Dredge selectivity in a Mediterranean striped venus clam (*Chamelea gallina)* fishery

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A B S T R A C T

The striped venus clam *Chamelea gallina* is the target of a large fleet of hydraulic dredgers, which represent an important fishing sector in terms of income and landings in the Mediterranean Sea. Although there is information on the catch rates, impact and discards related to this fishery, the size selection process carried out by the dredge during trawl under commercial conditions is practically unknown. The present study aimed to fill this gap, assessing the selectivity of the gear at different haul durations. We demonstrated that 25% of the clams entering the dredge were not size selected by it. Clams with a length (i.e. maximum distance between anterior and posterior margins) of 18.9 mm had 50% retention probability and tow duration did not affect the size selection process in the dredge. The dredge catch efficiency was 79% in numbers of clams and 89% in weight. 58% of the clams caught were below the minimum conservation reference size of 25 mm. The study demonstrates that to land only the legal sizes of clams, the additional size selection process carried out on board the fishing vessels by the sorting sieves is necessary.

1. Introduction

Dredge fisheries are widely spread in the Mediterranean Sea to harvest commercially important burrowing bivalve shellfish, which represent an important seafood product across the whole region (FAO, 2018). The striped venus clam *Chamelea gallina* is one the most important infaunal bivalves exploited by dredgers, with relevant socio-economic importance particularly in the Italian coastal waters of northern and central Adriatic Sea (Scarcella and Cabanelas, 2016). The design of the dredge employed to harvest this resource, in soft bottoms with depths ranging from 3 to 12 m, have evolved over the past decades (Froglia, 1989) from rakes operated by hands until the advent of the modern hydraulic dredges, which enabled the development of a very profitable fishery for a large number of vessels (over 700 in Adriatic; DGPEMAC, 2019).

The typical hydraulic dredge consists of a sort of parallelepiped-shape metal cage, which is commonly made of metal bars in its lower, upper and rear parts (Fig. 1). The cage rests on two skid-sledge runners that facilitate the sliding motion on the seabed during towing (Lucchetti and Sala, 2012). The adjective "hydraulic" derives from the pressurised water that is injected from a centrifugal water pump to different types of nozzles mounted on the dredge. These nozzles are arranged in parallel rows and placed both at the dredge mouth and inside the dredge (Sala et al., 2017). The former spray pressurised water downwards to penetrate the sea bottom and suspend the sediment, to make the bivalves emerge and at the same time to assist the movement of the dredge in the substrate. The latter are positioned backwards to help clearing the cage from materials such as sand, mud and debris that often clog it. The dredge towing on the seabed is responsible for the first selection of the striped venus clam by size. After towing, the cage is hauled on board and all the catch gathered is conveyed to vibrating sieves, which are made up of a series of successive grids with holes of decreasing diameter (Sala et al., 2017). The mechanical sorting carried out by the sieves represents the second selection process to obtain the commercial sized clams. The actual minimum conservation reference size (MCRS) is temporarily set at 22 mm of maximum distance between anterior and posterior margins
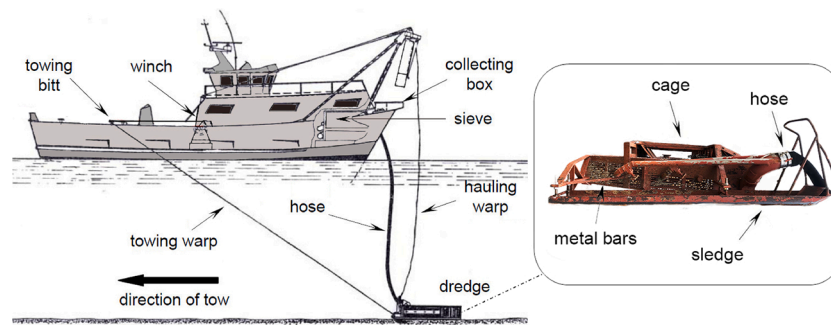

Fig. 1. Commercial hydraulic dredging gear characteristics and method of deployment (adapted from Lucchetti and Sala, 2012).

Fig. 2. Illustration of hydraulic dredge targeting Chamelea gallina and details of the net sampler used as a control to assess the size selectivity of the dredge: (A) metal cage located at the bow; (B) particular of the steel frame (40 × 18 cm) fixed inside the dredge mouth; (C) lateral view of the net sampler inside the cage; (D) emptying of the net sampler.

(length, hereafter) along the Italian coasts (Commission Delegated Regulation 2376/2016; Italian Ministerial Decreee, 27/12/2016), by way of derogation of (European Regulation EU 1967/2006, 2006) that set the MCRS at 25 mm.

The size selectivity of the dredge is primarily dependent on the spacing of metal bars that compose the cage (Sala et al., 2017). The bar spacing of the cage has a minimum width of 12 mm with a tolerance of less than 1 mm, according to the Italian regulation (Italian Ministerial Decreee, 12/22/2000), which is based on dated laboratory experiments

with different sieving equipment (Froglia and Gramitto, 1981).

While the size selectivity of vibrating sieves currently in use in the Adriatic *C. gallina* fishery has already been assessed (Sala et al., 2017), the first size selection process carried out by the dredge under fishing is practically unknown.

Studies on toothed dredges have established that tooth spacing is of no importance for the selectivity of these dredges, because the tooth bar located in front acts exclusively as a hoe, while mesh bar of the netting bag is responsible for the size selection (Gaspar et al., 2003, 1999).
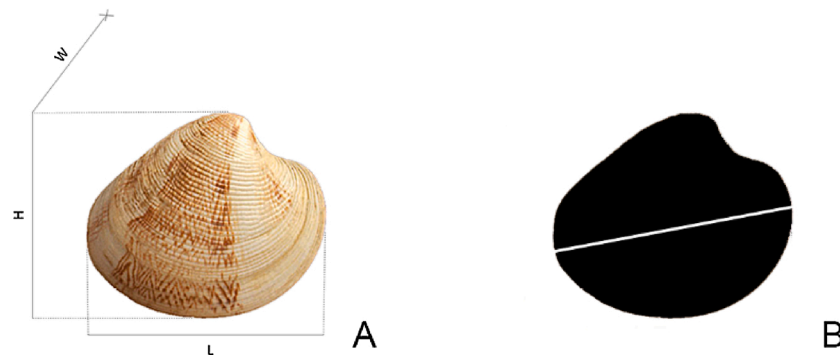
Fig. 3. A: Schematic representation of the striped venus clam shell measurements. H: height; L: length; W: width. B: Example of photograph processing with ImageJ software, that provides the Feret X (white line), which is the longest distance between any two points along the selection perimeter, thus representing the individual length (L).

