Canadian Journal of Fisheries and Aquatic Sciences
Journal canadien des sciences halieutiques et aquatiques

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Journal:	<i>Canadian Journal of Fisheries and Aquatic Sciences</i>
Manuscript ID	cjfas-2015-0199.R3
Manuscript Type:	Article
Date Submitted by the Author:	30-Jun-2016
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Keyword:	FISHERY MANAGEMENT < General, FISHING GEAR < General, FISH PROCESSING < General, MARINE FISHERIES < General, STATISTICAL ANALYSIS < General

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Assessment of size selectivity in hydraulic clam dredge fisheries

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Keywords

Hydraulic dredge capture efficiency; clam selectivity; *Chamelea gallina*.

Abstract

In hydraulic dredge clam fisheries the onboard mechanical sorting can be considered as the main catch selection process. The catch is mechanically sorted by a sieve made up of a series of successive grids with holes of decreasing diameter. The effect of the grid hole diameter and sorting speed of the vibrating sieve of a hydraulic dredger was investigated in a field study to determine its clam selection properties and to formulate proposals aimed at improving fishery management. Data analysis demonstrates that it is technically impossible to achieve a knife-edge selection and that there is scope for improving the size selection process, for instance by increasing grid hole diameter, which however can be accompanied by a reduced catch of both undersize individuals and commercial sizes. An increase in the hole diameter to 21.71 mm, while ensuring less than 5 % retention of undersize individuals would entail in retention of 67 % of the commercial sizes. The modelling approach applied can be extended to investigations of other dredge gear types and non-mobile benthic species.

Introduction

The striped venus clam, *Chamelea gallina*, is a bivalve mollusc typically found in coastal sandy and muddy-sandy areas at depths between 2 and 12 m (Morello et al. 2006). The advent of modern hydraulic dredges has led to more intense exploitation, making the fishery economically valuable, but in some areas it results in overexploitation (Morello et al. 2005).

The hydraulic dredge used to harvest clams consists of a 3 m wide metal cage whose bottom part is made of metal rods; the cage is mounted on two sledge runner skids to prevent it from digging into the sediment (Figure 1). In front of the cage, whose lower part is fitted with a scraper blade, a hose connected to a centrifugal water pump ejects pressurised water from nozzles placed at the dredge mouth and inside the cage, to dislodge the marine organisms living in sediment and facilitate their catch. At the end of the tow, the cage is hauled on board and its contents are tipped into a collecting box (Lucchetti and Sala 2012). The catch is sorted mechanically into different commercial classes by a vibrating sieve, which consists of multiple sieving grids (Figure 2). All unwanted material is directly thrown back into sea.

Figure 1.

Figure 2.

Selection is carried out either on the seabed, by the dredge itself, or on board, using the sieve grids. As in trawls, where size selectivity depends on codend mesh size, dredge size selection depends both on metal rod spacing on the bottom part of the cage and on grid hole diameter (Figure 2). However, Gaspar et al. (2003) reported that variation in the cage characteristics did not change the size-structure of the individuals caught in two bivalve fisheries. According to Kim et al. (2005), this is due to the fact that the dredges become clogged with sediment during the tow. Since the material collected by the dredge is subsequently sieved on board by the grids, mechanical sorting by the vibrating sieve can be considered as the main catch selection process. In general, sieves consist of a

series of successive grids with decreasing hole diameter (Figure 2). The holes in the top grid, which receives the bulk of the material, are usually > 32 mm in diameter: they block the larger organisms, which are immediately discarded, while all clams and any organisms having a similar diameter pass into the subsequent grids.

The primary goal of this field study was to refine estimates of the combined effect of dredging and sieving on clam size selectivity, to estimate the capture efficiency for clams in hydraulic dredges, and to help fisheries managers meet the restrictions imposed by legislations.

This field study, which investigates the retention of fraction of striped venus clam above and below an MLS (Minimum Landing Size) of 25 mm (EC Reg. 1967/2006), provides useful data for the design of improved vibrating sieves that maximize commercial size selection efficiency for a fixed rate of retention of undersize individuals.

The selectivity estimates obtained from our tests have the potential to be extended to commercial dredge-sieve systems with a similar design from different areas and fisheries.

Materials and methods

Characteristics of the vessel, hydraulic dredge and vibrating sieve

The field study took place in the Northern and Central Adriatic Sea (Mediterranean) during July 2012 aboard a fishing vessel with an overall length of 14 m, tonnage 12 GT, and 110.3 kW engine power. The dredge mouth was 278 cm wide and 40 cm high. The vibrating sieve consisted of 2 filters and 3 grids whose hole diameter was as follows: first filter, 32.5 mm; first grid, 21.5 mm; second grid, 21.1 mm; third grid 20.3 mm; final filter, 10.5 mm (Figure 3). The function of the top filter is to block bulky material and debris. Size sorting is achieved by the three successive grids with decreasing hole sizes. The first two can select commercial-size clams while the third sizes < 21 mm; the final filter selects the even smaller individuals. The first and last filter provide sieve stability during vibration.

Figure 3.

