26	546.26
		Probit	8758.78	4151.00	547.01
		Gompertz	8705.70	4177.59	568.12
		Richard	8702.18	4145.28	548.24
	Gompertz	Logit	8983.23	4324.61	594.36
		Probit	9016.58	4330.36	595.11
		Gompertz	8963.50	4356.95	616.23
		Richard	8959.98	4324.64	596.35
	Richard	Logit	8609.59	**4081.12**	**527.26**
		Probit	8642.94	4086.87	528.01
		Gompertz	8589.86	4113.45	549.12
		Richard	**8586.34**	4081.15	529.25
50D	Logit	Logit	6966.40	7860.45	975.65
		Probit	6974.93	7869.60	977.21
		Gompertz	6996.26	7902.64	993.91
		Richard	6959.24	7862.37	976.39
	Probit	Logit	6995.21	7865.42	971.84
		Probit	7003.74	7874.57	973.40
		Gompertz	7025.07	7907.61	990.10
		Richard	6988.05	7867.34	972.57
	Gompertz	Logit	6970.67	7858.36	978.99
		Probit	6979.20	7867.52	980.56
		Gompertz	7000.52	7900.55	997.26
		Richard	6963.51	7860.28	979.73
	Richard	Logit	6962.90	**7848.30**	**971.14**
		Probit	6971.43	7857.46	972.71
		Gompertz	6992.76	7890.49	989.41
		Richard	**6955.74**	7850.22	971.88

Table 6. Selectivity parameters for the best model describing the overall size-selection process leading to the landing probability ($L50_{land}, SR_{land}$), the size-selectivity of gear ($L50_{gear}, SR_{gear}, 1/\delta_{gear}$) and the fisher size-selection ($L50_{fisher}, SR_{fisher}, 1/\delta_{fisher}$) in the bottom trawl codend using the 40D (40 mm diamond), 40S (40 mm square) and 50D (50 mm diamond) meshes; 95% confidence intervals are shown in parenthesis; 1/δ is available only in the case of Richard model. (G: gear selectivity model; F: fisher selectivity model; DOF: degrees of freedom)

Species		Codend 40D	Codend 40S	Codend 50D
Hake	Model / Parameter	Model: G: Gompertz F: Richard	G: Richard F: Richard	G: Richard F: Richard
	$L50_{gear}$	7.14 (6.46-7.76)	13.75 (12.99-14.41)	10.32 (9.52-10.93)
	SR_{gear}	1.97 (1.24-2.71)	3.09 (2.25-3.93)	4.11 (2.79-5.43)
	$1/\delta_{gear}$		0.32 (0.10-1.24)	1.98 (0.63-10.0)
	$L50_{fisher}$	14.90 (14.14-15.66)	15.39 (14.91-15.90)	15.12 (14.66-15.55)
	SR_{fisher}	2.27 (1.80-2.78)	2.64 (2.07-3.21)	2.18 (1.64-2.71)
	$1/\delta_{fisher}$	2.01 (0.87-8.67)	4.62 (1.22-10.00)	1.84 (0.80-10.00)
	$L50_{land}$	14.90 (14.15-15.66)	15.78 (15.41-16.25)	15.30 (14.83-15.77)
	SR_{land}	2.27 (1.80-2.78)	2.30 (1.78-2.81)	2.24 (1.70-2.89)
	p-value	1.0000	0.9826	0.9996
	Deviance	43.22	60.66	42.75
	DOF	89	86	78
	AIC	2599.70	8586.34	6955.74
Horse Mackerel	Model / Parameter	Model: G: Logit F: Logit	G: Richard F: Logit	G: Richard F: Logit
	$L50_{gear}$	9.37 (8.85-10.83)	13.08 (11.50-14.45)	12.58 (10.59-13.39)
	SR_{gear}	2.86 (2.26-3.41)	2.92 (1.53-4.32)	5.15 (4.08-11.63)
	$1/\delta_{gear}$		0.39 (0.10-3.06)	2.58 (0.10-10.00)
	$L50_{fisher}$	21.37 (20.46-22.01)	20.77 (20.14-21.41)	21.11 (20.54-22.08)
	SR_{fisher}	1.74 (1.20-2.16)	1.48 (0.69-2.28)	1.73 (1.24-2.43)
	$L50_{land}$	21.37 (20.46-22.01)	20.77 (20.14-21.40)	21.18 (20.59-22.16)
	SR_{land}	1.74 (1.20-2.16)	1.48 (0.1-2.20)	1.76 (1.28- 2.50)
	p-value	0.4628	0.9275	0.4263
	Deviance	58.34	40.54	52.22
	DOF	58	55	51
	AIC	3719.89	4081.12	7848.30
Megrim	Model / Parameter	Model: G: Probit F: Probit	G: Richard F: Logit	G: Richard F: Logit
	$L50_{gear}$	7.53 (6.90-9.00)	9.26 (8.82-9.61)	8.45 (4.58-10.47)
	SR_{gear}	2.81 (1.94-3.69)	2.14 (1.32-3.02)	9.00 (4.40-15.60)
	$1/\delta_{gear}$		0.10 (0.10-0.23)	0.10 (0.10-0.71)
	$L50_{fisher}$	19.12 (18.27-20.19)	18.49 (17.90-19.50)	17.37 (16.82-17.99)
	SR_{fisher}	2.70 (1.88-3.34)	2.21 (1.70-2.55)	1.81 (1.19-2.17)
	$L50_{land}$	19.12 (18.27-20.19)	18.49 (17.90-19.50)	17.37 (16.82-17.99)
	SR_{land}	2.70 (2.00-3.41)	2.21 (1.70-2.55)	1.81 (1.20-2.16)
	p-value	1.0000	1.0000	0.9968
	Deviance	19.85	16.14	29.19
	DOF	56	55	53
	AIC	501.31	527.26	971.14