Moreover, Kim et al. (2005) pointed out that a percentage of the total clams caught have not come into contact with the dredge, due to clogging of tooth spacing by the sediments; as a consequence, these clams are not size sorted (Mituhasi et al., 2005). The clogging phenomenon could play an important role also in the selectivity of hydraulic dredges (Sala et al., 2017), where a large amount of material (clams, sand, mud, shells etc.) is usually hauled on board, despite the presence of the washing nozzles. This phenomenon could affect the actual number of clams that physically contact the metal bars of the cage and create the conditions for a size dependent escape process (i.e. the selectivity contact, Olsen et al., 2019). Moreover, Carlucci et al. (2015) suggested that the selectivity of the hydraulic dredge decreases with the increasing of tow duration, as clams larger than the bar spacing accumulate in the bottom of the cage and block the escapement of smaller clams.

Given these premises, the goals of the present study are:

i) to assess the first size selection process of the dredge under fishing with different tow durations.
ii) to estimate the amount of undersized and target-sized striped venus clam retained by the dredge, and the resulting discard ratio, considering both MCRS of 22 and 25 mm.
iii) to investigate the adequacy of the gear configuration currently used from a management point of view.

2. Materials and methods

2.1. Sea trials and data collection

Sea trials were conducted on board a commercial fishing vessel (110 kW; Length Over All 15.82 m; 9.97 GT) in the coastal waters of northern-central Adriatic Sea. The hydraulic dredge had a total weight of 600 kg and dredge mouth was 280 cm wide (Fig. 2 A). Bar spacing was on average 11.5 ± 0.6 (s.d.) mm, as obtained from measurement with a calliper at 12 points selected at random. To assess the size selectivity of the dredge, a net sampler (40 cm wide and 18 cm high steel frame) adapted to the dredge height, was fixed inside the dredge mouth (Fig. 2 B, C). The net sampler had 12 mm meshes to act as a control, while the remaining portion of the dredge (240 cm wide) was our test. Hauls were carried out close to each other in the same fishing area, to minimize differences due to the patchy distribution of the species (Morello et al., 2005a). The average towing speed was maintained at 1.8 knots, which falls inside the range of the commercial fishing procedures (Romanelli et al., 2009). The haul duration was set at 3, 6 and 9 min, respectively, since the average duration range of commercial hauls was 5−10 min during the sampling period. After each haul, and once being washed from the sediment, shells and other benthonic species, the total catch of

C. gallina derived from both test and control compartment was weighted. Before this process, a non – washed subsample of 2.5–3 kg from each compartment had been put aside for following clam measurements.

The length measurements were performed by video analysis, according to Stagioni (2010) protocol. Groups of 60–80 individuals of clam sample were consecutively placed on a backlit table to be photographed by a digital camera mounted at a fixed distance above the table. Photographs were processed with ImageJ software (Rasband, 2018) that provides for each clam the Feret X parameter, which is the longest distance between any two points along the selection perimeter, thus representing the individual length (Fig. 3 B). For each photograph, the central clam was manually measured with the calliper, to calibrate the analysis and minimize any error due to any lens movement or distortion among photographs. The length measurements were performed to an accuracy of 0.2 ± 0.1 mm. Consequently, clams were grouped into 1 mm length classes for each haul in the test and control compartments, respectively.

Finally, a random subsample of around 1000 clams obtained from the previous 2.5–3 kg subsamples and including a wide range of length classes, was taken for determination of length-weight and shell morphometric relationships (length-height, length-width, following Gaspar et al. (2002); Fig. 3 A) using a manual calliper (precision of 0.1 mm) and a digital balance (precision of 0.1 g). Length (L)-weight (We) relationship was determined according to the following equation:

$$We = a \times L^b$$

while length-height (H) and length-width (W) relationships were modeled by linear regressions with slope and intercept.

2.2. Size selectivity analysis

The catch data (i.e. the numbers of clams of each length class obtained from the video analysis for each compartment and haul, and the associated subsampling ratios) were used for the size selectivity analysis.

Data were analyzed using the method described below, which was implemented in the software tool SELNET (Herrmann et al., 2012). The catch data from test and control were collected in pairs. Therefore, it was realistic to assume that both compartments of the dredge were fishing a population of clams with the same size distribution. The catch data from individual hauls were analyzed separately for the three tow durations (3, 6, 9 min), and the paired gear estimation method (Wileman et al., 1996) was applied on the data pooled over hauls to determine the average size selectivity of the test compartment for each tow duration. Thus, the average size selectivity of the test was estimated by minimizing the following equation:

$$-\sum_{l}\sum_{i=1}^{m}\left\{\frac{nT_{li}}{qT_i}\times ln\left(\frac{SP\times r(l,\mathbf{v})}{SP\times r(l,\mathbf{v})+1-SP}\right)+\frac{nC_{li}}{qC_i}\times ln\left(1.0-\frac{SP\times r(l,\mathbf{v})}{SP\times r(l,\mathbf{v})+1-SP}\right)\right\} \tag{1}$$

Where nT_{li} and nC_{li} represent the number of clams of each length class l retained and length measured in the ith haul for the test and control, respectively. qT_i and qC_i represent the fractions of the catch in haul i that were length measured for the test and control, respectively (i.e. the subsampling ratio). m represents the total number of hauls for the specific duration. SP is the split parameter that quantifies the sharing of the total catch between the test and the control, and $\mathbf{v}$ is a vector of parameters in the size selection model $r(l,\mathbf{v})$. Differences in the entrance of clams between test and control compartments will be reflected in the value of SP, and therefore will not bias the estimation of the size selectivity $r(l,\mathbf{v})$ for the test. In fact, high SP values are expected in case of a marked difference between the areas of the two compartments. In the present experimental design, the SP can be calculated as a ratio between the width of the test and the width of the test + control (240 / 280 = 0.86). Minimizing the expression (1) is equivalent to maximizing the likelihood for the experimental data based on a formulation of the negative log likelihood for binominal data.

Since the dredge is made up of a single bar spacing, the size selection carried out by the test compartment would traditionally be described by the standard *Logit* model (Wileman et al., 1996):

$$r(l,\mathbf{v})=r_{Logit}(l,\mathbf{v})=\frac{exp\left(\frac{ln(9)}{SR}\times(l-L50)\right)}{1.0+exp\left(\frac{ln(9)}{SR}\times(l-L50)\right)} \tag{2}$$

$$\mathbf{v}=(L50,SR)$$

Where *L50* is the length of a clam with 50% probability of being retained, given it has entered the test, whereas *SR* is the difference in length of clams having respectively 75% and 25% probability of being retained by the test, conditioned they entered it. Model (2) assumes that every clam that enters the test compartment is size selected by the bar spacing before the dredge is retrieved on board the fishing vessel. However, a fraction of all clams entering the test may not be size sorted, for example due to the clogging of the dredge. Therefore, instead of modeling the size selection based only on the *Logit* model (2), we also considered the *CLogit* model (3), which can account for the possibility that only a fraction *C* of the clams entering the test compartment makes contact with the bar spacing and is subjected to a size selection process (Herrmann et al., 2013):

$$r(l,\mathbf{v})=r_{CLogit}(l,C,L50_c,SR_c)=(1-C)+C\times Logit(l,L50_c,SR_c)$$
$$=1.0-\frac{C}{1.0+exp\left(\frac{ln(9)}{SR_c}\times(l-L50_c)\right)} \tag{3}$$

Where $L50_c$ and SR_c account only for the clams that make selectivity-contact with the bar spacing. The parameter *C* holds a constant value that ranges between 0.0 (no clams make selectivity-contact with the bar spacing) and 1.0 (all clams entering the test make selectivity-contact with the bar spacing). When $C = 1.0$, the *CLogit* model simplifies to the traditional *Logit* model.