Study protocol

The experiment was conducted at three different vibrating speeds, which were directly proportional to the rotational speed of the main engine. The speeds tested were 1180, 1210, and 1230 RPM (revolutions per minute). Since during commercial fishing cruises standard vibrating sieve speed is around 1210 RPM, the experiments assessed the effect of sorting speed on sieve size selectivity both above and below such standard speed. As shown in Figure 3, sorting involved that the content of each cage ($P0$) was divided into 6 fractions (*debris*, n_1 - n_4 , and $P5$), as follows: 1) *debris*: fraction containing bulky material and a few large organisms retained by the top filter (32.5 mm holes); 2) n_1 : fraction containing commercial-sized clams retained by the first grid (21.5 mm holes); 3) n_2 : fraction containing individuals smaller than the commercial size retained by the second grid (21.1 mm holes); 4) n_3 : fraction retained by the third grid (20.3 mm holes); 5) n_4 : fraction retained by the final filter (10.5 mm holes); and 6) $P5$: material not retained by any filter or grid.

Biometric measurements were performed by video analysis as described by Stagoni (2010). Individuals were subdivided into groups of 60-80, placed on a table, and photographed by backlight illumination with a digital camera mounted on the table. Photographs were processed with *ImageJ* analysis software (Rasband 2010), which measures the maximum length of individual clams (parameter *Feret X*, the longest distance between any two points along the selection boundary). To minimise any error due to lens distortion, calibration took into account the known length of the central clam (Sala et al. 2014). Biometric measurements were performed to an accuracy of 0.5 mm.

Statistical analysis of the size selectivity of each grid of the vibrating sieve

The size selectivity of each grid, *grid 1*, *grid 2* and *grid 3* (Figure 3), was assessed using the covered codend method described by Wileman et al. (1996) by analysing the ratio of the material it retained to the total amount of material it received, the latter being the sum of retained and released

material. Similar to the covered codend method (Sala et al. 2006; 2007; 2008), any material passing through a grid was caught by the subsequent grids or by the final filter (Figure 3). The 10.5 mm hole diameter mm was about half of those of the grids 1, 2, and 3; therefore the size selection of each grid could be assessed by the covered codend method without considering the P5 fraction - i.e. the very small clams that passed through the final filter - because there would be no overlap in the size selection of the final filter and the main grids. Fraction P5 was therefore ignored in data collection. The sizes of all individuals in fractions n_1 to n_4 (Figure 3) were measured to assess the size selection of each grid. Their maximum length was used to quantify the size of each clam in fractions n_1 - n_4 . For each fraction, clams were sorted into size classes ℓ containing all the clams whose length was ± 0.25 mm with reference to length ℓ . For each length class ℓ the number of clams was respectively $n_{1\ell}, n_{2\ell}, n_{3\ell}$ and $n_{4\ell}$. Consequently, the size-dependent experimental retention probability $r(\ell)$ of each grid is given by the following ratios:

$$\begin{cases} r_{1\ell} = \frac{n_{1\ell}}{n_{1\ell} + n_{2\ell} + n_{3\ell} + n_{4\ell}} \\ r_{2\ell} = \frac{n_{1\ell} + n_{2\ell}}{n_{1\ell} + n_{2\ell} + n_{3\ell} + n_{4\ell}} \\ r_{3\ell} = \frac{n_{1\ell} + n_{2\ell} + n_{3\ell}}{n_{1\ell} + n_{2\ell} + n_{3\ell} + n_{4\ell}} \end{cases} \quad (\text{Eq. 1})$$

The expression for $r_{2\ell}$ applies the assumption that a clam which was retained by grid 1, that has a bigger hole diameter than grid 2, would also have been retained by grid 2 if it arrived to this grid and is sieved without grid 1. A similar assumption is applied for $r_{3\ell}$ but here regarding the clams that was retained by grid 1 or grid 2 during the sequential sieving.

118 The retention probability $r(\ell)$ was modelled for each grid by means of the logistic selectivity
 119 curve: $r(\ell) = \frac{\exp(\ln(9) \times (\ell - L50) / SR)}{1 + \exp(\ln(9) \times (\ell - L50) / SR)}$, where $r(\ell)$ is the probability that a clam of length ℓ
 120 that came in contact with the grid was retained (Wileman et al. 1996). L50 and SR are the grid
 121 selection parameters considered. L50 is the length of clams that have a 50 % probability of being
 122 retained by the grid after coming in contact with it. SR is the difference in length of individuals
 123 having respectively 75 % and 25 % probability of being retained by the grid. The term $\ln(9)$ is the
 124 natural logarithm of 9 and appears in the formula for the logistic selection curve when this is
 125 described in terms of the parameters L50 and SR (consult Wileman et al. 1996 for further details).
 126 In addition to the logistic curve, which is symmetrical around L50, an asymmetric alternative was
 127 also initially considered by fitting the Richard's curve (Wileman et al. 1996) to the retention data:

128 $r(\ell) = \left(\frac{\exp(\ln(9) \times (\ell - L50) / SR)}{1 + \exp(\ln(9) \times (\ell - L50) / SR)} \right)^\delta$. In addition to parameters L50 and SR, the Richard curve
 129 includes an additional parameter δ that models the extent of asymmetry. However, an initial
 130 inspection on the analysis of the data revealed that in the Richard curve fits in general resulted in
 131 higher AIC values (Akaike 1974) than for the logistic curve; therefore the logistic curve was
 132 preferred for the data analysis.