Table 7. Discard parameters (with confidence intervals in parenthesis) based on the best model for the overall size-selection process by the gear and the fisher describing also the discard probability; the discard range (cm) at several probability levels ($DR_{0.05}, DR_{0.25}, DR_{0.5}, DR_{0.95}$), the maximum discard probability value (Dp_{max}), the length (cm) at the maximum discard probability (LDp_{max}) and the surface of the discard bell-shape curve when probability ≥0.05 ($DA_{0.05}$). *: notoen defined

		CODEND		
Species	**Parameter**	**40D**	**40S**	**50D**
Hake	$DR_{0.05}$	13.14 (11.46-15.14)	11.62 (8.83-13.71)	12.82 (11.24-17.36)
	$DR_{0.25}$	9.87 (18.79-11.35)	4.74 (3.40-5.85)	7.87 (7.07-9.39)
	$DR_{0.5}$	7.73 (6.76-9.01)	0.00 (0.00-1.95)	4.56 (3.59-5.60)
	$DR_{0.75}$	5.47 (4.31-6.75)	0.00 (0.00-0.00)	0.00 (0.00-2.07)
	$DR_{0.95}$	1.90 (0.00-3.35)	0.00 (0.00-0.00)	0.00 (0.00-0.00)
	Dp_{max}	0.98 (0.92-1.00)	0.43 (0.36-0.63)	0.75 (0.66-0.82)
	LDp_{max}	11.62 (11.56-12.71)	15.23 (14.35-15.50)	13.51 (12.53-13.60)
	$DA_{0.05}$	7.56 (6.44-8.79)	2.60 (1.89-3.29)	4.79 (4.23-5.82)
Horse mackerel	$DR_{0.05}$	18.36 (16.15-19.68)	14.78 (12.56-19.42)	16.61 (15.12-*)