Estimation of the average size selection with a *CLogit* model requires finding the values for the parameters C, $L50_c$, SR_c, and SP that minimize (1), conditioned by the collected catch data. Knowing the values of contact selectivity parameters $L50_c$ and SR_c is important to evaluate whether dredge bar spacing is appropriate for the desired selection pattern in the fishery.

Based on $L50_c$, SR_c and C, the available selection parameters $L50_a$ and SR_a, which account for all the clams entering the test compartment, are calculated using the procedure presented in Herrmann et al. (2013):

$$L50_a=L50_c+\frac{SR_c\times ln(2\times C-1)}{ln(9)}$$

$$SR_a=\frac{SR_c\times ln\left(3\times\frac{(C-0.25)}{(C-0.75)}\right)}{ln(9)} \tag{4}$$

Here, SR_a becomes undefined if $C < 0.75$, as the retention probability cannot then reach a value as low as 0.25. Contrary to contact selectivity parameters, $L50_a$ and SR_a incorporate the effect that not necessary all clams get size selected by the dredge bar spacing; knowing their values also has importance.

The ability of the size selection models (*Logit* and *CLogit*) to describe the experimental data was evaluated based on the p-value, which expresses the probability of obtaining by chance alone at least as big a discrepancy between the experimental data and the model as observed, assuming that the model is correct, and based on the model deviance versus the degrees of freedom (DOF). However, in situations of strong subsampling and pooled data (as in our case), the p-value could be < 0.05, that is the lower limit for the selection model to describe the experimental data sufficiently well (Wileman et al., 1996), and the ratio deviance / DOF could be >> 1. With poor fit statistics, the residuals were visually inspected to determine whether the poor result was due to structural problems when modeling the experimental data, or overdispersion in the data (Wileman et al., 1996). In addition, the models were evaluated by plotting the fitted curves against the experimental length-dependent retention rates, to visually check if the curves reflected the main trend in the experimental data.

The size-selection models were compared using the Akaike information criterion (AIC; Akaike, 1974), with the lowest-value model subsequently selected.

We estimated the uncertainties for each size selection curve and the associated selection parameters resulting from the three tow durations. Specifically, confidence limits were estimated using a double bootstrap method for paired data. This method accounted for between-haul variation in the dredge size selection, by selecting *m* hauls with replacement from the pool of hauls for the specific tow duration. Within each resampled haul, an inner bootstrap was used on data for each length class, to account for the uncertainty in the haul, due to a finite number of clams being caught and length measured (i.e. within-haul variation). This inner resampling was performed prior to the raising of the data with subsampling factors qT_i and qC_i, to avoid underestimation of the uncertainty derived by subsampling (Eigaard et al., 2012). The resulting dataset obtained from each bootstrap repetition was analyzed as described above. Based on the bootstrap results, we estimated the Efron percentile 95% confidence intervals (CIs; Efron, 1982) for both the selection curve and the selection parameters. We performed 1000 bootstrap repetitions.

To examine differences between the selection curves, quantified as the difference (Delta) in retention probability, we used a method based on separately obtained bootstrap files. This method is described in Larsen et al. (2018). Specifically, the potential effect of changing from tow duration *Y* to another *Z* on the dredge size selection curve $r(l)$ was estimated by:

$$\Delta r(l)=r_Z(l)-r_Y(l) \tag{5}$$

Where $r_Y(l)$ represents the selection curve obtained for *Y*, and $r_Z(l)$

Table 1
Number of hauls carried out in the selectivity experiments, with the number of clams measured and the subsampling ratio (in parentheses).

Haul	Duration (min)	Nr in dredge (Test)	Nr in net sampler (Control)
1	3	615 (0.03)	434 (0.13)
2	3	586 (0.03)	349 (0.12)
3	3	598 (0.03)	464 (0.11)
4	3	553 (0.03)	390 (0.11)
5	3	564 (0.03)	332 (0.11)
6	3	604 (0.07)	171 (0.12)
7	6	648 (0.02)	354 (0.08)
8	6	655 (0.02)	523 (0.08)
9	6	553 (0.01)	334 (0.06)
10	6	599 (0.03)	391 (0.06)
11	6	453 (0.02)	423 (0.06)
12	6	589 (0.03)	438 (0.08)
13	9	659 (0.02)	307 (0.05)
14	9	546 (0.01)	458 (0.07)
15	9	635 (0.01)	268 (0.07)
16	9	476 (0.01)	440 (0.07)
17	9	422 (0.01)	379 (0.07)
18	9	364 (0.01)	157 (0.11)

represents the selection curve obtained for Z. The Efron percentile 95% CIs for $\Delta r(l)$ were obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each) for both $r_Y(l)$ and $r_Z(l)$. As they were obtained independently, a new bootstrap population of results was created for $\Delta r(l)$ by:

$$\Delta r(l)_i = r_Z(l)_i - r_Y(l)_i, i \in [1\ldots1000] \tag{6}$$

Where i denotes the bootstrap repetition index. As the bootstrap resampling was random and independent for the two groups of results, it is valid to generate the bootstrap population of results for the difference based on (6), by using the two independently generated bootstrap files (Herrmann et al., 2018). Based on this bootstrap population, the Efron percentile 95% CIs were obtained for $\Delta r(l)$ as described above. If these CIs contained the value 0.0 for all l then no significant difference between the selection curves was detected.

In case of lack of significant differences among the selection curves derived from the three tow durations, catch data obtained from all the hauls were pooled, and an additional double bootstrap method with 1000 repetitions was applied to determine a single selection curve with 95% CIs and associated selection parameters.

The density function d_l of the size structure of the population present at seabed contacting the gear was estimated, from the clams collected in the control compartment of the dredge, by:

$$d_l = \frac{\sum_{i=1}^{m}\left\{\frac{nC_{li}}{qC_i}\right\}}{\sum_{l}\sum_{i=1}^{m}\left\{\frac{nC_{li}}{qC_i}\right\}} \tag{7}$$

The estimation by (7), incorporated into the double bootstrap method described above, allowed us to obtain the Efron percentile 95% CIs for this density function and a population of bootstrap results for it. The latter was then applied by multiplying it with the population of bootstrap results for the dredge selection curve, also to obtain an estimate for the retained proportion of the population entering the dredge, together with its 95% CIs. This method is identical to the one described in Melli et al. (2020). Last, we used the result for the retained population

to calculate the proportion out of the total population of clams retained, also considering the clams under and above the MCRS (both 22 mm and 25 mm), and the resulting discard ratio (in number and weight). This last step in the analysis also followed the procedure described in Melli et al. (2020).