133 Analysis of clam size selection in the vibrating sieve followed a two-step procedure. First, L50 and
 134 SR values were obtained for each sieving process and grid by fitting the logistic curve to the data
 135 $(n_{1\ell}, n_{2\ell}, n_{3\ell}, n_{4\ell})$ maximizing the likelihood for the observed data, in line with the
 136 recommendations described for the covered codend method (Wileman et al. 1996). Evaluating the
 137 ability of the logistic curve to describe the data sufficiently well was based on inspecting the fit
 138 statistics, i.e., the p -value and the model deviance versus the degrees of freedom (DOF), following
 139 the procedures described in Wileman et al. (1996). This p -value quantifies the probability to obtain

at least as large a discrepancy between the fitted model and experimental data as observed by coincidence. In case of a poor fit statistics (p -value being <0.05 ; deviance being $\gg \text{DOF}$), the residuals were inspected to determine whether the poor result was due to structural problems when describing the experimental data using the model or if it was due to overdispersion in the data (Wileman et al. 1996).

Next in the second step of the analysis, the individual L50 and SR values from each sieving process, their covariance's matrix $\mathbf{R}$, the hole diameter m and the vibrating speed s were used to obtain a predictive model for sieving size selection. The covariance's matrix $\mathbf{R}$ represents the measure of the uncertainty in estimation and is called within sieving variation. This second step follows the procedure described by Fryer (1991) and considers both random and fixed effect for size selection in the sieving process besides the uncertainty in the estimation in the first step (within sieving variation). The random variation of selection parameters (L50, SR) between sieving processes is quantified by a 2x2 between sieving variation matrix $\mathbf{D}$. Matrix elements D_{11} and D_{22} quantifies the between sieving's variation in respectively L50 and SR, whereas D_{12} quantifies the covariation between L50 and SR. Since we are interested in predicting the effect of grid hole diameter and vibrating speed on the size selection of a grid, the following general model was used as the reference (Eq. 2) for the predictive model of how the mean value for a sieving process is expected to depend on the fixed effects:

$$\begin{aligned} L50_{mean} &= a_0 + a_1 \times m + a_2 \times s + a_3 \times m \times s \\ SR_{mean} &= b_0 + b_1 \times m + b_2 \times s + b_3 \times m \times s \end{aligned} \quad (\text{Eq. 2})$$

The values for parameters $a_0 \dots a_3$ and $b_0 \dots b_3$ were then estimated based on the full set of L50, SR, m , and s values for each grid and sorting. Besides Eq. 2, the 255 additional models that can be derived from it - by leaving out one or more parameters simultaneously - were also considered as candidates for the predictive model. Model selection was then performed based on the AIC-values

(Akaike 1974) calculated according to the procedure described by Wienbeck et al. (2011). To check that the selected model was capable of representing the trends of the data on which it was based, the L50 and SR values calculated for each grid and sorting were plotted with the 95 % confidence intervals (95 % CI) as a function of the respective grid hole diameters against the corresponding data obtained from application of the predictive model. The latter considered both within-sieving and between-sieving variation in size selection in the upper and lower CI for the predicted L50 and SR values. Thus the upper and lower range values of the 95 % CI of the estimated total variation of the predicted selection parameters (*limL50* and *limSR*) were calculated using the following equation:

$$\begin{aligned} \lim L50 &= L50_{mean} \pm 1.96 \times \sqrt{\text{var } L50_{mean} + D_{11}} \\ \lim SR &= SR_{mean} \pm 1.96 \times \sqrt{\text{var } SR_{mean} + D_{22}} \end{aligned} \quad (\text{Eq. 3})$$

where $L50_{mean}$ and SR_{mean} are the values estimated from the predictive model derived based on Eq. 2, and D_{11} and D_{22} are the diagonal elements of the *between-sieving variation* matrix, which models the between sieving's variation in the selectivity parameters following the description above (Fryer, 1991). The reader is referred to for additional information on this type of modelling framework. The above size selection analysis was conducted using the analysis tool SELNET (Herrmann et al. 2012; Sala et al. 2015), which implements the procedures described above according to the recommendations of Wileman et al. (1996) and Fryer (1991).

