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Combining selection models and population structures to inform fisheries management: a case study on hake in the Mediterranean bottom trawl fishery

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Abstract

The reduction of juvenile catch and discards are important targets in fisheries policy. This work examines how selection models can predict the size structure (LFD) of discards and landings considering the effects of area, time period, gear and fisher behaviour. Additional exploitation indicators related to the gear used, fisher's selection pattern, and discards were also estimated. The approach is demonstrated in a study concerning hake in the Mediterranean trawl fishery, focusing on high (HRA) and low (LRA) recruitment areas in Saronikos Gulf (Eastern Mediterranean) during two periods (June, September) using two codends (40 mm square - 40S, 50 mm diamond - 50D mesh). The predicted discards LFDs revealed generally higher percentages in the HRA in June when using the 50D codend. The predicted landings LFDs showed higher percentages in the LRA in September for both codends, but undersized hake were always included. LFDs and exploitation indicators indicated that both codends were inappropriate for sustainable fishing of hake in the HRA, where 50D performed worse than the 40S. Fishing with both codends in the LRA in September revealed the lowest discards rates and minimum sizes of landings close to MCRS (minimum conservation reference size). These results can provide information to fisheries management aiming to protect juveniles and reduce discards through spatio-temporal fishing closures.

Keywords: Discards; juvenile protection; selectivity; nursery; square mesh; diamond mesh; trawl; *Merluccius merluccius*.

Introduction

The setting up of marine protected areas or fisheries restricted areas in essential fish habitats has been considered as one effective approach in Mediterranean fisheries management (Caddy, 1993, 2009; Apostolaki *et al.*, 2002; Sardà *et al*., 2015). Colloca *et al*. (2015) has noted that a reduction in juvenile mortality is considered as one of the main prerequisites for the future sustainability of trawl fisheries in the Mediterranean. Regulation 1967/2006 (EC, 2006) and Regulation 1380/2013 (EU, 2013) for EU countries promote the spatial closure of areas where juveniles aggregate. Recently, the Working Group on Marine Protected Areas (WGMPA, 2019) of the General Fisheries Commission for the Mediterranean (GFCM) has recommended the establishment of a network of protected areas on essential fish habitats in the Mediterranean, focusing among other species on European hake (*Merluccius merluccius* L., 1758).

European hake (namely hake hereafter) is one of the main target species in the Mediterranean. A minimum conservation reference size (MCRS) of 20 cm total length for hake and the use of 40 mm square or 50 mm diamond mesh in the trawl codend have been legislated for Mediterranean countries (EC, 2006; GFCM, 2009). A reduction of juvenile hake catches and discards had been expected after the implementation of these regulations. However, undersized individuals still constitute a large part of the hake catch (Bellido *et al*., 2017; Tsagarakis *et al*., 2017) due to low gear selectivity (Guijarro & Massuti, 2006; Lucchetti, 2008; Sala *et al*., 2008; Mytilineou *et al*., 2018), and are either discarded or landed as marketable catch due to low regulation compliance of fishers and limited control (Damalas & Vassilopoulou, 2013; Keskin *et al.*, 2014; Bellido *et al.*, 2014, 2017; Tsagarakis *et al.*, 2017; Damalas *et al.*, 2018). In addition, some Mediterranean non-EU fleets still use mesh sizes that are smaller than what has been legislated by the GFCM. Moreover, the discard ban, introduced by Regulation 1380/2013 (EU, 2013) has been treated with scepticism (Damalas, 2015; Sardà *et al.*, 2015; Bellido *et al.*, 2017; Celić *et al.*, 2018) and derogations have already been adopted (EU, 2017) that permit the discarding of hake up to 7% for 2018 and 6% for 2019 of the total annual catches of this species.

Looking for a reduction in juvenile hake mortality, several studies have delineated and modelled the geographical distribution of hake juveniles and nursery grounds in the northern Mediterranean over the last two decades (Fiorentino *et al.*, 2003; Maynou *et al.*, 2003; Bartolino *et al.,* 2008, 2011; Tserpes *et al.,* 2008; Colloca *et al.*, 2015; Druon *et al.*, 2015). A number of recent studies have also mapped the distribution of hake discards and the most suitable areas for fishing (Vilela & Bellido, 2015; Maeda *et al.*, 2017). In addition, bio-economic models simulating management scenarios in the Mediterranean (Russo *et al.*, 2014, 2019; Khoukh & Maynou, 2018) have been tested for the effectiveness of spatial and temporal fishing closures in hake nursery areas. On the other hand, many studies have focused on improving hake size-selectivity in the Mediterranean bottom trawl fleets (Sardà *et al.*, 2004; Özbilgin *et al.*, 2005; Tokaç *et al.*, 2010; Sala & Lucchetti, 2011; Brčić *et al.*, 2016; Sola & Maynou, 2018; Vitale *et al.*, 2018). To date, no study in the Mediterranean has combined information on gear and fisher size selection models with hake population structure in nursery areas to predict discards and landings size structure.

Mytilineou *et al.* (2018) presented a model describing gear and fisher size selection processes for escapees, discards and landings for hake and other species. The model predicts fisher discard and landing probability for hake, which can be used for the prediction of discards and/or landings size structure given data on the hake population size structure. Therefore, differences in discards and landings size structure can be examined with respect to differences in the species population structure in space and time, which may offer useful information for management purposes.

The objective of this study is to predict discards and landings size structure of hake in the Mediterranean bottom trawl fishery while taking into consideration gear and fisher size-selection with different codend mesh sizes and shapes and differences in hake population structure, particularly, in areas and periods of high and low hake recruitment. Exploitation pattern indicators were additionally examined to evaluate the efficiency of the gear in retaining unwanted catch and the sorting behaviour of fishers into discards and landings with respect to the rules. The use of this type of indicators was inspired by those used in other studies (Wienbeck *et al.*, 2014; Sala *et al.*, 2015). The aim was to show how selection models could support considerations for reducing catches of juveniles and discards, and consequently for management. The case study was conducted in two areas of high and low hake recruitment in Saronikos Gulf (E. Mediterranean), one of the important hake fishing (Maina *et al.*, 2018) and nursery (Tserpes *et al.*, 2008; Druon *et al.*, 2015; Colloca *et al.*, 2015) grounds in Greek waters, during two periods (June, September) and using two trawl codends (40 mm square mesh – 40S and 50 mm diamond mesh – 50D).