	$DR_{0.25}$	14.38 (12.62-15.39)	10.23 (8.63-11.83)	11.78 (10.62-18.62)
	$DR_{0.5}$	12.00 (10.36-12.84)	7.82 (6.29-9.31)	8.46 (7.33-10.77)
	$DR_{0.75}$	9.59 (7.99-10.34)	5.75 (4.12-6.93)	4.66 (2.29-5.75)
	$DR_{0.95}$	5.74 (3.97-6.45)	2.43 (0.00-4.26)	0.00 (0.00-0.00)
	Dp_{max}	0.99 (0.99-0.99)	0.99 (0.93-1.00)	0.89 (0.79-0.94)
	LDp_{max}	17.73 (16.59-18.77)	17.53 (17.22-20.05)	18.70 (18.61- 19.75)
	$DA_{0.05}$	11.89 (10.24-12.73)	8.00 (6.63-9.32)	8.14 (7.24-10.61)
Megrim	$DR_{0.05}$	18.45 (15.75-20.37)	16.81 (14.60-18.65)	* (17.46-*)
	$DR_{0.25}$	14.40 (12.84-15.97)	11.76 (10.83-12.70)	15.55 (10.91-*)
	$DR_{0.5}$	11.59 (10.28-12.61)	9.27 (8.67-10.22)	8.923 (6.87-13.25)