Calculation of the fraction above and below the minimum landing size retained by the grids

The mean proportions of individuals below (nP^-) and of those equal to or above (nP^+) the MLS retained by each grid (MLS: 25 mm, EC Regulation 1967/2006), and the ratio of their number ($nRatio$) were calculated for grids 1, 2 and 3. The mean proportions were obtained using the formulae reported in Eq. 4.

$$\begin{aligned}
 nP^- &= 100 \times \frac{\sum_j \left(\sum_{\ell < MLS} n_{CD\ j\ell} \right)}{\sum_j \left(\sum_{\ell < MLS} n_{CD\ j\ell} + n_{CV\ j\ell} \right)} & wP^- &= 100 \times \frac{\sum_j \left(\sum_{\ell < MLS} w_\ell \times n_{CD\ j\ell} \right)}{\sum_j \left(\sum_{\ell < MLS} w_\ell \times n_{CD\ j\ell} + w_\ell \times n_{CV\ j\ell} \right)} \\
 nP^+ &= 100 \times \frac{\sum_j \left(\sum_{\ell \geq MLS} n_{CD\ j\ell} \right)}{\sum_j \left(\sum_{\ell \geq MLS} n_{CD\ j\ell} + n_{CV\ j\ell} \right)} & wP^+ &= 100 \times \frac{\sum_j \left(\sum_{\ell \geq MLS} w_\ell \times n_{CD\ j\ell} \right)}{\sum_j \left(\sum_{\ell \geq MLS} w_\ell \times n_{CD\ j\ell} + w_\ell \times n_{CV\ j\ell} \right)} \quad (\text{Eq. 4}) \\
 nRatio &= \frac{\sum_j \left(\sum_{\ell < MLS} n_{CD\ j\ell} \right)}{\sum_j \left(\sum_{\ell \geq MLS} n_{CD\ j\ell} \right)} & wRatio &= \frac{\sum_j \left(\sum_{\ell < MLS} w_\ell \times n_{CD\ j\ell} \right)}{\sum_j \left(\sum_{\ell \geq MLS} w_\ell \times n_{CD\ j\ell} \right)}
 \end{aligned}$$

185 The sampling design used for the on board tests allowed size selectivity analysis to be performed
 186 for each grid as if in presence of two-compartment binomial data. The clams received by each grid
 187 for each sorting, j , were either caught by the grid (CD), or else they passed through it (CV) to be
 188 caught by the next grid(s) or by the final filter (see Figure 3). In practice, a two-compartment
 189 binomial data format involved that for each size class, ℓ there was a certain number of clams both
 190 in compartment CV ($n_{CV\ j\ell}$) and in compartment CD ($n_{CD\ j\ell}$), i.e. a length-dependent retention
 191 likelihood. For each haul, indicator nP^- provides an estimate of the fraction of undersize clams
 192 retained ($< MLS$), thus providing information on the size selectivity of a given grid towards the
 193 small clams of a given population. The value of nP^- should therefore be as low as possible.
 194 Similarly, indicator nP^+ provides information on the efficiency of a given grid in selecting
 195 marketable sizes ($\geq MLS$) when sorting a given population. In such case, provided that the species
 196 being analysed is a target species, nP^+ should be as high as possible (close to 100). Indicator $nRatio$
 197 is the ratio of the number of retained undersized/commercial size individuals. Therefore, when
 198 sorting a given population, the size selection properties of a grid are suited to a given MLS if the
 199 $nRatio$ is very low, approaching 0. The above indicators, calculated on the basis of the formulae of
 200 Eq. 4, are based on specimen number. Indicators based on weight (wP^- , wP^+ , $wRatio$) can also be

calculated using the same formulae. To do this, the weight w_ℓ of each individual of size ℓ was estimated according to the relationship: $\log(w) = -3.167 + 2.601 \times \log(\ell)$ (Arneri et al. 1997). Prediction of the effect of grid hole diameter on the indicators nP^- , nP^+ , $nRatio$, wP^- , wP^+ and $wRatio$ was obtained using the best predictive model derived based on Eq. 2 and the total clam population received by the vibrating sieve. It is important to clarify that such retained fractions are affected by the size composition of clam population coming into contact with the grids. Results are presented as guidelines, whose application allows identification of the sieving techniques that provide improved size selectivity. Therefore, this section describes how we applied results from the field experiments to predict the selectivity characteristics of vibrating sieves systems that were not actually field-tested.

Guidelines for the design of a more size-selective vibrating sieve

The guidelines proposed herein are based on the premise that size selection depends critically on the major technical parameter grid hole diameter. The guidelines provide information that can be used to design a vibrating sieve with improved clam size selection ability, which have the potential to be extended to similar dredge fisheries. The data presented here are critical for stock management purposes, because they allow setting the desired selection parameter ranges based on the two key technical parameters. The guidelines consist of an isometric diagram showing the isocurves of the retention probability for different clam lengths dependent on the hole diameter of the grid. The analysis considered a potential variation range for hole diameter of 20-22 mm. In addition, to provide a comprehensive analysis of size selectivity, another diagram shows graphically the size selection potential of a grid, thus providing useful information for its correct dimensioning with a

view to minimising the proportion of retained undersize clams ($< \text{MLS}$) and at the same time maximising efficiency in selecting the commercial sizes ($\geq \text{MLS}$).

Results

Selectivity of the vibrating sieve

The selectivity parameters of each replicate sorting for each grid are reported from Table A1 to Table A3 on the Appendix, while the single-sieving fitted size selection curves are shown in Figure 4. The p -value and deviance vs. degrees of freedom indicated that there were no problems in using the logistic curve to describe the retention data relating to each sorting.

Figure 4.