Material and Methods

Predicting landings and discards size structure

The size structure of the discarded and landed portions of the catch in the bottom trawl fishery, operating in different areas and time periods and using different codends, can be estimated as the product of the hake population size structure in each case and the size-dependent discard or landing probability of the species according to fisher behaviour and the selectivity of the trawl codend. Therefore, for a given area *a*, period *t* and codend *g*, the formulas for the discards $[pop_{disc}(l,a,t,g)]$ and landings $[pop_{land}(l,a,t,g)]$ are as follows:

$$\begin{aligned} pop_{disc}(l,a,t,g) &= pop(l,a,t) \times p_{disc}(l,g) \\ pop_{land}(l,a,t,g) &= pop(l,a,t) \times p_{land}(l,g) \end{aligned} \quad (1)$$

where $pop(l,a,t)$ is the population of hake in length class *l* in a given area *a* and time period *t*; $p_{disc}(l,g)$ and $p_{land}(l,g)$, the length-dependent discard and landing probability of hake, respectively, for a given trawl codend *g*.

The length-dependent discard and landing probability of hake, $p_{disc}(l,g)$ and $p_{land}(l,g)$ in equations (1), have been estimated by Mytilineou *et al.* (2018), using an overall (gear and fisher) size-selection model for 40S or 50D trawl codends based on the population entering each codend. Their uncertainties (95% Efron percentile confidence intervals (CI); Efron, 1982) have also been provided along with the bootstrap sets given by 1000 repetitions for their calculation.

The hake population for an area *a* and time period *t,* in formulas (1), was assumed to be the total amount of fish entering the trawl codend in this area *a* and time period *t*. In this work, we have used experimental data for selectivity studies (codend catch + cover catch) to obtain the average population size structure of hake entering the trawl codend. Since fishers often tend to compensate for low abundance with increased fishing effort and because catch per unit effort will depend on trawl wing and door spread, in order to make results as general as possible, we used the length size structure in percentage instead of the population in total numbers, however, with the length structure reflecting that found in the area *a* and time period *t*. The formula for $pop(l,a,t)$ is as follows:

$$pop(l,a,t) = 100 \times \frac{n(l,a,t)}{\sum_l n(l,a,t)} \quad (2)$$

where $n(l,a,t)$ is the number of fish at length l entering the codend in a given area *a* and time period *t*. The summation in (2) is over all length classes *l* of the population. As a result of the above-mentioned, the size structure of the discards and landings by size class in formulas (1) are also expressed as percentages of the total population in terms of numbers. However, it should be noted, that if the impact of the actual fisheries is investigated, then the formulas (1) and (2) should be scaled according to the abundance/density of the population and the fishing effort allocated in the study area.

Uncertainties (95% CI) for the estimated $pop_{disc}(l,a,t,g)$ and $pop_{land}(l,a,t,g)$ were obtained based on combining the uncertainties for $pop(l,a,t)$ and $p_{disc}(l,g)$ or $p_{land}(l,g)$ by using the method described by Herrmann *et al*. (2018) for estimating the bootstrap set for a product as in equation (1). All procedures were implemented using the computer software SELNET (SELection in trawl NETting; Herrmann *et al*., 2012, 2013).

Identifying hake population size structure in high/low recruitment areas

Data were collected during two experimental fishing surveys (September 2014 and June 2015) conducted by a hired commercial trawler on two fishing grounds in Saronikos Gulf (Aegean Sea - E. Mediterranean); off south Aegina Island, a high recruitment area (HRA) and off south Salamina Island, a low recruitment (LRA) area (Fig. 1). The fishing depth ranged between 85 and 265 m. The detection of HRA and LRA was based on the abundance (number/km^2) of hake recruits and the proportion of hake recruits (%) to the total number of individuals per sampling area and period. Given that recruits are defined as the youngest fish of a stock entering as an exploited component in a fishery for the first time (GFCM, 2006), hake recruits were considered as individuals smaller than 16 cm (total length). Although threshold size might be considered as the MCRS (20 cm) or a larger size related to the length at first maturity of hake (to include all immature juveniles), the selection of recruits (the youngest of the juveniles) and the size of 16 cm were considered more adequate, based on biological and fisheries information from the literature, and explained in Supplementary material A.

A total number of 15 hauls, taken at 5 different locations, was performed during each survey (2 survey-replications in time). Sampling was carried out using three different codends (40 mm and 50 mm diamond and 40 mm square mesh) with the same external cover (10 mm diamond mesh) as described in Mytilineou *et al*. (2018). In each haul, a three compartment (escapees, discards, and landings) sampling scheme was followed (as described in Mytilineou *et al*., 2018). Total length (TL, mm) of hake individuals was measured to the nearest 1 mm. Measurements took place for all individuals of each compartment or from randomly selected sub-samples when catch in a compartment was large. The equation (2) for the estimation of the hake population size structure, considering the three compartment sampling design as well as the sub-sampling in each compartment, is presented in Supplementary material B. In each haul, the hake population was assumed to be the total amount of hake entering the trawl codend, which is retained by the codend (discards and landings) and the cover (escapees). The overall size structure of the hake population was estimated from the pooled data of all hauls (independently of the codend, since the same cover was used in all cases), and separately for the high and low recruitment areas (HRA/LRA) and for each time period. Although, all hauls were used for the population estimation, the codends examined for the prediction of discards and landings size structures were only those in use in the Mediterranean according to the Council Regulation 1967/2006: (i) the codend of 40 mm square mesh (40S) and (ii) the codend of 50 mm diamond mesh (50D), which can be used if it is more selective than the 40S.

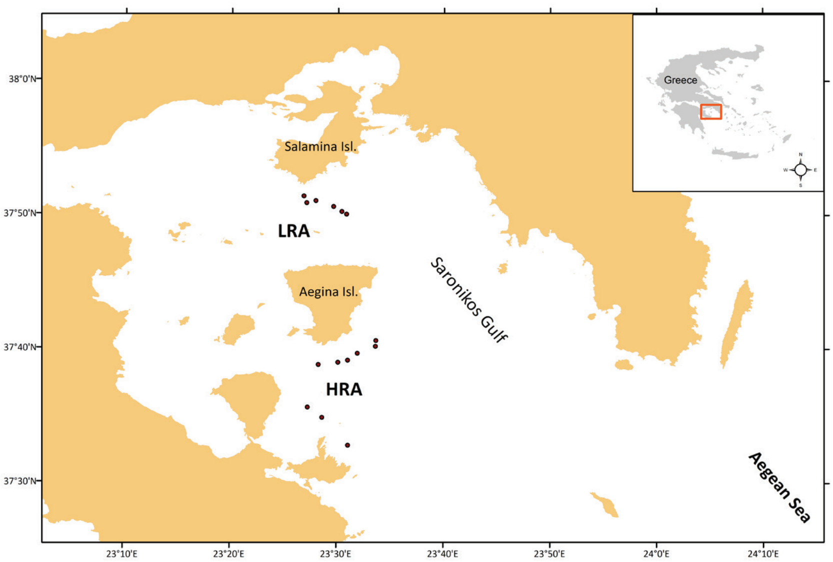

*Fig. 1***:** Map of the study area with the two sampling areas (HRA, LRA) in Saronikos Gulf (Aegean Sea-GSA22, Eastern Mediterranean). HRA: high recruitment area; LRA: low recruitment area.