3. Results

3.1. Catch data

A total of 18 hauls (6 for each tow duration) were carried out; the number of clams measured for each haul and each compartment, together with the subsampling ratio from the total catch, are listed in Table 1. The length-weight ($L – We$) and shell morphometric regression parameters ($L – H$; $L - W$) are represented in Table 2; a and b values were used in the selectivity results section below.

3.2. Size selectivity results

A comparison of the AIC values obtained for the *Logit* model (1) and the *CLogit* model (2) revealed that the latter better described the experimental size selectivity data for each tow duration (Table 3). These results confirmed our hypothesis that a percentage of clams did not make contact with the bar spacing of the cage and therefore were not subject to a size selection process. Consequently, the *CLogit* model was selected to describe the experimental data.

The p-values were always below 0.05. However, the inspection of the modeled curves against the experimental rates did not indicate any length dependent patterns in the deviations (Fig. 4 A, C, E). Therefore, we assumed that the low p-values were due to overdispersion in the experimental rates rather than a lack of fit.

The selectivity curves with CIs are represented in Fig. 4 B, D, F, and their associated selectivity parameters and fit statistics are summarized in Table 4. It was observed that the expected *SP* fell within the *SP* CIs estimated for 3 and 6 min duration, but not for 9 min duration (Table 4).

The average C was estimated to be 0.70 for 3 min hauls, 0.86 for 6 min hauls and 0.78 for 9 min hauls; it was significantly below 1.0 only for 3 min hauls (Table 4).

$L50_a$ and SR_a accounted for the available selectivity, i.e. considering all the clams entering the dredge, while $L50_c$ and SR_c reflected the selectivity only for those clams that effectively made contact with the dredge; the latter parameters have higher values than the former, as expected (Table 4). Moreover, the lower CIs of SR_a were never estimated because of C being lower than 0.75 that did not allow the model to define a $L25$.

No significant differences between the selection curves for the three haul durations were detected, since the CIs for the curves in the delta plot contained 0.0 in all cases (Fig. 5 B, D, F). Therefore, we

Table 3
Value of AIC (Akaike information criterion) for the Logit and CLogit models for each tow duration.

	AIC		
	3 min	6 min	9 min
Logit	103479.9	186016.4	192884.3
CLogit	103239.4	185941.8	192587.2

Table 2
Summary of the length-weight and morphometric relationships derived from individuals of Chamelea gallina collected during the sea trials.

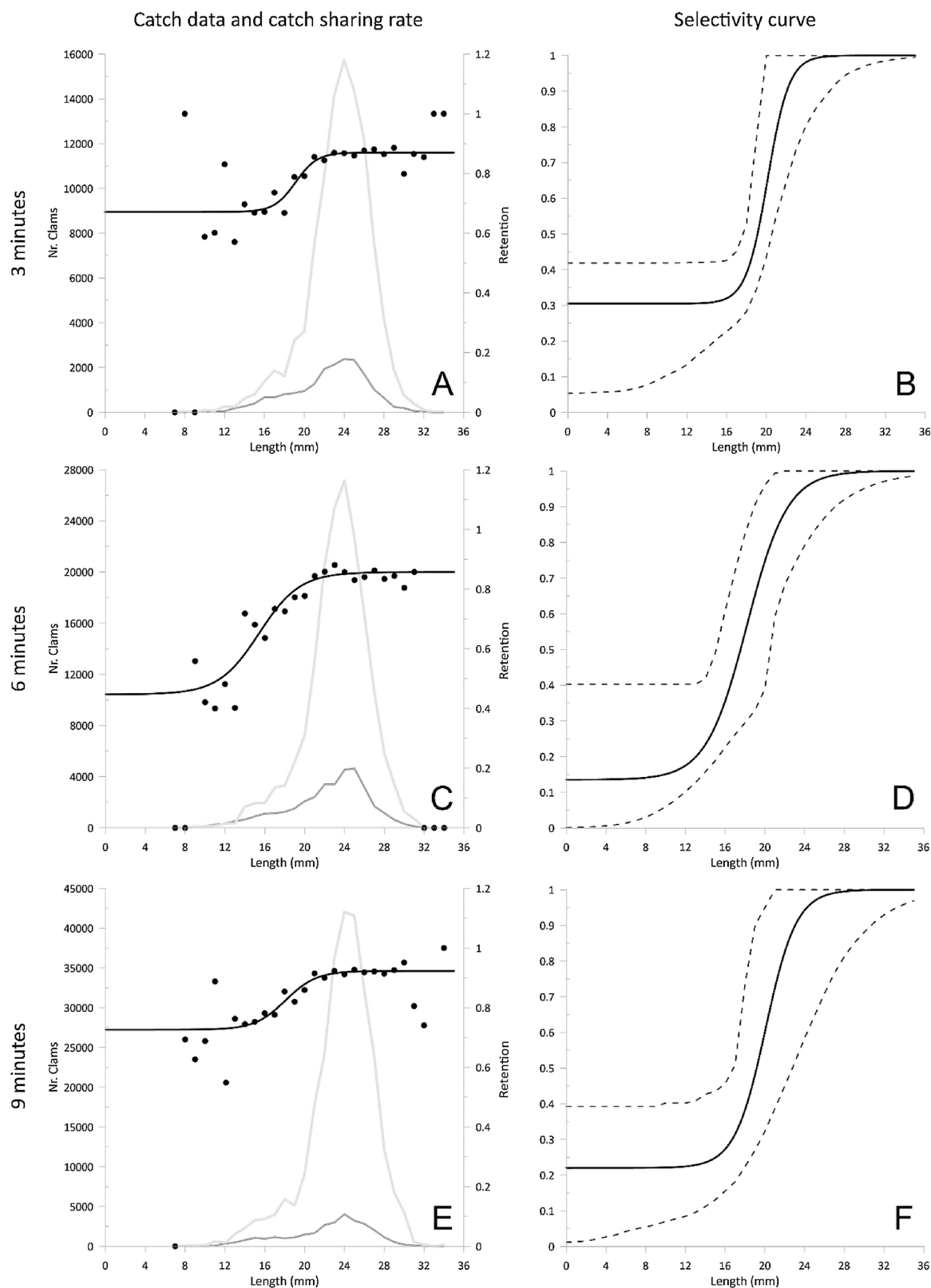| Relationship	Model	Nr of measured clams	a	b	Adjusted R^2	std error a	std error b	p-value
Length - Weigth	$We = a*L^b$	1155	0.308	2.875	0.987	0.016	0.010	< 0.001
Length - Heigth	$H = a + b*L$	765	0.827	1.152	0.984	0.004	0.093	< 0.001
Length - Width	$W = a + b*L$	765	0.426	0.906	0.937	0.004	0.097	< 0.001

Fig. 4. Selectivity representation of the three different haul durations: the left column (A, C, E) shows the size distributions of the clams caught with the test (i.e. dredge; light grey) and control (i.e. net sampler; dark grey) together with the experimental retention data obtained (black dots) and the CLogit curve (black line). The right column (B, D, F) shows the size selectivity curve (full line) with confidence intervals (dashed lines).