We examined 54 sortings (i.e. 6 replicates $\times$ 3 speeds $\times$ 3 grids). All were valid and were used to estimate the predictive model for the size selectivity of the grids. An analysis for L50 and SR was conducted according to Fryer (1991) based on the general models reported in Eq. 2 and on the other simplified forms derived from it. All models were automatically evaluated using the SELNET software. The final models are reported in Table 1 and their analytical form is reported below:

$$\begin{aligned} L50 &= a_0 + a_1 \times m_i \\ SR &= b_0 + b_1 \times m_i \end{aligned} \quad (\text{Eq. 5})$$

A significant effect of hole diameter (m) can be noted on both L50 and SR. No effect was exerted by sorting speed (s) on both parameters (Table 1). The L50 and SR predictions based on the model of Table 1 are reported in Figure 5 (continuous curves).

Table 1.

Figure 5.

The expected mean values of the size selectivity parameters (L50 and SR), calculated for each grid according to the Fryer (1991) best model, are reported in Table 2. The best selectivity performance,

highest mean value of L50 and lowest SR (Table 2), was the one of grid 1 (L50=25.01 mm, SR=1.05 mm), followed by the one of grid 2 (L50=24.29 mm, SR=1.27 mm) and grid 3 (L50=22.84 mm, SR=1.71 mm).

Table 2.

The clam fraction under the MLS (nP^-) caught by grid 1 was 11.3 (Table 2), with a selection efficiency for the commercial sizes, represented by nP^+ of 77.5 %. The $nRatio$, i.e. the ratio of undersized retained individuals to those of commercial size, was 0.15, i.e. close to 0, as it should be when the size selection properties of a grid are appropriate for a certain MLS.

The clams that were not caught by the first grid were sequentially sifted by the second, which retained an additional fraction of clams arriving at 32.8 % (nP^-) of individuals < MLS. It should be noted that besides the grid selection properties, retained fractions are also affected by the size distribution of the clam population coming into contact with the sieves. The efficiency of grid 2 (nP^+) increased to 90.1 %, since adult individuals of marketable size can be largely caught by grid 1 and subsequently by grid 2. Finally, the value of $nRatio$ confirmed the poorer selectivity of grid 2. In fact, for each retained individual of commercial size it also retained 0.31 undersized individuals (Table 2). Despite grid 3 showed the best efficiency for the commercial sizes, arriving at 97.2 % (nP^+), the small hole diameter of 20.3 mm caused the retention 71.8 % of small clams entering the vibrating sieve. With such hole diameter, for each retained commercial individual, 0.77 undersized individuals are also retained. The values calculated based on weight are not very different from those calculated in terms of number.

Vibrating sieve design guidelines

An isometric diagram was drawn based on the selectivity models reported in Table 1, to predict the size selection properties of a single grid of a vibrating sieve (Figure 6) for hole diameter ranging from 20 to 22 mm. The two vertical lines in Figure 6 mark the hole diameters > 21 mm of the first

two grids used by the fishermen to select commercial-size clams. The horizontal line marks the MLS of 25 mm. Figure 6 shows that hole diameters ranging from 21.1 to 21.5 result in a considerable retention of individuals below the MLS (e.g. 49.3 % and 77.4 % for grid 1 and 2, respectively).

Figure 6.

The nP - and nP + curves in the diagram in Figure 7 should be read together, because the optimum grid hole diameter is a trade-off between minimisation of retained undersized individuals (nP - or wP -) and the lowest acceptable efficiency in retaining commercial-sized individuals (nP + or wP +). For example, let's assume that an amount of retained undersized individuals (nP -) equal to 5 % is acceptable from the management standpoint. The grid hole diameter should be 21.71 mm. Entering this value into the diagram in Figure 7 results in a grid efficiency of 66.9 %. The same considerations apply to the weight indicators. In such case, a grid with holes 21.71 mm in diameter will retain 0.07 undersized clams for each commercial-sized individual retained ($nRatio$, Figure 7). This suggests that the design choice derives from a trade-off between size selectivity and efficiency. This scenario is summarised in Figure 7.

Figure 7.

Discussion

This field study filled some knowledge gaps in clam fishery size selectivity by applying a rigorous experimental and modelling approach to investigate the influence of vibrating sieve characteristics on clam catches and their ability to affect clam fisheries management. Regulations involving sieve characteristics are among the easiest to monitor since they enable onshore compliance inspections. No effect was exerted by the sorting speed of a vibrating sieve on clam selectivity in the speed range examined, whereas a significant effect of grid hole diameter was noted on both length of 50 % retention (L50) and selection range (SR). The present study found that the sieve could not

294 achieve knife-edge selection, in which the sieve retains all the clams not smaller than the minimum
295 landing size (MLS) and none of the clams less than the MLS. In the case of striped venus clam this
296 is 25 mm (EC Regulation 1967/2006), corresponding to individuals aged about 2 years, which have
297 therefore reproduced at least once (Frogia, 1989). However, it is interesting to note that grids with
298 a hole diameter > 21 mm demonstrated a satisfactory selection ability, with very low values of the
299 SR and almost knife-edge logistic curves. In addition, the selection properties of the first two grids,
300 which have holes measuring > 21 mm, seem to be suitable for the 25 mm MLS, because their
301 Selection Factors (SF) range from 1.15 to 1.16. The present findings indicate that there is scope for
302 improving the vibrating sieve size selection process, for instance by increasing hole diameter, which
303 however is accompanied by a reduced catch of both undersize individuals and commercial sizes.
304 Selectivity monitoring and improvement, in conjunction with responsible management of the
305 fishing effort, are essential, but insufficient by themselves for correct stock management (FAO
306 1995; Santiago et al. 2015).