Estimating differences in hake population, discards and landings size structure

To identify the length-dependent differences $\Delta(l)$ in the hake populations $[\Delta pop(l)]$, discards $[\Delta pop_{disc}(l)]$ and landings $[\Delta pop_{land}(l)]$ between areas in each period *t* and between periods in each area *a,* and for each gear *g*, the change in each length class *l* was examined for each case as follows:

$$\Delta pop(l) = pop(l, a_k, t_k) - pop(l, a_j, t_j)$$
$$\Delta pop_{disc}(l) = pop_{disc}(l, a_k, t_k, g_k) - pop_{disc}(l, a_j, t_j, g_j) \quad (3)$$
$$\Delta pop_{land}(l) = pop_{land}(l, a_k, t_k, g_k) - pop_{land}(l, a_j, t_j, g_j)$$

where $k \neq j$. It should be noted that formulas (3) express differences in percentages (%) for each *Δ(l)* size class. Therefore, if the impact of the actual fisheries is investigated, then formulas (3) should be scaled according to the abundance/densities of the population and the total fishing effort allocated in the study area. Efron 95 % percentile confidence limits for each *Δ(l)* were also estimated based on the bootstrap files for each population in the area *a* and the period *t* (and for each gear *g*). The bootstrap re-sampling was random and independent for each population, and therefore, a new bootstrap could be performed for the difference *Δ(l).* If the 95% CI of the difference in a length class include the 0-axis then the difference is not statistically significant for this length class. This methodology has been described and applied by Herrmann *et al*. (2018) and Larsen *et al*. (2018).

Estimating exploitation indicators

In order to evaluate how efficient is a gear at retaining and releasing individuals below and above MCRS, how fisheries impact a stock, and if fishers discard all individuals below MCRS and land all individuals above MCRS, a set of indicators was calculated. The indicators used in the present work were inspired by those presented by Wienbeck *et al*. (2014) and applied in several studies afterwards (Sala *et al*., 2015; Santos *et al*., 2016; Brčić *et al*., 2016; Larsen *et al.,* 2018). To quantify the effect of the trawl and the impact of trawl fisheries on the hake stock by fishing in different areas *a* (HRA/LRA), periods *t* (June/September) and using different gears *g* (40S/50D), the average percentage of retained individuals below MCRS (*nP_*) and the average discard ratio *ndRatio* of the retained individuals below MCRS to the total retained individuals, were estimated as follows:

$$nP\_(a,t,g) = 100 \times \frac{\sum_{l<MCRS}\{pop_{disc}(l,a,t,g) + pop_{land}(l,a,t,g)\}}{\sum_{l<MCRS} pop(l,a,t)} \quad (4)$$

$$ndRatio(a,t,g) = 100 \times \frac{\sum_{l<MCRS}\{pop_{disc}(l,a,t,g) + pop_{land}(l,a,t,g)\}}{\sum_{l}\{pop_{disc}(l,a,t,g) + pop_{land}(l,a,t,g)\}}$$

The first indicator shows the retention efficiency of the gear to the fish entering the trawl codend with size below the MCRS, considering the size structure of individuals entering the codend that are below MCRS. This indicator should be low (close to zero) for the best selectivity of the gear. The second indicator is related to the undersized catch that should be discarded, and therefore should also be close to zero.

However, since the on-board sorting behavior of fishers does not typically result in knife-edge selection corresponding to the MCRS (i.e. individuals under the MCRS may be retained or individuals above the MCRS may be discarded), it is relevant to define indicators that account for the fishers behaviour and compare these with those expected according to the regulations. Based on the second above-mentioned indicator, a new one, the average fisher discard ratio (*$ndRatio_f$*) to the total catch, was adjusted to describe fishers' predicted sorting pattern into discards and landings as follows:

$$ndRatio_f(a,t,g) = 100 \times \frac{\sum_l\{pop_{disc}(l,a,t,g)\}}{\sum_l\{pop_{disc}(l,a,t,g) + pop_{land}(l,a,t,g)\}} \quad (5)$$

The above-mentioned indicators were also estimated in terms of weight (*wP_*, *wdRatio* and *$wdRatio_f$*). The formulas are presented in Supplementary material C. Discards have no economic value, therefore discard ratio indicators assigned to their economic value would be zero. However, since in reality, undersized individuals are included in the landings, the ratio indicators based on the MCRS, are expected to have a value. To identify the economic value of the undersized individuals (below MCRS) that are included by the fisher in the landings, to the value of the landings according to the rules (individuals above MCRS), another indicator for the undersized landings ratio in value (v*$ulRatio_f$*) was also estimated (Supplementary material D). All these indicators are independent of the population total abundance, and depend only on the population structure, since any total numbers will be included in both the nominator and denominator of formulas (4) and (5), and therefore cancelled out. All the indicators were expressed as percentage.

Efron 95% percentile confidence intervals for each of the above-described indicators were estimated based on the new bootstrap sets resulting from the bootstrap sets for $pop(l,a,t)$, $pop_{disc}(l,a,t,g)$ and $pop_{land}(l,a,t,g)$ as described before, and calculated using the software SELNET (Herrmann *et al*., 2012, 2013). Furthermore, the difference in the hake exploitation indicators between areas *a*, periods *t* and gears *g,* and between the discard ratios based on MCRS and fisher selection behaviour were examined. The uncertainty for the differences was obtained as described for differences in populations (see section above).

Results

Hake population size structure

In the area of high recruitment (HRA) in June, the main bulk of individuals in the hake population size structure ranged between 8 - 14 cm TL, whereas in LRA it was between 12 - 21 cm TL (Fig. 2a). In September, the main bulk of hake individuals moved to larger sizes between 11 - 17 cm and 18 - 27 cm TL in HRA and LRA, respectively (Fig. 2b). The significant differences in the