	$DR_{0.75}$	8.79 (7.80-9.63)	7.26 (6.76-8.35)	4.55 (3.63-6.68)
	$DR_{0.95}$	4.88 (3.58-5.84)	4.56 (4.11-5.93)	0.00 (0.00-1.31)
	Dp_{max}	1.00 (0.99-1.00)	1.000(0.997-1.000)	0.92 (0.90-0.99)
	LDp_{max}	13.53 (13.47-15.72)	12.26 (11.01-13.65)	15.33 (14.56-15.75)
	$DA_{0.05}$	11.50 (10.20-12.52)	9.65 (8.98-10.62)	9.81 (7.79-11.83)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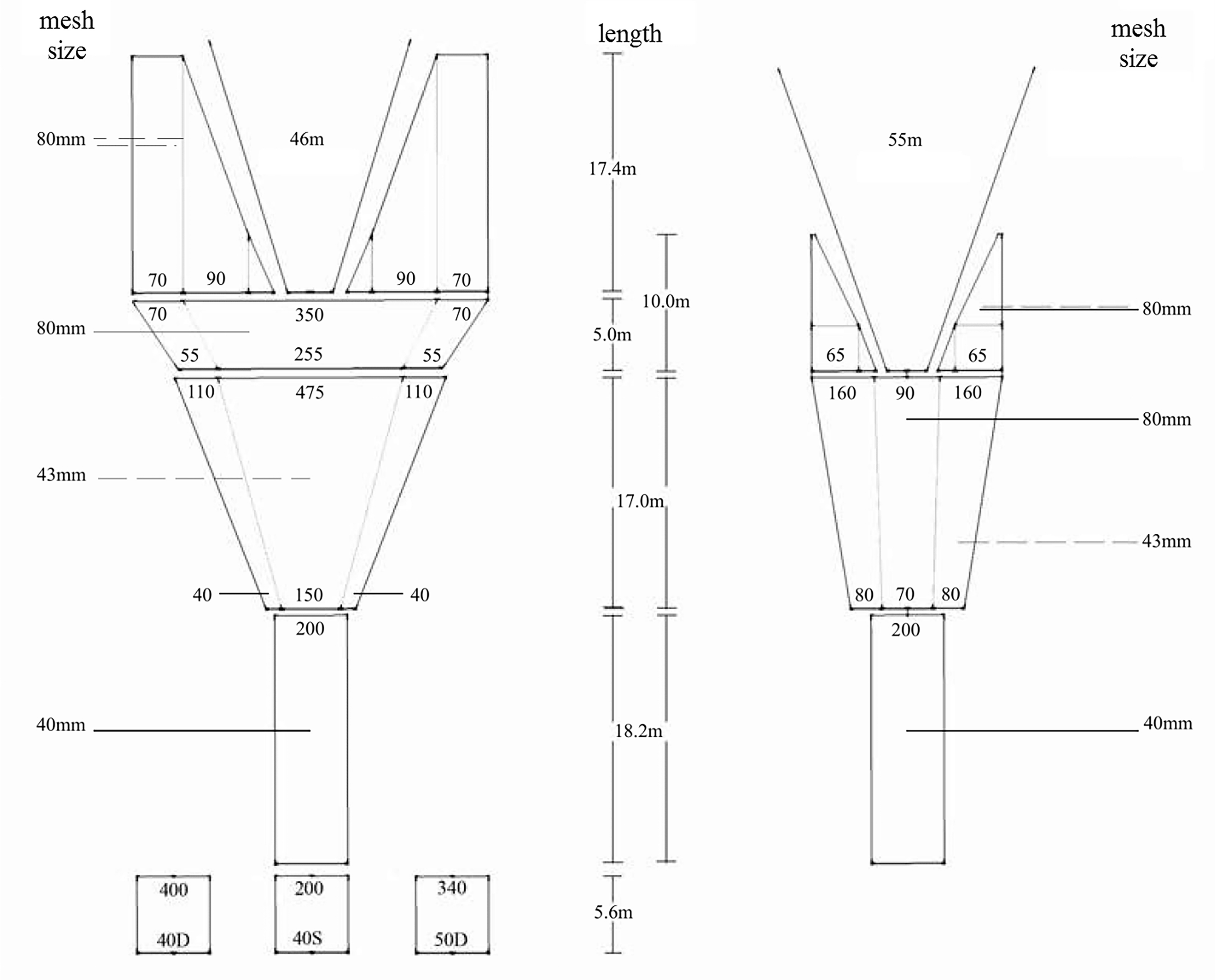
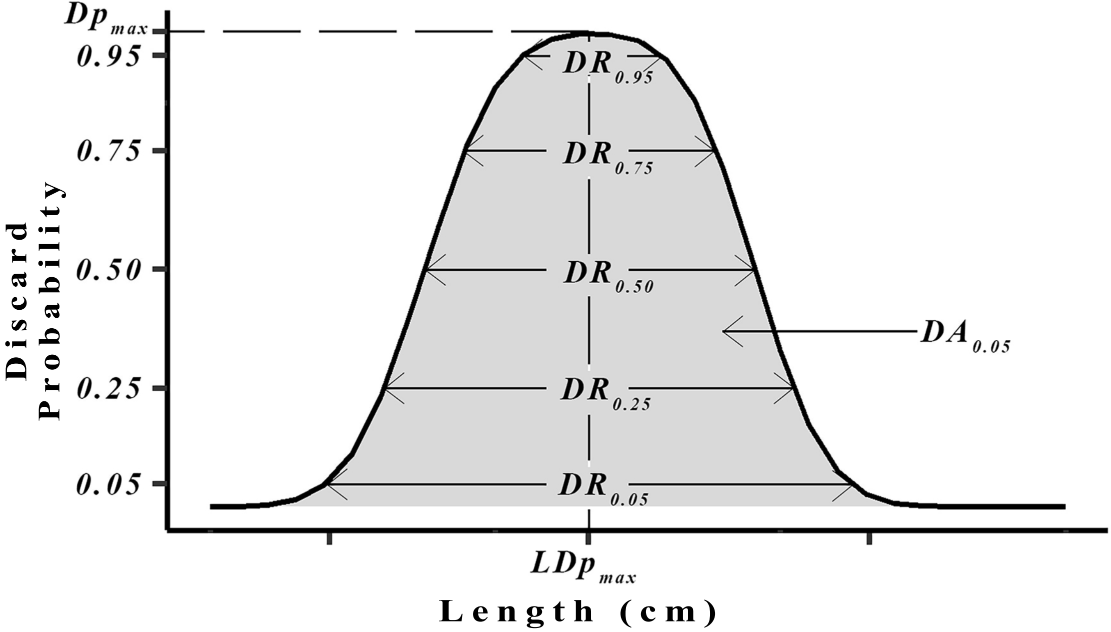
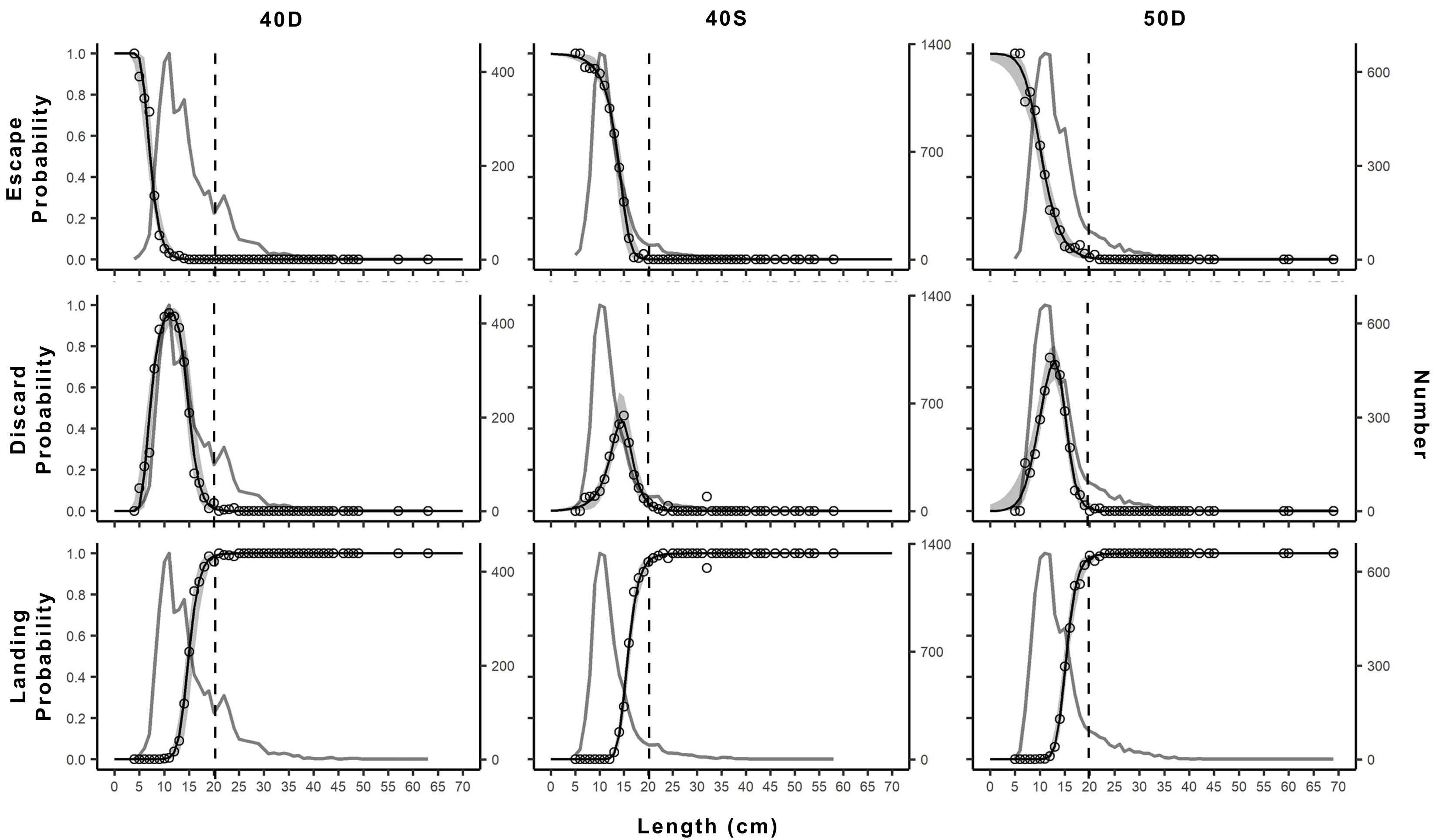
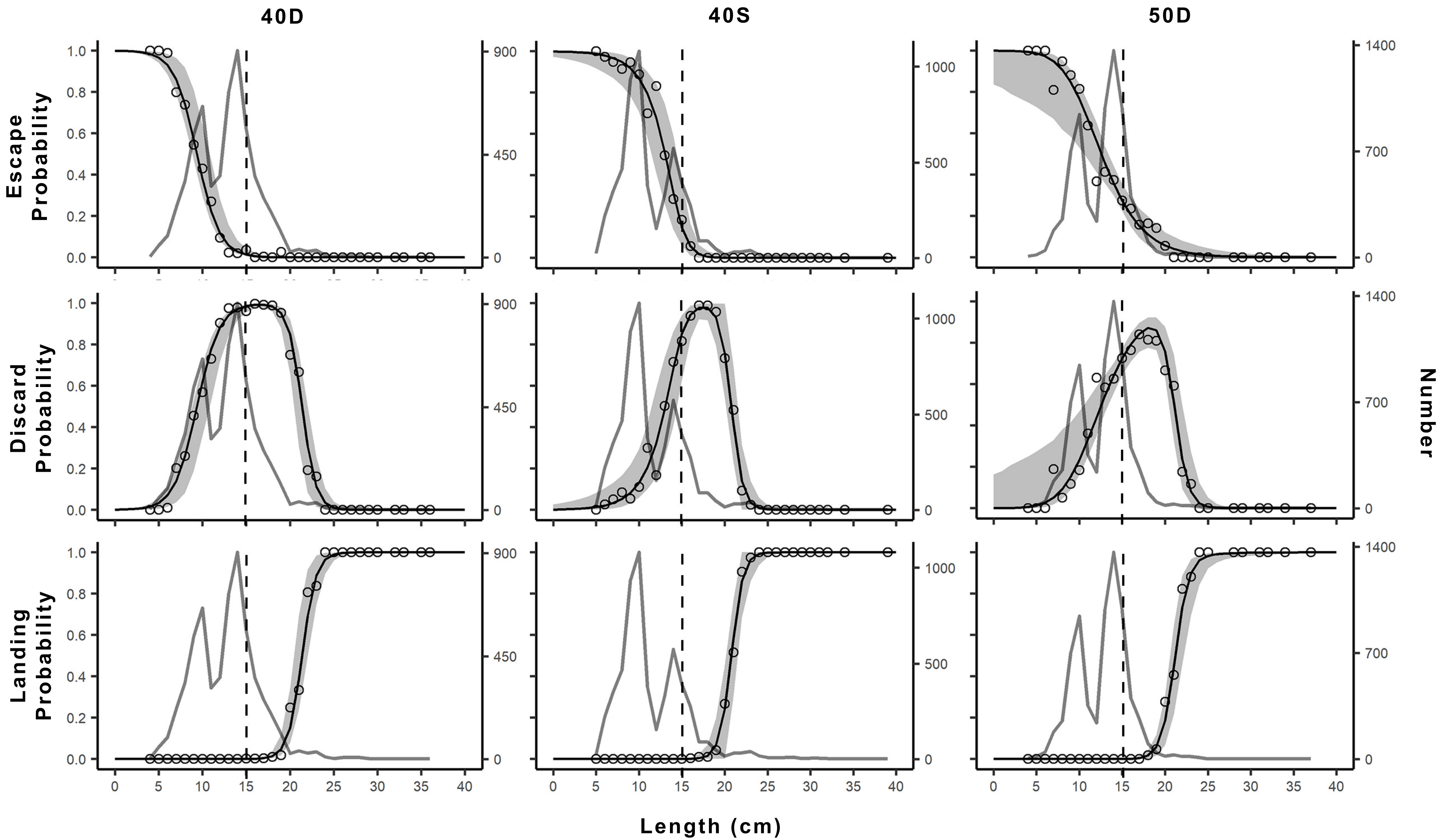
GREECE
0 15 30 60 Kilometers