307 **Future works**

308 Future work should include more research for the investigation of the effect of other parameters,
309 such as larger range of vibrating speed, amplitude and frequency of the vibration, time of sieving,
310 catch size and grids inclination, on the mechanical sorting by the vibrating sieve. Our
311 recommendation would be also to continue this work in other commercial hydraulic dredgers where
312 the vibrating sieve is made up of a series of successive grids with parallel rods instead of holes to
313 see if results are analogous.

314 Furthermore, survival studies need to be extended to the hydraulic clam dredge fisheries with the
315 implementation of a standardised methodology for the evaluation of the survival rates of undersized
316 clams that are caught and returned to the sea. This aspect should be taken into proper account by

decision-makers when addressing management policy aimed at mitigating dredging impact and sustainable harvesting of the clam stocks.

Acknowledgements

This study was funded by the Italian Ministry “*Ministero per le Politiche Agricole e Forestali, Direzione Generale della Pesca e dell’Acquacoltura*”. It does not necessarily reflect the Ministry’s views and in no way anticipates its future policy. The authors are grateful to *Word Designs* for the language revision. We acknowledge gratefully the critical comments of the editor and the reviewers, which we feel have greatly improved our manuscript.

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Table 1. Results of model application (see Eq. 2). The best model considered both *fixed* and *random effects* according to Fryer (1991). The values $a_0...a_3$ and $b_0...b_3$ of the predictive model represent how the mean L50 and SR for a sieving process are expected to depend on the fixed effects grid hole diameter m and vibrating speed s . The between sieving variation (random effect) in L50 and SR is modelled by the matrix **D**. Matrix elements D_{11} and D_{22} quantifies the between sieving's variation in respectively L50 and SR, whereas D_{12} quantifies the covariation between L50 and SR. For details see section “*Statistical analysis of the size selectivity of each grid of the vibrating sieve*” or Fryer (1991). The p -value expresses the significance level of the factor parameters; m : grid hole diameter; s : sorting speed; 95% CI: 95 % confidence interval; SE: standard error.

Statist.	Factor	Multiplier	Value	SE	95% CI		p -value
					Low	High	
L50 _{mean}	a_0	Intercept	-13.86	1.32	-16.48	-11.25	8.4E-18
	a_1	m	1.81	0.06	1.68	1.93	6.2E-50
	a_2	s	-	-	-	-	-
	a_3	$m \times s$	-	-	-	-	-
SR _{mean}	b_0	Intercept	12.90	1.11	10.70	15.09	2.9.E-20
	b_1	m	-0.55	0.05	-0.66	-0.45	9.8.E-18
	b_2	s	-	-	-	-	-
	b_3	$m \times s$	-	-	-	-	-
D	D_{11}		0.045	-	-	-	-
	D_{12}		-0.021	-	-	-	-
	D_{22}		0.026	-	-	-	-

Note: General model as defined in Eq. 2: $L50_{mean} = a_0 + a_1 \times m + a_2 \times s + a_3 \times m \times s$; $SR_{mean} = b_0 + b_1 \times m + b_2 \times s + b_3 \times m \times s$

Table 2. Size selection parameters estimated for the grid 1 (G1), grid 2 (G2) and grid 3 (G3). Mean values calculated according to Fryer model (1991). Retained length 50 % (L50), selection range (SR) with mean (Estimate). The two confidence intervals reported express the uncertainty of the mean and of the total variation considering also the effect of sieving (*between-sieving-variation*), 95% CI *mean* and *total* respectively. For each scenario, besides the retained length 50 % and selection range, the table reports the percentage of the fractions below (*nP-*) and equal to or above (*nP+*) the minimum landing size (MLS) expressed as specimen number or as specimen weight (*wP-* and *wP+*). See for details Eq. 4. The other indicators represent the ratio of retained undersized to retained marketable-size clams, considering specimen number (*nRatio*) or weight (*wRatio*).

Parameter / grid			G1	G2	G3
L50[mm]	Estimate		25.01	24.29	22.84
	95% CI	<i>mean</i>	(24.93-25.10)	(24.23-24.35)	(22.74-22.95)
		<i>total</i>	(24.59-25.44)	(23.87-24.71)	(22.41-23.27)
SR[mm]	Estimate		1.05	1.27	1.71
	95% CI	<i>mean</i>	(0.98-1.12)	(1.22-1.32)	(1.62-1.80)
		<i>total</i>	(0.73-1.37)	(0.95-1.59)	(1.38-2.04)
nP-[%]			11.3	32.8	71.8
nP+[%]			77.5	90.1	97.2
wP-[%]			12.0	34.5	73.6
wP+[%]			79.3	90.9	97.4
nRatio[-]			0.15	0.38	0.77
wRatio[-]			0.12	0.31	0.61

Figure 1. Commercial hydraulic clam dredge with dredging gear.