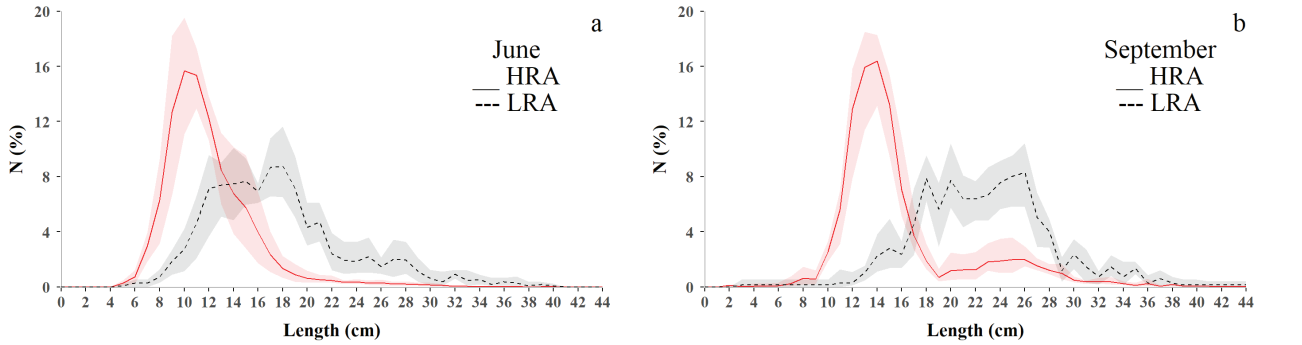

Fig. 2: Size structure of the hake population entering the trawl codend in HRA (continuous line) and LRA (dashed line) in June (a) and September (b). 95% Efron percentile confidence intervals are also given (coloured area around lines). HRA: high recruitment area, LRA: low recruitment area.

size structure of hake populations between areas and periods revealed that HRA and June were dominated by the smallest hake (June: <12 cm TL in HRA, but >15 cm TL in LRA; September: <16 cm TL in HRA, but >18 cm TL in LRA) (Fig. 3).

Hake discards size structure

Based on the plots for the discards size structure and those for the differences (Fig. 4 and Fig. S1 & Fig. S2), significantly higher percentages in respect to the total population were predicted in HRA than in LRA (except in June for 40S); higher in LRA in June, but in HRA in September and higher in 50D than in 40S (except in September in LRA). In more detail, for the 40S codend in June, the hake discards constituted 19.3% and 18.4% of the total population in HRA and LRA, respectively, with the main bulk ranging between 8 - 18 cm and 10 - 20 cm TL, respectively (Fig. 4a). No significant differences were detected between the two areas in June (except in the smaller sizes 10 - 12 cm TL with higher percentages in HRA, and the larger sizes 18 - 20 cm TL with higher percentages in LRA) (Fig. S1a).

For the 40S codend in September, hake discards constituted 26.5% (mainly between 10 - 18 cm TL) and 6.4% (mainly between 13 - 21 cm TL) of the total population in HRA and LRA, respectively (Fig. 4b). Significant differences were observed for the percentages of the sizes 10 - 16 cm between the two areas in September being higher in HRA, and between the two periods in LRA being higher in June (Fig. S1b, f).

For the discards size structure using 50D (Fig. 4c, d), higher percentages were presented than for 40S, except

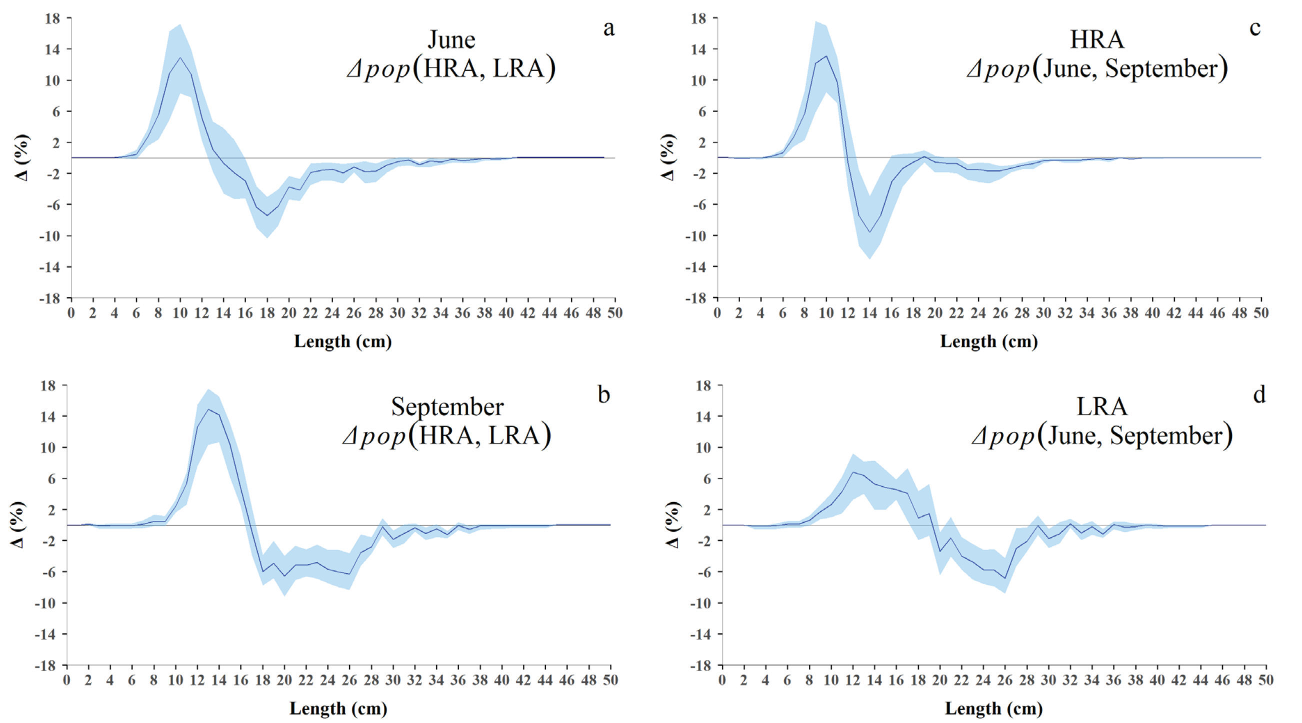

Fig. 3: Difference in the hake population size structure entering the trawl codend between HRA and LRA in June (a) and September (b) and between June and September in HRA (c) and LRA (d). 95% Efron percentile confidence intervals are also given (coloured area around lines). HRA: high recruitment area, LRA: low recruitment area, Δ (%): difference in percentage (%).