mesh size
80mm
46m
70
90
90
70
70
350
70
80mm
55
255
55
110
475
110
43mm
40
150
40
200
40mm
400
40D
200
40S
340
50D
length
17.4m
10.0m
5.0m
17.0m
18.2m
5.6m
mesh size
55m
80mm
65
65
160
90
160
80mm
43mm
80
70
80
200
40mm

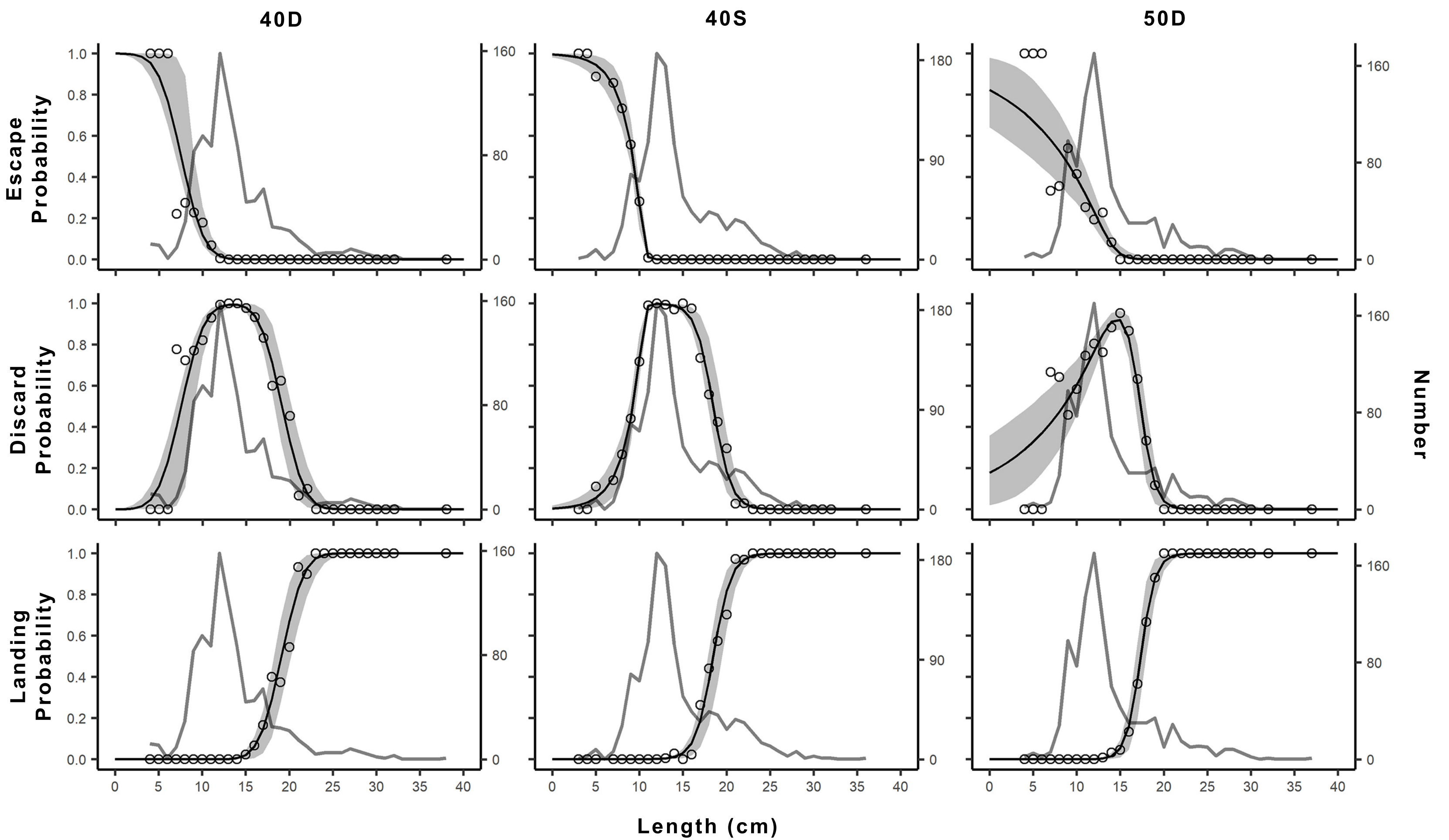


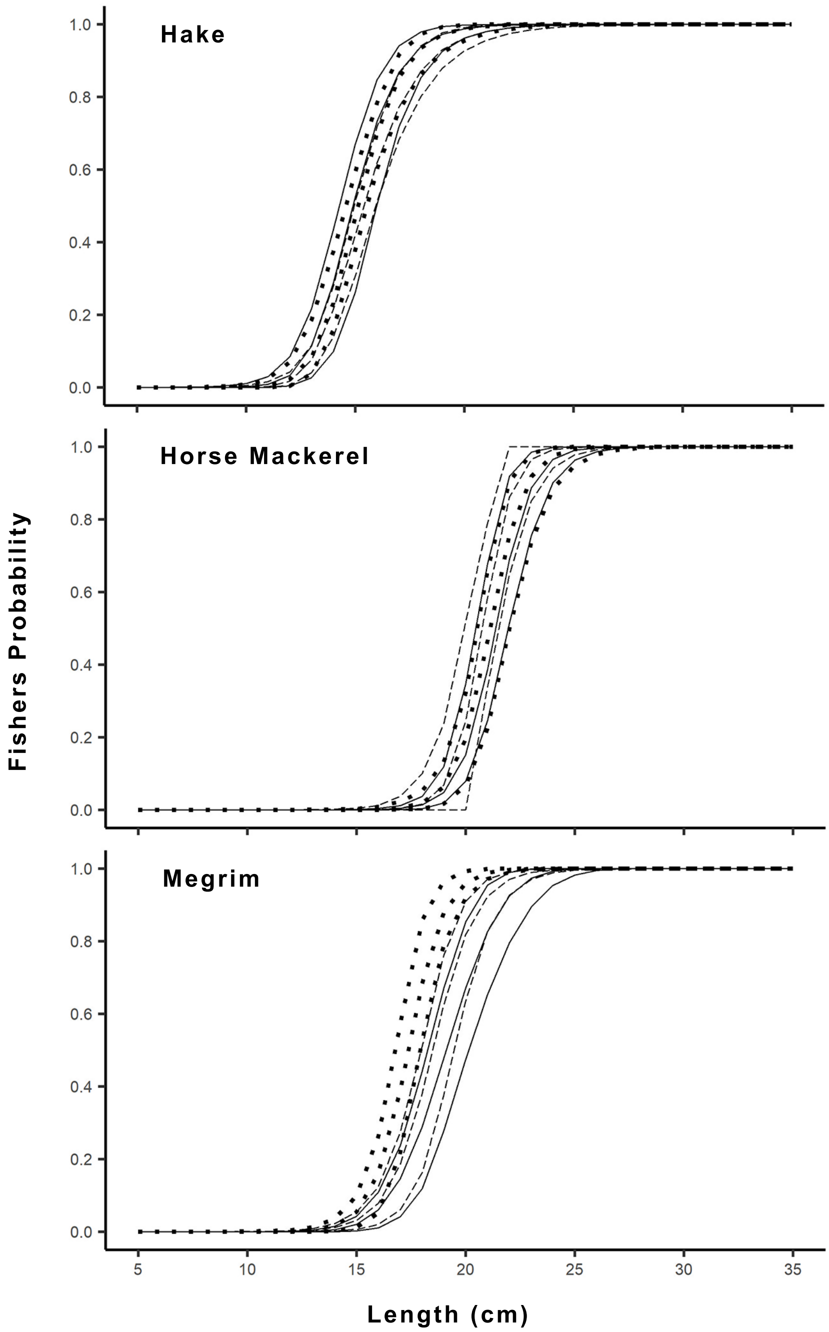
Dp max
0.95
0.75
0.50
0.25
0.05
Discard Probability
DR 0.95
DR 0.75
DR 0.50
DA 0.05
DR 0.25
DR 0.05
LDp max
Length (cm)