Table 4
Selectivity parameters and fit statistics from the *CLogit* model. SP: split parameter. C: contact parameter. $L50_a$ and SR_a (Selection Range): selection parameters considering all the clams (available selectivity). $L50_c$ and SR_c: selection parameters considering only the clams that effectively make contact with the dredge. DOF: degree of freedom. *: undefined. Values in parentheses indicate the Efron 95 % confidence intervals.

	SP	C	$L50_a$	SR_a (mm)	$L50_c$	SR_c	p-value	Model deviance	DOF
3 min	0.87 (0.85−0.90)	0.70 (0.58−0.95)	19.11 (17.72−20.56)	* (*−9.45)	20.13 (18.54−21.59)	2.38 (0.1−6.42)	0.02	48.79	24
6 min	0.86 (0.80−0.90)	0.86 (0.60−1.00)	17.54 (15.09−20.73)	5.67 (*−8.50)	18.19 (15.15−21.22)	4.49 (0.39−8.28)	<0.01	109.36	23
9 min	0.92 (0.90−0.95)	0.78 (0.61−1.00)	19.17 (16.91−22.32)	6.17 (*−10.10)	20.07 (17.03−23.39)	3.41 (0.1−8.8)	<0.01	64.35	23
pooled data	0.89 (0.86−0.92)	0.75 (0.62−0.92)	18.92 (17.65−20.36)	* (*−9.13)	19.91 (18.58−21.19)	3.04 (1.24−6.78)	<0.01	109.47	24

subsequently applied the *CLogit* model to the pooled data considering all the 18 hauls, regardless of the tow duration. The resulting selectivity curve with CIs derived from the double bootstrap is represented in Fig. 6, and the associated estimated parameters are listed in Table 4. On average, C was 0.75 and SP 0.89; $L50_a$ was 18.92 mm, while $L50_C$ and SR_C were 19.91 and 3.04 mm, respectively.

The regression parameters derived from the shell morphometric relationships were used for checking the maximum height and width that allowed a clam to pass through the average bar spacing of the gear (11.5 mm), since the escape process mainly depends on the clam orientation in these two sides of the shell. We demonstrated that the interval between these two measures (vertical red lines, Fig. 6) is perfectly included into the size selection range of the selectivity curve. On the contrary, clams with a height lower than bar spacing were able to escape through both the orientations, while clams with a width higher than bar spacing could not pass in any way through the metal bars of the cage.

The size structures of both the total population encountered and the population retained by the dredge are represented in Fig. 7, with vertical red lines representing the actual (22 mm) and the previous (25 mm) MCRS. The respective proportions of clams caught by the dredge (test compartment) out of the total population contacting the gear (control compartment) are listed in Table 5. Overall, the dredge had a great catch efficiency, being able to retain, on average, 78.99% in number (*Nr*) and 89.37% in weight (*We*) of the total population of clams encountered. Moreover, the average percentages of undersized clams retained decreased from 69.03 to 46.98% (*Nr*) and from 79.73 to 54.43% (*We*) when lowering the MCRS from 25 to 22 mm. On the contrary, while the average percentage of the oversized clams retained was almost 100% (*Nr* and *We*) considering the 25 mm MCRS, it decreased to around 96% (*Nr* and *We*) if we considered the 22 mm MCRS (Table 5). Finally, the clams discard ratio fell from 58.32% to 20.41% (*Nr*) lowering the MCRS from 25 to 22 mm, and this difference was more pronounced using the percentages in weight (from 44.78% to 10.40%), because of the nonlinear length-weight regression.

4. Discussion

Scientific studies on the benthic impact, discards, and selectivity of the hydraulic dredge should be given priority for management purposes in the striped venus clam fishery. The impact of hydraulic dredging on the benthic community is well discernible (Morello et al., 2006; Vasapollo et al., 2020), although the species belonging to these soft bottoms are already naturally adapted to constant environmental stress and exceptional phenomena (in particular, significant wave movements, strong currents). The proportion of discards (small clams and other species) produced by this fishery is estimated to be high, reaching almost 50% of total catch, with 30% of which is composed of small individuals of *C. gallina* (Morello et al., 2005b). Regarding the selectivity, the first size selection process carried out by the dredge during trawl under commercial conditions had never been explored, contrary to that of the

vibrating sorting sieves (Sala et al., 2017). The present study represents the first, to our knowledge, to fill this gap, through assessing the selectivity of the gear at different haul durations.

The analyses demonstrated that a clogging phenomenon occurred in the dredge, as it was hypothesized by Carlucci et al. (2015) and Sala et al. (2017) because not all the clams caught had come into contact with the metal bars of the cage, thus not creating the conditions for a size dependent escape process to occur. We applied this selectivity contact concept through the *CLogit* model, which provided a better fit to the data than the traditional *Logit* model, after comparing the AIC values obtained. The *CLogit* model allowed us to calculate the fraction C of the striped venus clams that were effectively size sorted.

The causes of clogging could be multiple: presence of thickened sand and mud that are not suspended by the pressure water jets; presence of large amounts of shells and other benthonic organisms (non-target molluscs, polychaetes, crustaceans and sea urchins; Morello et al. (2005a, b, 2006)); presence of large quantities of the target species which gradually accumulate in the cage.

Contrary to what suggested by Carlucci et al. (2015), the increasing of the tow duration (from 3 to 6 and 9 min) did not have significant effect neither on C nor on selectivity parameters (*L50* and *SR*, respectively). Although selectivity is not supposed to change within the range of the durations tested, the results could be different for longer hauls (> 15 min), which are carried out occasionally due to several reasons, such as favorable fishing conditions (i.e. optimal sediment type and sea conditions) or scarce availability of the resource (DGPEMAC, 2019).