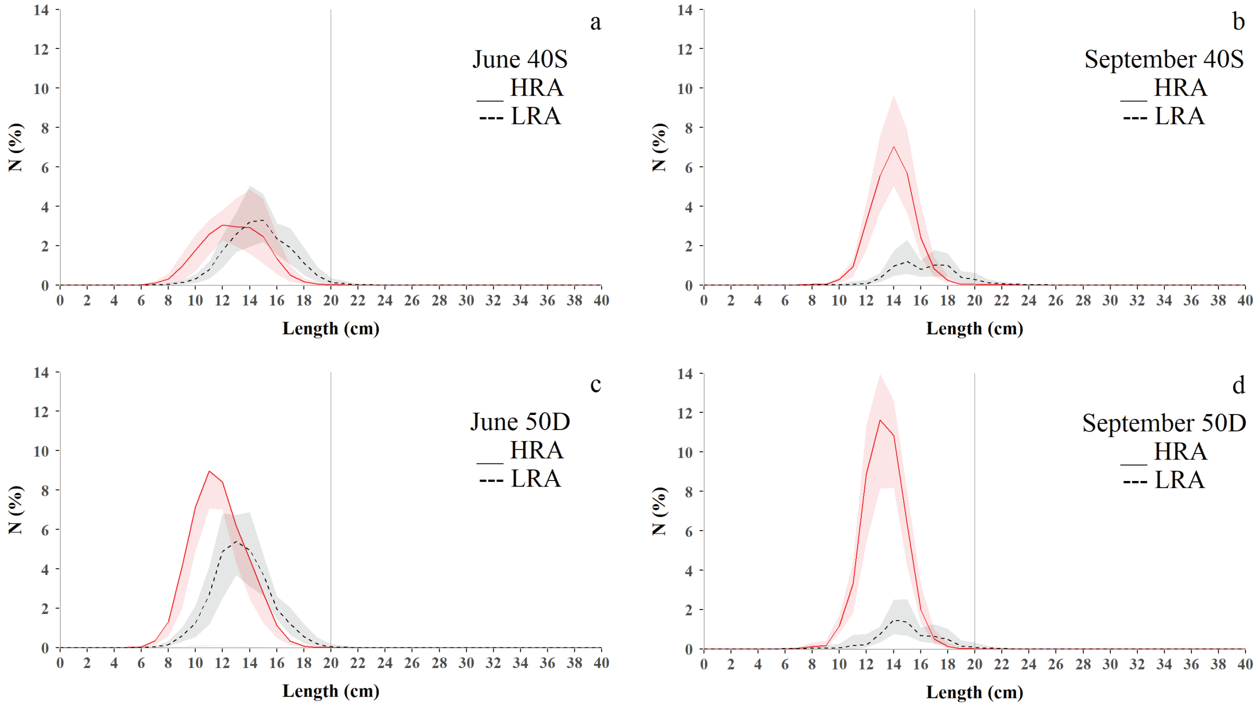

Fig. 4: Hake discards size structure in HRA (continuous line) and LRA (dashed line) using 40S in June (a) and September (b) and using 50D in June (c) and September (d). 95% Efron percentile confidence intervals are also given (coloured area around line). 40S: 40 mm square mesh in the trawl codend; 50D: 50 mm diamond mesh in the trawl codend; HRA: high recruitment area, LRA: low recruitment area.

in LRA in September (June HRA: 45.3%; June LRA: 27.7%; Sept. HRA: 45.4%; Sept LRA: 6.3%). Significant differences were always detected between the two areas and periods (Fig. S1c, d, g, h). Differences were also significant between the two codends, with 50D presenting higher percentages in small size classes (7 - 14 cm), particularly in HRA (Fig. S2a, b, c), with the exception of September in LRA, where differences were almost null (Fig. S2d).

Hake landings size structure

Based on *nP_* the plots for the landings size structure and those for the differences (Fig. 5 and Fig. S3 & Fig. S4), significantly higher percentages in respect to the total population were predicted in LRA than HRA for each period and codend used; higher in September than in June for each area and codend, but quite similar between the two codends in the same area and period (for 40S, June HRA: 13.0%, June LRA: 55.8%, Sept. HRA: 33.5%, Sept LRA: 89.0%) (for 50 D, June HRA: 15.4%, June LRA: 59.9%, Sept. HRA: 38.3%, Sept LRA: 90.9%). Differences in landings between the two areas were significant for the percentages in length classes 16 - 38 cm being higher in LRA in June (Fig. S3a); in September, in size classes 10 - 16 cm TL being higher in HRA and most of the size classes >18 cm being higher in LRA (Fig. S3b). Similarly, significant differences were detected for 50D (Fig. S3). Comparisons in hake landings between the two codends in each area and sampling period revealed higher frequencies for 50D, but without significant differences (Fig. S4).

In all cases, undersized individuals (<20 cm TL) were included in the landings with lower percentage in HRA in June for 40S and higher for the same period in LRA for 50D (for 40S, June HRA: 8.8%, June LRA: 28.0%, Sept. HRA: 15.5%, Sept LRA: 17.9%; for 50D, June HRA: 11.2%, June LRA: 31.9%, Sept. HRA: 20.3%, Sept LRA: 19.6%) (Fig. 5). Removal of these portions from the actual landings, gave similar percentages of regulated landings for both codends (June HRA: 4%, June LRA: 28%, Sept. HRA: 18%, Sept LRA: 71%).

Exploitation indicators

The estimation of *nP_* showed that in all cases, the percentage of individuals below MCRS that were retained in the codend was statistically significantly lower in HRA than LRA; in June than in September (except in LRA for 50D), and for 40S than 50D (Table 1, Table S3 & Table S4). Similarly, significant differences were also detected for in all cases, except between the two codends in LRA in September (Table 1, Table S3 & Table S4).

The *ndRatio* was significantly lower for 40S than 50D in all cases (Table S4), with the lowest value (~25%) predicted in LRA in September (Table 1). For both gears, it was significantly higher in HRA than LRA in both periods; and higher in June than September in both areas (Table 1, Table S3 & Table S4). Similar significant differences were also detected for *wdRatio* in all cases, except between the two codends in LRA in September (Table 1, Table S3 & Table S4).