40D
40S
50D
Escape Probability
Discard Probability
Landing Probability
Number
Length (cm)
0.0
0.2
0.4
0.6
0.8
1.0
0
200
400
700
1400
300
600
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70



40D
40S
50D
Escape Probability
Discard Probability
Landing Probability
Number
Length (cm)


40D
40S
50D
Escape Probability
Discard Probability
Landing Probability
Number
Length (cm)
0.0
0.2
0.4
0.6
0.8
1.0
0
80
160
90
180
0
5
10
15
20
25
30
35
40


Hake
Horse Mackerel
Megrim
Fishers Probability
Length (cm)
0.0
0.2
0.4
0.6
0.8
1.0
5
10
15
20
25
30
35

Supplement

The selection models used in the present work are presented below according to Wileman *et al.* (1996).

Logit Model

The **Logistic (logit) selection curve** is the cumulative distribution function of a logistic random variable:

$$r(l) = \frac{\exp(a+bl)}{1+\exp(a+bl)}$$

Where a, b parameters to be estimated. More specific for the needs of selectivity, the above equation can be rewritten in terms of L50 and SR, where:

$$L_{50} = -{}^{a}/_{b} \ , \quad \mathrm{SR} = \frac{2\ln(3)}{b} = \frac{\ln(9)}{b}$$

So, we have:

$$r(l) = \left(\frac{exp\left(\frac{\ln(9)}{SR}(l - L_{50})\right)}{1 + exp\left(\frac{\ln(9)}{SR}(l - L_{50})\right)} \right)$$

Probit Model

The **Probit selection curve** (Normal probability ogive) is the cumulative distribution of a normal random variable,

$$r(l) = \Phi(a + bl)$$

Where Φ is the cumulative distribution function of a standard normal random variable, while a, b parameters to be estimated. Likewise the previous equation, the probit can be rewritten in terms of L50 and SR, where:

$$L_{50} = -{}^{a}/_{b} \ , \quad \mathrm{SR} = \frac{2probit(0.75-0.25)}{b} \approx \frac{1.349}{b}$$

So, we have:

$$r(l) \approx \left(\frac{exp\left(\frac{1.349}{SR}(l - L_{50})\right)}{1 + exp\left(\frac{1.349}{SR}(l - L_{50})\right)} \right)$$

Compertz Model

The **Gompertz/Extreme value selection curve** is expressed by the following equation:

$$r(l) = \exp(-\exp(-(a + bl)))$$

It can also be rewritten in terms of L50 and SR where:

$$L_{50} = \frac{-\ln(-ln(0.5)) - a}{b} \approx \frac{0.3665 - a}{b} \quad , \quad \mathrm{SR} = \frac{\ln\left(\frac{\ln(0.25)}{\ln(0.75)}\right)}{b} \approx \frac{1.573}{b}$$

So, we have:

$$r(l) \approx \exp\left(-\exp\left(-\left(0.3665 + \frac{1.573}{SR}(l - L_{50})\right)\right)\right).$$

Richard Model

The last of the four selection curves presented here is the **Richards curve** which has an extra parameter, named δ. This parameter controls the asymmetry of the curve. While δ > 1 the curve has a longer left tail and when 0<δ<1 the curve has a longer right tail. When δ = 1 the curve is the same as the logistic curve. The equation of Richards selection curve is the following:

$$r(l) = \left(\frac{\exp(a + bl)}{1 + \exp(a + bl)}\right)^{1/\delta}$$

Rewritten in terms of L50 and SR with:

$$L_{50} = \frac{logit(0.5^{\delta}) - a}{b}$$

$$\mathrm{SR} = \frac{logit(0.75^{\delta}) - logit(0.25^{\delta})}{b}$$

and

$$r(l) = \left(\frac{exp\left(logit(0.5^{\delta}) + \left(\frac{logit(0.75^{\delta}) - logit(0.25^{\delta})}{SR}\right)(l - L_{50})\right)}{1 + exp\left(logit(0.5^{\delta}) + \left(\frac{logit(0.75^{\delta}) - logit(0.25^{\delta})}{SR}\right)(l - L_{50})\right)}\right)$$