Both the $L50_a$ and $L50_C$ values reported for the pooled data (considering all the 18 hauls) were below the actual MCRS of 22 mm. These results underline that it is not sufficient to carry the selection on the seabed, and stress the importance of the additional size selection process carried out on board by the sorting sieves. Sala et al. (2017) demonstrated that it is possible to obtain a satisfactory selection (low values of the *SR* and almost knife-edge logistic curve) using specific hole diameters on the grids composing the sieves, which can be changed according to the MCRS set for the species. Although the sorting sieves are potentially able to ensure less than 5% retention of undersized individuals (Sala et al., 2017), the high proportion of the small clams that are returned to the sea after the mechanical sorting could be subjected to physiological stress (Morello et al., 2005b), and physical damage (Moschino et al., 2003). Nevertheless, clams show high potential of survivability after fishing operations (STECF, 2020), but the high and prolonged fishing effort on the same grounds (multiple criss-crossed trawl marks on bottoms; Lucchetti and Sala, 2012) should not be overlooked, as clams may be harvested up to 20 times a year (Morello et al., 2005b). According to Ballarin et al. (2003), this repeated disturbance caused by dredging may weaken the undersized clams, making them more susceptible to pathogens, predators and environmental stressors. In this respect, our findings showed that when the 22 mm MCRS is applied, the percentage of the undersized clams caught, and thus the discard ratio, markedly decreased from the situation with the 25 mm
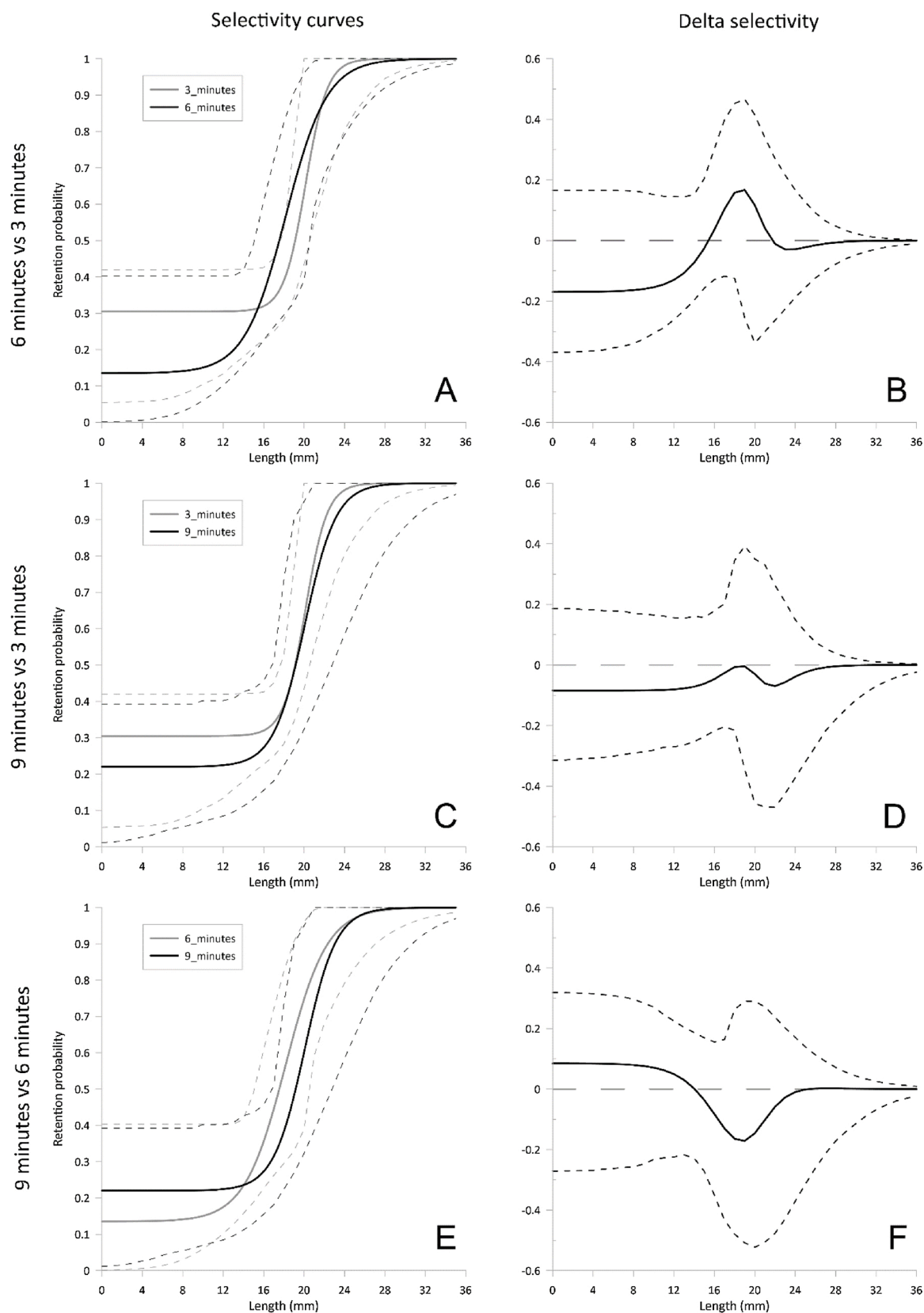
Fig. 5. Comparisons between the different haul durations: the left column (A, C, E) shows the selectivity curves (black and grey full lines) with confidence intervals (dashed lines). The right column (B, D, F) shows the differences between the two selectivity curves compared (delta plot).
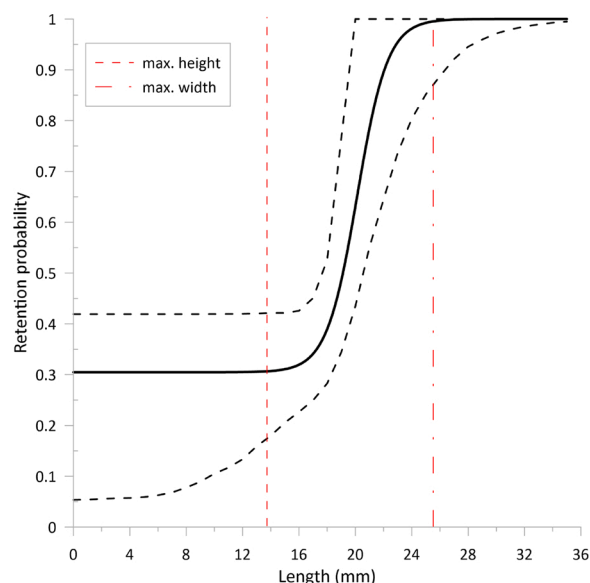
Fig. 6. Selectivity curve for the pooled data (black full line) with confidence intervals (stippled lines). The two vertical red lines show the maximum height and width that allowed a clam to pass through the average bar spacing of the gear (11.5 mm), since the escape process mainly depends on the clam orientation in these two sides of the shell.
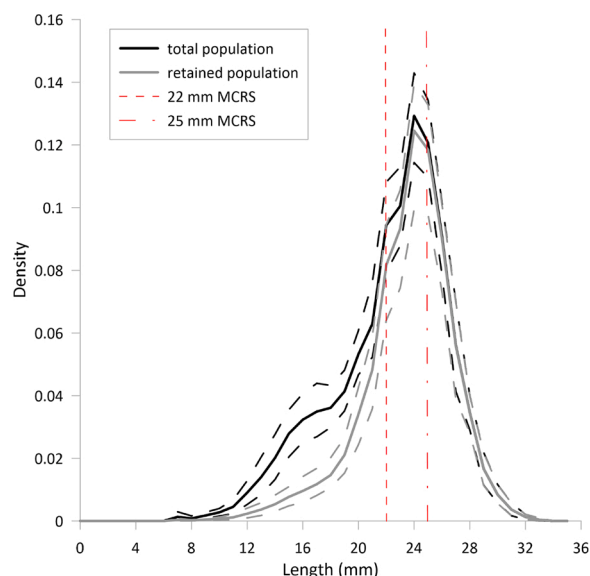

Fig. 7. Density functions of the size structure of the population present at sea bed contacting the gear (black full line), and of the effective population retained by the dredge (grey full line). Both curves are represented with confidence intervals (dashed lines). The two vertical red lines show the actual (22 mm) and the previous (25 mm) MCRS.