The fisher discard ratio indicator ($ndRatio_f$) showed

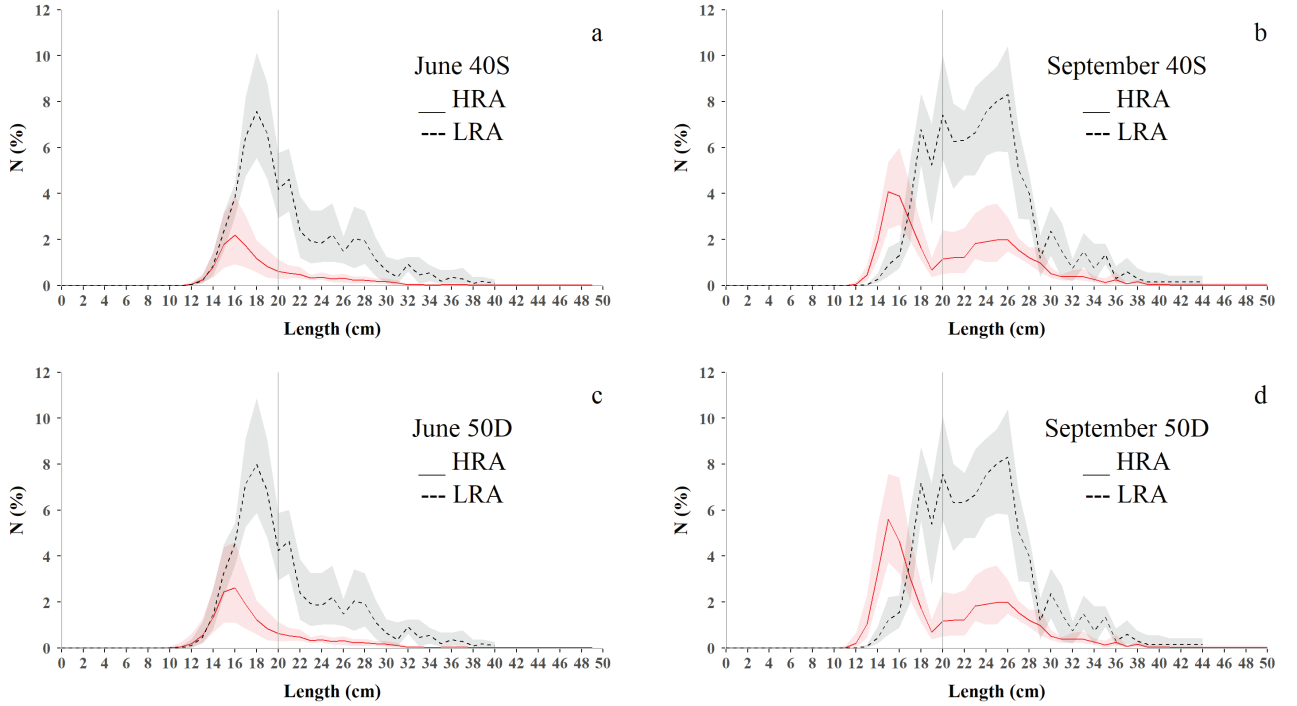

Fig. 5: Hake landings size structure in HRA (continuous line) and LRA (dashed line) using 40S in June (a) and September (b) and using 50D in June (c) and September (d). 95% Efron percentile confidence intervals are also given (coloured area around line). 40S: 40 mm square mesh in the trawl codend; 50D: 50 mm diamond mesh in the trawl codend; HRA: high recruitment area, LRA: low recruitment area

Table 1. Exploitation indicators (in numbers and weight) for the hake trawl fishing in areas of high (HRA) or low (LRA) recruitment in the Saronikos Gulf (E. Mediterranean) in June and September and using 40 mm square (40S) or 50 mm diamond (50D) meshes in the codend; 95% CI are also presented in parenthesis below the indicator value.

Exploitation Indicator	Codend	June		September	
		H-ROA	L-ROA	H-ROA	L-ROA
nP_ **(%)**	**40S**	29.28 (19.47 - 40.43)	64.08 (56.23 - 76.16)	51.14 (42.95 - 62.72)	84.10 (73.60 - 92.35)
	50D	59.08 (49.95 - 71.75)	82.86 (77.63 - 89.09)	79.94 (73.76 - 87.50)	90.82 (83.40 - 96.68)
wP_ **(%)**	**40S**	50.05 (36.46 - 62.50)	81.36 (74.08 - 88.13)	62.85 (53.03 - 75.62)	92.78 (87.18 - 96.45)
	50D	75.43 (66.00 - 84.85)	91.36 (86.94 - 95.38)	85.73 (80.10 - 92.42)	95.68 (92.16 - 98.12)
ndRatio **(%)**	**40S**	86.90 (79.63 - 91.03)	62.02 (50.43 - 71.89)	69.79 (55.96 - 78.26)	25.00 (20.41 - 30.46)
	50D	93.07 (90.28 - 95.03)	67.93 (56.18 - 77.20)	78.34 (67.13 - 85.19)	26.52 (21.72 - 32.53)
wdRatio **(%)**	**40S**	49.73 (31.14 - 65.61)	28.17 (19.78 - 37.07)	24.70 (15.19 - 32.36)	8.42 (6.61 - 10.91)
	50D	59.90 (44.35 - 73.42)	30.61 (21.81 - 39.77)	30.93 (19.77 - 39.22)	8.67 (6.89 - 11.28)
$ndRatio_f$ **(%)**	**40S**	59.77 (48.99 - 68.05)	24.74 (16.49 - 32.68)	44.11 (31.96 - 54.23)	6.81 (4.08 - 10.25)
	50D	74.66 (65.00 - 82.88)	31.64 (21.89 - 40.22)	54.12 (42.02 - 62.86)	6.46 (4.34 - 10.17)
$wdRatio_f$ **(%)**	**40S**	26.16 (16.84 - 35.65)	8.30 (4.92 - 11.97)	13.26 (7.57 - 18.93)	2.00 (1.02 - 3.41)
	50D	37.09 (28.54 - 44.87)	9.05 (5.70 - 12.92)	17.74 (10.80 - 23.86)	1.45 (0.90 - 2.60)
$vulRatio_f$ **(%)**	**40S**	29.5 (10.7 - 63.8)	20.0 (12.4 - 29.2)	8.4 (4.8 - 12.1)	5.1 (3.9 - 6.6)
	50D	30.0 (10.8 - 66.6)	20.0 (12.4 - 29.6)	8.5 (5.0 - 12.4)	5.1 (3.9 - 6.6)

similar patterns between areas, periods and gears as did the discard ratio indicator *ndRatio,* which considers a knife-edge division between landings and discards at the MCRS (Table 1). However, in LRA in September, no significant differences were detected between the two codends (Table S4). Moreover, in terms of weight, $wdRatio_f$ did not differ between the two codends in LRA in both periods (Table S4). It is worth noting that the values of $ndRatio_f$ were always significantly lower than those of *ndRatio* with differences ranging between 18 - 27% for 40S and 18 - 36% for 50D in terms of numbers and 6 - 23% for 40S and 7 - 23% for 50D in terms of weight (Table S5).

The economic value of the undersized landings v$ulRatio_f$ was similar for the two codends in each area and period; higher in HRA than LRA and in June than in September. The highest value was found in HRA in June (30%), whereas the lowest (5%) was in LRA in September (Table 1).

Discussion

In the present work, the length structure of discards and landings and related exploitation indicators have been predicted for first time, using fishing gear and fisher behaviour selection models, while also taking into consideration spatio-temporal differences in the population size structure and the effect of codend selectivity. The approach was based on a case study for hake in areas and periods of high and low recruitment, and by testing the codends in use in the Mediterranean trawl fishery.