Figure 2. Dredge gear. Metal cage (left) on hydraulic clam dredgers. The cage is lowered and hoisted from the bow. At the end of the tow the dredge is hoisted and tipped into a large container, the collecting box (right), which in turn is emptied into a mechanical vibrating sieve for clam selection. The hydraulically operated mechanical vibrating sieve commonly consists of a first filter with holes 32.5 mm in diameter, three successive grids with holes 21.5, 21.1, and 20.3 mm in diameter, from top to bottom, and a final filter with holes 10.5 mm in diameter.

Figure 3. Clams are sorted through 3 successive grids and a top and a bottom filter. The material obtained from the vibrating sieve usually includes: *debris*: the fraction retained by the top filter (hole diameter, 32.5 mm), containing the bulkier material and a few large individuals; n_1 : fraction caught by the first grid; n_2 : fraction caught by the second grid; n_3 : fraction caught by the third grid; n_4 : fraction retained by the bottom filter; P_5 : fraction retained by none of the grids or filters. The “retention probability” (r_i) of each grid is given by the ratio of the retained fraction to the total material that entered it, which is the sum of the retained and released material.

Figure 4. Mean size selectivity curves modelled for the first grid G1; the second grid G2; and the third grid G3. The mean values were calculated according to Fryer (1991). Circle points represent the experimental data; black thick continuous and dotted grey curves indicate the mean and single-sieving fitted size selection curves; vertical grey dash-dot line represents the minimum landing size (MLS); thin dashed black curves represent the released population of clams while thick black dashed curves show the population of clams retained in the grids/sieves. The whole population of clams entering the vibrating sieve is shown on the lower-right graph.

Figure 5. Predicted selectivity parameters L50 and SR of a single grid in a vibrating sieve as function of hole diameter based on the model reported in Table 1. The direct estimates of L50 and SR of the 1st grid G1 (□), 2nd grid G2 (○), and 3rd grid G3 (Δ), are reported. Continuous lines represent the values predicted by the model, dashed lines the 95 % confidence intervals of the total variation (i.e. between-sieving variation + variation of the mean estimated value). For a clearer graphical presentation, the results were jittered along the x-axis..

Figure 6. Design guide for the sieve hole diameter. It quantifies the retention probability for different hole diameter (x-axis) and different lengths of clams (y-axis). The iso-curves represent different levels of retention probability respectively at 5, 25, 50, 75 and 95 %. The two vertical lines mark the hole diameters > 21 mm of the only first two grids used by the fishermen to select commercial-size clams. The horizontal line marks the minimum landing size (MLS) of 25 mm.

Figure 7. Isometric diagrams. Analysis of the size selection properties of a single grid as a function of hole diameter of a grid in a vibrating sieve. The indicator pairs expressed as % (nP_- and nP_+) and (wP_- and wP_+) represent respectively the mean proportion of the fractions below and equal to or above the Minimum Landing Size (MLS) in relation to specimen number and weight (see for details Eq. 4). The indicators $nRatio$ and $wRatio$ are the ratio of retained undersized/commercial size individuals in terms of specimen number and weight, respectively. The two vertical lines mark the hole diameters > 21 mm of the only first two grids (G1 and G2) used by the fishermen to select commercial-size clams. While the vertical lines GV marks the hole diameter of 21.71 mm, which results in an expected amount of retained undersized individuals (nP_-) equal to 5 %.

Table A1. Size selection parameters estimated for the 1st sieve (G1), having a hole diameter of 21.5 mm (Diam). Each value corresponds to a sorting speed (Speed), i.e. 1180, 1210, or 1230 RPM. Data were analysed according to Fryer (1991). Retention length 50 % (L50); selection range (SR); *p*-value quantifies the probability to obtain at least as large a discrepancy between the fitted model and experimental data as observed by coincidence; Deviance; degrees of freedom (DOF); L50 and SR confidence interval ($\pm$ DelL50, $\pm$ DelSR); L50 and SR standard deviation (SdL50, SdSR); covariance's matrix **R** measures the uncertainty in estimation (called within sieving variation); minimum and maximum retained length (MinL, MaxL); total number of specimens sorted; retained and released (NrTot, NrTes, NrCov).