MCRS applied. As a consequence, the temporary reduction of the MCRS along the Italian coasts (Commission Delegated Regulation 2376/2016) would lead to a lesser fishing time spent to reach the daily quota of 400 kg of target-sized clams per each fishing vessel (DGPEMAC, 2019), and thus a decreased number of times a given area is swept. Therefore, a reduced impact on the associated benthic community and generally on the seabed is expected, thus favoring the recovery (Vasapollo et al., 2020).

The reduction of the MCRS is not incompatible with the length of first maturity (LFM) of about 15–17 mm, that is reached by the species in the first year of life, as stated for Atlantic Ocean (Gaspar et al., 2004), Marmara Sea (Deval, 2001) and Adriatic Sea (Bargione et al., 2020). Therefore, a clam of 22 mm, which is around 2 years old, has already theoretically had the chance to reproduce. Despite this, the scientific community, together with the fishing sector, aim to bring the MCRS back to 25 mm in the next future (DGPEMAC, 2019). In fact, larger clams have a greater reproductive capacity, which guarantee a larger recruitment and a stronger population size structure (Delgado et al., 2013), and have a higher economic value that leads to a more competitive product on the market (Spagnolo, 2007).

Considering the LFM, the results here displayed for the selectivity of the dredge showed that the gear seems to be able to avoid the catch of the smallest immature individuals. Nevertheless, the average total catch efficiency of the gear found in this study is very high, and in line with other works (80–100 %; Romanelli et al., 2009). To reduce direct and indirect mortality of the undersized clams due to mechanical sieving, Scarcella and Cabanelas (2016) suggested to improve the hydraulic dredges selectivity through increasing the width between the bars of the cage. However, further works are needed to determine how the selectivity changes with the increasing of bar spacing. The possible outcomes, together with the results presented in this paper, could be used for updated limitations regarding bar spacing, since at present the regulation is supported by dated scientific studies carried out with sorting equipment in the laboratory (Froglia and Gramitto, 1981), without reflecting the actual selection process at seabed.

Future works should also include other additional factors that are known to affect dredge selectivity, such as the technical properties of the dredge (blade length and angle, dredge weight, water pressure on the nozzles), other operational factors than tow duration (i.e. towing speed) and environmental conditions (sea state, type of sediment).

Author contributions

AL, MV and AP conceived and performed research; MV and AP collected data; AP and BH analyzed data; AP wrote the paper with support of BH, MV, AL, GB and CV. AL was the scientific responsible of the research.

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Table 5

Percentages of both total clams and clams below and above MCRS (22 and 25 mm), caught by the dredge (test compartment) out of the total population encountered (control compartment), and the subsequent discard ratio (in number *Nr* and weight *We*). Values in parentheses indicate the Efron 95 % confidence intervals.

%	22 mm		25 mm	
	Nr	We	Nr	We
Total	78.99 (64.46−85.88)	89.37 (74.91−94.34)	78.99 (64.46−85.88)	89.37 (74.91−94.34)
Below MCRS	46.98 (35.68−58.29)	54.43 (40.70−66.90)	69.03 (56.83−81.24)	79.73 (62.09−88.36)
Above MCRS	95.72 (79.70−99.71)	96.56 (82.13−99.79)	98.98 (87.86−100.00)	99.08 (88.42−100.00)
Discard ratio	20.41 (17.21−23.82)	10.40 (8.65−12.19)	58.32 (55.07−61.25)	44.78 (41.59−47.67)

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgments

References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Automat. Contr. 19, 716–723.

Ballarin, L., Pampanin, D.M., Marin, M.G., 2003. Mechanical disturbance affects haemocyte functionality in the Venus clam Chamelea gallina. Comp. Biochem. Physiol. 136, 631–640. https://doi.org/10.1016/S1095-6433(03)00216-2.

Bargione, G., Vasapollo, C., Donato, F., Virgili, M., Petetta, A., Lucchetti, A., 2020. Age and growth of striped venus clam Chamelea gallina (Linnaeus, 1758) in the mid-western Adriatic Sea: a comparison of three laboratory techniques. Front. Mar. Sci. 7. https://doi.org/10.3389/fmars.2020.582703.

Carlucci, R., Piccinetti, C., Scardi, M., Del Piero, D., Mariani, A., 2015. Valutazione Degli Effetti Sulla Risorsa Vongole Dell'eventuale Ridefinizione Della Taglia Minima Ed Una Migliore Gestione Biologica E Commerciale Del Prodotto. Report Progetto di Ricerca Coordinato per il MIPAAF (In Italian).

Commission Delegated Regulation (EU) 2376/2016, 2016. Council regulation establishing a discard plan for mollusc bivalve Venus spp. in the Italian territorial waters. Off. J. Eur. Union, pp. 48–49.

Delgado, M., Silva, L., Juárez, A., 2013. Aspects of reproduction of striped venus Chamelea gallina in the Gulf of Cádiz (SW Spain): implications for fishery management. Fish. Res. 146, 86–95. https://doi.org/10.1016/j.fishres.2013.04.005.

Deval, M.C., 2001. Shell growth and biometry of the striped venus Chamelea gallina (L) in the Marmara Sea, Turkey. J. Shellfish Res. 20, 155–159.

DGPEMAC, 2019. Piano di gestione nazionale per le attività di pesca con il sistema draghe idrauliche e rastrelli da natante. Public Law No. 9913, 17/06/2019. Italian Ministry for Agricultural, Food and Forestry Policies, Roma.

Efron, B., 1982. The Jackknife, the Bootstrap and Other Resampling Plans. Society for Industrial and Applied Mathematics (SIAM).

Eigaard, O.R., Herrmann, B., Nielsen, J.R., 2012. Influence of grid orientation and time of day on grid sorting in a small-meshed trawl fishery for Norway pout (Trisopterus esmarkii). Aquat. Living Resour. 26, 15–26. https://doi.org/10.1051/alr/2011152.

European Regulation (EU) 1967/2006, 2006. Council regulation concerning management measures for the sustainable exploitation of fishery resources in the Mediterranean Sea. Off. J. Eur. Union 75.

FAO, 2018. The State of Mediterranean and Black Sea Fisheries. General Fisheries Commission for the Mediterranean, Rome.

Froglia, C., 1989. Clam fisheries with hydraulic dredges in the Adriatic Sea. J. Caddy (editor). Mar. Invertebr. Fish. J. Wiley 507–524.

Froglia, C., Gramitto, E., 1981. Considerazioni sulla selettività dei dispositive di setacciatura utilizzati nella Pesca delle vongole (Venus gallina L.) (in Italian). Quad. Lab. Tecnol. Pesca 3, 37–46.

Gaspar, M.B., Castro, M., Monteiro, C.C., 1999. Effect of tooth spacing and mesh size on the catch of the Portuguese clam and razor clam dredge. ICES J. Mar. Sci. 103–110. https://doi.org/10.1006/jmsc.1998.0423.

Gaspar, M.B., Santos, M.N., Vasconcelos, P., Monteiro, C.C., 2002. Shell morphometric relationships of the most common bivalve species (Mollusca : bivalvia) of the Algarve coast (southern Portugal). Hydrobiologia 73–80. https://doi.org/10.1023/A:1021009031717.