Several works modelling hake selectivity, discards, and population size structure (for nurseries) have been previously conducted, however, these typically confronted each of these objectives separately (Guijarro & Massuti, 2006; Bartolino *et al*., 2008, 2011; Damalas & Vassilopoulou, 2013; Colloca *et al*., 2015). Heath & Cook (2015) developed a complex model to estimate discards composition in the North Sea demersal fisheries by combining fisheries dependent data for landings and discards and fisheries independent data from surveys for population abundance. The proposed method here was based on the selection model described by Mytilineou *et al.* (2018) for hake and selectivity data for the hake population in Saronikos Gulf. It is a simple and general method providing indicators independent of population abundance. The discards and landings size structure were also given in a generalized form, as percentage of the total population. The method can be applied as an alternative, additional and cost-beneficial approach, particularly when other types of data are missing or are fragmented (often observed in the Mediterranean). However, if the actual discards, landings and fisheries impact are investigated, then, population abundance and fisheries effort allocation should be considered.

Hake is generally overexploited in the Mediterranean (Vasilakopoulos *et al*., 2014), with high quantities of undersized individuals in the catch (Bellido *et al*., 2017; Tsagarakis *et al*., 2017). Therefore, any information that may lead to a more sustainable exploitation of hake is important. In this aspect, the results of the present work were quite informative. The exploitation indicators *nP_* and *wP_*, although expected to be ideally close to zero, showed that both codends always retained an important part of the undersized individuals of the population (i.e. juveniles) ranging from 30 to 91% in terms of numbers or from 50 to 95% in terms of weight depending on the area and season. Thus, both codends are not effective in leaving juvenile hake to escape, which is in line with selectivity studies (Lucchetti, 2008; Sala *et al*., 2008; Mytilineou *et al*., 2018). Similar to the findings of Mytilineou *et al*. (2018) from selectivity studies, the indicators used in the present work showed that the 40S codend was more effective than 50D for the smallest of the undersized individuals of hake (i.e. recruits), which mainly occur in HRA in June. In addition, the absence of significant differences between the two codends in LRA in September, when the largest undersized hake occur, indicates that both codends behave similarly as young hake grow with time.

The predicted discards size structure of hake showed that, generally, a significantly higher percentage of the total population is discarded in HRA than LRA, in June than in September and when using the 50D than the 40S. Deviations observed (i.e. no difference between the two areas in June for the 40S and between the two codends in LRA in September, and higher percentages of discards in HRA in September) can be attributed to te gear selectivity, fisher selection behaviour and population structure and growth of hake. In fact, the smallest hake occurring in HRA in June have a high probability to escape through the more selective 40S (resulting in a discards size structure in HRA similar to that of LRA), but their growth in size across the months results in an increasing probability to be retained by the codend in this area in September, and therefore to be discarded (resulting in higher discards percentages in HRA in September). In contrast, the juveniles occurring in LRA in September are large enough to be retained with a similar pattern by both codends, and therefore to be discarded or landed according to fisher selection behaviour (resulting in similar discards structure for 40S and 50D in LRA in September). All the above-mentioned factors (e.g. population structure, gear selectivity, fisher behaviour, market) have been reported in the literature as factors affecting discards (Catchpole *et al*., 2005; Feekings *et al*., 2012, 2013).

The results for the hake landings size structure suggested that fishing in LRA in September using both codends produces much higher landings percentages for both the actual (90%) and the regulated landings (71%). No significant differences were detected for the two codends in the same area and period indicating a stable fisher selection pattern for hake landings, as also mentioned by Mytilineou *et al.* (2018). The results also showed that many of the largest undersized hake (18 - 20 cm) were included in landings. Mytilineou *et al*. (2018) found that fishers sort with a discard probability <0.75 and a landing probability between 0.5 - 1 for sizes between 15 and 20 cm for both codends. Damalas & Vassilopoulou (2013) and Damalas *et al*. (2018) mentioned that hake is one of the species exhibiting very low compliance to the MCRS concerning the landings. Based on observer data collected on board commercial fishing vessels, they showed that the discard probability for hake decreases from 0.5 to 0 for the size range 15 - 18 cm TL. Damalas *et al*. (2018) mentioned that undersized hake 17 - 19 cm are mainly included in the hake landings. All these findings, based on fisheries data, support our results, although derived from experimental fishing and the limitation of using only one fishing vessel as representative of the fishing fleet.

Considering the total amount of discards and landings in each case, it is worth highlighting that fishing with both codends in LRA in September seems to impact less the population (discards 6% of the total population) and at the same time to be more profitable for the fisher (landings 90%); the opposite was true in HRA, where fishing with 50D is worse than with 40S in terms of discards. However, if undersized hake included in landings are considered as discards, the total amount of undersized hake catch increases almost identically for both codends in LRA in September to ~25%, becoming considerably higher for the 40S in HRA in September and LRA in June (42 - 46%) and extremely higher for 50D in the other cases (57 - 72%), reflecting an important impact on the population.

The discard ratio *ndRatio* was always higher in HRA, in June and for 50D. This was explained by a catch of almost exclusively undersized individuals and the low percentage of predicted landings, even lower than discards, in HRA in June. The opposite occurred in LRA in September (discard ratio ~25%). However, the values of this indicator in terms of weight were much lower and decreased to ~8% in LRA in September for both codends, which is close to the value (6 - 7%) required for the *de minimis* exceptions from the landings obligation for hake (EU, 2017).

The fisher's discard ratio showed that the discard ratio does not reflect the real impact of trawling on hake stock, because undersized hake in the landings may cause an important reduction of the latter indicator (18 - 37 % in numbers or 6 – 23% in weight). A parallel effect of this is that the economic value of hake landings may increase from 5 to 30% depending on the area and period as shown by the v*ulRatio*. Undersized hake in landings has been widely reported in the Mediterranean (Keskin *et al*., 2014; Tsagarakis *et al*., 2017). Based on fisheries data from observers, the discard ratio reported for hake in GSA 22 (where Saronikos Gulf is located) ranges between 3.3-11.2% (Damalas & Vasilopoulou, 2013; MEDAC, 2016; Tsagarakis *et al*., 2017; DCF data, 2014 - 2019). These values, compared with our fisher discard ratio in weight for 40S (the codend used in the area), were within the range of our results (2.0 - 26.2%), which verifies that the data used in our work represent quite well what happens in commercial fisheries although they are derived from two limited sampling areas and periods, from experimental fishing and from only one fishing vessel.

The results from this study imply that fishing in areas and periods of high recruitment for hake is: (i) harmful for the stock since it removes large amounts of juveniles, (ii) produces a catch of low economic value for the fisher and (iii) produces a large amount of discards that should be landed if the discard ban is enforced. Although results were significantly better for 40S than 50D, both codends seem inappropriate in this case. Trawling in areas and periods of low recruitment with both codends showed similar impacts considering juveniles and discards.