Gaspar, M.B., Leitão, F., Santos, M.N., Sobral, M., Ch, A., 2003. Size selectivity of the Spisula solida dredge in relation to tooth spacing and mesh size. Fish. Res. 60, 561–568. https://doi.org/10.1016/S0165-7836(02)00140-6.

Gaspar, M.B., Pereira, A.M., Vasconcelos, P., Monteiro, C.C., 2004. Age and Growth of Chamelea Gallina from the Algarve Coast (Southern Portugal): Influence of Seawater Temperature and Gametogenic Cycle on Growth Rate, Vol. 70. Journal of Molluscan Studies. The Malacological Society of London, pp. 371–377.

Herrmann, B., Sistiaga, M., Nielsen, K.N., Larsen, R.B., 2012. Understanding the size selectivity of redfish (Sebastes spp.) in North Atlantic Trawl Codends. J. Northwest Atl. Fish. Sci. 44, 1–13. https://doi.org/10.2960/J.v44.m680.

Herrmann, B., Sistiaga, M., Larsen, R.B., Nielsen, K.N., 2013. Size selectivity of redfish (Sebastes spp.) in the Northeast Atlantic using grid-based selection systems for trawls. Aquat. Living Resour. 120, 109–120. https://doi.org/10.1051/alr/2013051.

Herrmann, B., Krag, L.A., Krafft, B.A., 2018. Size selection of Antarctic krill (Euphausia superba) in a commercial codend and trawl body. Fish. Res. 207, 49–54. https://doi.org/10.1016/j.fishres.2018.05.028.

Italian Ministerial Decree 22/12, 2000. Decreto Ministeriale 22 Dicembre 2000. Disciplina della pesca dei molluschi bivalvi. Italian Ministry for Agricultural, Food and Forestry Policies (In Italian).

Italian Ministerial Decree 27/12, 2016. Decreto Ministeriale 27 Dicembre 2016. Adozione del Piano Nazionale di Gestione dei rigetti degli stock della vongola Venus spp. (Chamelea gallina). Italian Ministry for Agricultural, Food and Forestry Policies (In Italian).

Kim, I.O., Mituhasi, T., Jo, T.H., Park, C.D., Tokai, T., 2005. Effect of tooth spacing on the contact selection and available selection of a dredge for the equilateral Venus clam Gomphina melanaegis. Fish. Sci. 71, 713–720. https://doi.org/10.1111/j.1444-2906.2005.01020.x.

Larsen, R.B., Herrmann, B., Sistiaga, M., Brčić, J., Brinkhof, J., Tatone, I., 2018. Could green artificial light reduce bycatch during Barents Sea Deep-water shrimp trawling? Fish. Res. 204, 441–447. https://doi.org/10.1016/j.fishres.2018.03.023.

Lucchetti, A., Sala, A., 2012. Impact and performance of Mediterranean fishing gear by side-scan sonar technology. Can. J. Fish. Aquat. Sci. 69, 1806–1816. https://doi.org/10.1139/f2012-107.

Melli, V., Herrmann, B., Karlsen, J.D., Feekings, J.P., Krag, L.A., 2020. Predicting optimal combinations of by-catch reduction devices in trawl gears: a meta-analytical approach. Fish Fish. Oxf. (Oxf) 21, 252–268. https://doi.org/10.1111/faf.12428.

Mituhasi, T., Kitakado, T., Hu, F., Tokai, T., 2005. Modelling the contact probability and size-selectivity of toothed dredges. Fish. Sci. 703–712. https://doi.org/10.1111/j.1444-2906.2005.00996.x.

Morello, E.B., Froglia, C., Atkinson, R.J.A., Moore, P.G., 2005a. Impacts of hydraulic dredging on a macrobenthic community of the Adriatic Sea, Italy. Can. J. Fish. Aquat. Sci. 2087, 2076–2087. https://doi.org/10.1139/F05-122.

Morello, E.B., Froglia, C., Atkinson, R.J.A., Moore, P.G., 2005b. Hydraulic dredge discards of the clam (Chamelea gallina) fishery in the western Adriatic Sea, Italy. Fish. Res. 76, 430–444. https://doi.org/10.1016/j.fishres.2005.07.002.

Morello, E.B., Froglia, C., Atkinson, R.J.A., Moore, P.G., 2006. Medium-term impacts of hydraulic clam dredgers on a macrobenthic community of the Adriatic Sea (Italy). Mar. Biol. 401–413. https://doi.org/10.1007/s00227-005-0195-y.

Moschino, V., Deppieri, M., Marin, M.G., 2003. Evaluation of shell damage to the clam Chamelea gallina captured by hydraulic dredging in the Northern Adriatic Sea. ICES J. Mar. Sci. 3139, 393–401. https://doi.org/10.1016/S1054.

Olsen, L., Herrmann, B., Sistiaga, M., Grimaldo, E., 2019. Effect of gear soak time on size selection in the snow crab pot fishery. Fish. Res. 214, 157–165. https://doi.org/10.1016/j.fishres.2019.02.005.

Rasband, W.S., 2018. ImageJ. Available from. US National Institutes of Health, Bethesda, Maryland, USA. https://imagej.nih.gov/ij/.

Romanelli, M., Cordisco, C.A., Giovanardi, O., 2009. The long-term decline of the Chamelea gallina L. (Bivalvia : Veneridae) clam fishery in the Adriatic Sea: is a synthesis possible? Acta Adriat. 50, 171–204.

Sala, A., Brcic, J., Herrmann, B., Lucchetti, A., Virgili, M., 2017. Assessment of size selectivity in hydraulic clam dredge fisheries. Can. J. Fish. Aquat. Sci. 74, 339–348. https://doi.org/10.1139/cjfas-2015-0199.

Scarcella, G., Cabanelas, A.M., 2016. Research for PECH Committee - the Clam Fisheries Sector in the EU - the Adriatic Sea Case. Directorate-general for Internal Policies.

Spagnolo, M., 2007. The decommissioning scheme for the Italian clam fishery: a case of success, in: fisheries buybacks. In: Curtis, R., Squires, D. (Eds.), Fisheries Buybacks. Blackwell Publishing. Wiley Online Library, pp. 133–144.

Stagioni, M., 2010. Considerations on minimum commercial size of Chamelea gallina (L.). Biol. Mar. Mediterr. 17, 352–353.

STECF, 2020. Scientific, Technical and Economic Committee for Fisheries. 62Rrd Plenary Report – Written Procedure (PLEN-20-01).

Vasapollo, C., Virgili, M., Bargione, G., Petetta, A., 2020. Impact on macro-benthic communities of hydraulic dredging for razor clam Ensis minor in the Tyrrhenian Sea. Front. Mar. Sci. https://doi.org/10.3389/fmars.2020.00014.

Wileman, D.A., Ferro, R.S.T., Fonteyne, R., Millar, R.B., 1996. Manual of methods of measuring the selectivity of towed fishing gears. ICES. Coop. Res. Rep. 132.