The change in trawl selectivity, adopted by Regulation 1967/2006 (EC, 2006), seems insufficient to protect young hake, which has already been reported in selectivity studies (Mytilineou *et al*., 2018; Vitale *et al*., 2018). Unless a different measure is found for trawl selectivity improvement, these results imply the need for spatial and temporal closures in areas of high hake recruitment (nursery hot-spots), if young hake are to be protected and discards to be mitigated under the objectives of a sustainable fishery. Many researchers have also proposed this alternative management for hake. Apostolaki *et al*. (2002) have predicted the positive effects of fishing closures in Mediterranean hake nurseries and Colloca *et al*. (2009) estimated that such a closure in the Tyrrhenian and Ligurian Seas would result in the protection of 40% of recruit abundance (but see Bartolino *et al*., 2011). Using various complex bio-economic models, Russo *et al.* (2014) found that even the closure of a single nursery area in the Strait of Sicily can substantially improve the biomass of the studied, and possibly other, species in the short term, while Khoukh & Maynou (2018) showed that the fishing closure of an essential ground for hake recruits in the Catalan Sea was the best scenario comparable to a reduction of fishing effort up to 20%. Russo *et al.* (2019), with a more complex model, predicted improvement in hake biomass, however without reaching sustainability and with economic losses for the fleet; the closed summer scenario giving the best biological effects. This is in line with our results for a higher fishing impact on the hake population in HRA in June. Russo *et al*. (2019), however, concluded that for hake, a combination of fishing effort reduction, the protection of nurseries and/or the use of a more selective gear are necessary to reach the acceptable level of fishing mortality. Trawl fishing in Greek waters is prohibited from the beginning of June to the end of September, which seems to favor hake stocks. At the local scale, in Saronikos Gulf, the extension of the fishing closure of the inner part of the gulf to include HRA is under discussion with stakeholders. In other Mediterranean regions, the closure of trawl fishing is limited to only two summer months or trawl fishing is permitted all year and 50 mm diamond or smaller meshes are still in use.

The proposed method, although based on the assumption that the hake population is the total amount of fish entering the trawl codend and a simplification of the real conditions of the commercial fishing fleet, provided important information on the gear, fisher and fisheries exploitation pattern, which can be helpful in fisheries management for hake juvenile catch reduction and discards mitigation, particularly as a precautionary approach. Models can have a key role in the development of new technological solutions as they may assist managers and fishers in identifying new rules to reduce unwanted catches (Maeda *et al*., 2017). This work showed the applicability of the selection model described by Mytilineou *et al*. (2018) and its utility in policy. Although it was focused on hake in the Mediterranean trawl fishery, the presented methodology is readily applicable to other species, fisheries and areas.

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Supplementary data

The following supplementary information is available on line for the article:
A. Identification of high and low recruitment areas
B. Estimation of the population entering the trawl codend size structure
C. Exploitation Indicators in weight
D. Estimating the Exploitation Indicator in value
References (not included in the main manuscript)

Fig. S1: Difference $\Delta pop_{disc}(l,a,t,g)$ in the hake discards size structure between the two sampling areas (HRA, LRA) in June for 40S (a), September for 40S (b), June for 50D (c), and September for 50D (d) and between the two sampling periods (June, September) in HRA for 40S (e), LRA for 40S (f), HRA for 50D (g) and LRA for 50D (h). 95% Efron percentile confidence intervals are also given (coloured area around line). HRA: high recruitment area, LRA: low recruitment area, 40S: 40 mm square mesh in the trawl codend; 50D: 50 mm diamond mesh in the trawl codend; Δ (%): difference in percentage (%).
Fig. S2: Difference $\Delta pop_{disc}(l,a,t,g)$ in the hake discards size structure between 40S and 50D codends in HRA in June (a), HRA in September (b), LRA in June (c) and LRA in September (d). 95% Efron percentile confidence intervales are also given (coloured area around line). 40S: 40 mm square mesh in the trawl codend; 50D: 50 mm diamond mesh in the trawl codend; HRA: high recruitment area, LRA: low recruitment area; Δ (%): difference in percentage (%).
Fig. S3: Difference $\Delta pop_{land}(l,a,t,g)$ in the hake landings size structure between the two sampling areas (HRA, LRA) in June for 40S (a), September for 40S (b), June for 50D (c), and September for 50D (d) and between the two sampling periods (June, September) in HRA for 40S (e), LRA for 40S (f), HRA for 50D (g) and LRA for 50D (h). 95% Efron percentile confidence intervals are also given (coloured area around line). HRA: high recruitment area, LRA: low recruitment area, 40S: 40 mm square mesh in the trawl codend; 50D: 50 mm diamond mesh in the trawl codend; Δ (%): difference in percentage (%).
Fig. S4: Difference $\Delta pop_{land}(l,a,t,g)$ in the hake landings size structure between 40S and 50D codends in HRA in June (a), HRA in September (b), LRA in June (c) and LRA in September (d). 95% Efron percentile confidence intervals are also given (coloured area around line). 40S: 40 mm square mesh in the trawl codend; 50D: 50 mm diamond mesh in the trawl codend; HRA: high recruitment area, LRA: low recruitment area; Δ (%): difference in percentage (%).

Table S1. Mean abundance (n/km^2) of hake new recruits, their proportion to the total number of individuals, 75% percentile of the sizes and depth range by sampling area (southern/northern) and time period (June/September). HRA: high hake recruitment area, LRA: low hake recruitment area.
Table S2. Average market values of hake (Euro/kg) for each market category.
Table S3. Difference in hake exploitation indicators between the two areas (HRA, LRA) or the two periods (June, September) using two different trawl codends (40S, 50D). 95% CI are also presented entre parenthesis below the difference value. Expl. Indicat.: Exploitation Indicator; HRA: high hake recruitment area; LRA: low hake recruitment area; 40S: 40 mm square mesh, 50D: 50 mm diamond mesh.
Table S4. Difference in hake exploitation indicators between the two studied trawl codends (40S, 50D) in each area (HRA or LRA) during each period (June or September). 95% CI are also presented entre parenthesis below the difference value. 40S: 40 mm square mesh, 50D: 50 mm diamond me sh, HRA: high hake recruitment area, LRA: low hake recruitment area.
Table S5. Difference in hake discard Ratio between that estimated based on the MCRL (*dRatio*) and that based on the fisher behaviour ($dRatio_f$) in each area (HRA or LRA) during each period (June or September) using different trawl codends (40S or 50D). 95% CI are also presented entre parenthesis below the difference value. HRA: high hake recruitment area, LRA: low hake recruitment area, 40S: 40 mm square mesh, 50D: 50 mm diamond mesh.