Code	Speed	Diam	L50	SR	<i>p</i> -value	Deviance	DOF	DeIL50	SdL50	DeISr	SdSR	R			MinL	MaxL	NrTot	NrTes	NrCov
<i>Sieve-Spe-Haul</i>	[RPM]	[mm]	[mm]	[mm]				[mm]	[mm]	[mm]	[mm]	R11	R12	R13	[mm]	[mm]			
G1-1230-1	1230	21.5	25.05	0.94	0.935	11.40	20	0.07	0.03	0.09	0.04	0.001	0.000	0.002	21.5	32.0	1877	909	968
G1-1230-1	1230	21.5	25.25	1.07	0.119	26.41	19	0.07	0.03	0.09	0.05	0.001	0.000	0.002	21.5	32.0	2399	885	1514
G1-1210-1	1210	21.5	24.95	1.01	1.000	3.22	18	0.08	0.04	0.12	0.05	0.001	0.000	0.003	21.5	31.0	1422	694	728
G1-1210-1	1210	21.5	24.92	1.12	0.959	9.75	19	0.07	0.03	0.11	0.05	0.001	0.000	0.003	21.5	33.0	1827	927	900
G1-1180-1	1180	21.5	24.96	1.24	0.799	13.74	19	0.07	0.04	0.12	0.06	0.001	0.000	0.003	21.5	32.5	1868	904	964
G1-1180-1	1180	21.5	25.05	1.03	0.981	8.51	19	0.07	0.03	0.11	0.05	0.001	0.000	0.003	21.5	31.5	1710	843	867
G1-1230-2	1230	21.5	25.01	1.11	0.923	8.76	16	0.09	0.04	0.13	0.06	0.002	0.001	0.004	21.5	30.0	1275	515	760
G1-1230-2	1230	21.5	24.88	1.10	0.041	28.33	17	0.13	0.06	0.20	0.10	0.004	0.000	0.009	21.5	31.0	900	454	446
G1-1210-2	1210	21.5	24.93	1.27	0.209	20.26	16	0.09	0.04	0.14	0.07	0.002	0.000	0.004	21.5	30.0	1566	677	889
G1-1210-2	1210	21.5	24.78	1.36	0.688	13.70	17	0.10	0.05	0.17	0.08	0.002	0.000	0.006	21.5	31.0	1234	580	654
G1-1180-2	1180	21.5	24.80	1.12	0.963	7.46	16	0.09	0.04	0.13	0.06	0.002	0.000	0.004	21.5	30.0	1351	566	785
G1-1180-2	1180	21.5	24.78	1.67	0.578	15.25	17	0.12	0.06	0.24	0.11	0.003	0.001	0.012	21.5	31.5	1080	484	596
G1-1230-3	1230	21.5	24.75	1.03	0.957	9.82	19	0.07	0.03	0.10	0.05	0.001	0.000	0.002	21.5	32.0	1757	869	888
G1-1230-3	1230	21.5	24.70	1.12	0.916	10.45	18	0.06	0.03	0.10	0.05	0.001	0.000	0.002	21.5	31.0	2315	1174	1141
G1-1210-3	1210	21.5	24.88	1.14	0.641	15.30	18	0.07	0.03	0.11	0.05	0.001	0.000	0.003	21.5	31.0	2025	963	1062
G1-1210-3	1210	21.5	24.90	0.83	0.084	26.76	18	0.06	0.03	0.09	0.04	0.001	0.000	0.002	21.5	33.0	1711	857	854
G1-1180-3	1180	21.5	24.81	0.97	0.778	13.23	18	0.07	0.03	0.10	0.05	0.001	0.000	0.002	21.5	32.0	1776	828	948
G1-1180-3	1180	21.5	24.96	1.18	0.098	24.85	17	0.08	0.04	0.12	0.06	0.001	0.000	0.003	21.5	30.5	1836	807	1029

Table A2. Size selection parameters estimated for the 2nd sieve (G2). For details see caption of Table A1.

Code	Speed	Diam	L50	SR				DeIL50	SdL50	DeISR	SdSR	R			MinL	MaxL			
<i>Sieve-Spe-Haul</i>	[RPM]	[mm]	[mm]	[mm]	<i>p-value</i>	Deviance	DOF	[mm]	[mm]	[mm]	[mm]	R11	R12	R13	[mm]	[mm]	NrTot	NrTes	NrCov
G2-1230-1	1230	21.1	24.56	1.28	0.021	34.78	20	0.11	0.05	0.17	0.08	0.003	0.000	0.006	21.1	32.0	1877	1113	764
G2-1230-1	1230	21.1	24.91	1.09	0.089	27.72	19	0.06	0.03	0.10	0.05	0.001	0.000	0.002	21.1	32.0	2399	1077	1322
G2-1210-1	1210	21.1	24.56	1.00	0.991	6.95	18	0.08	0.04	0.12	0.05	0.001	0.000	0.003	21.1	31.0	1422	832	590
G2-1210-1	1210	21.1	24.50	0.99	0.108	26.84	19	0.07	0.03	0.10	0.05	0.001	0.000	0.002	21.1	33.0	1827	1110	717
G2-1180-1	1180	21.1	24.57	1.19	0.615	16.63	19	0.07	0.03	0.12	0.06	0.001	0.000	0.003	21.1	32.5	1868	1087	781
G2-1180-1	1180	21.1	24.69	1.00	0.788	13.92	19	0.07	0.03	0.11	0.05	0.001	0.000	0.003	21.1	31.5	1710	999	711
G2-1230-2	1230	21.1	24.44	1.19	0.140	22.10	16	0.09	0.04	0.15	0.07	0.002	0.000	0.005	21.1	30.0	1275	697	578
G2-1230-2	1230	21.1	24.14	1.37	0.036	28.87	17	0.17	0.08	0.26	0.13	0.006	-0.003	0.016	21.1	31.0	900	598	302
G2-1210-2	1210	21.1	24.43	1.40	0.143	21.99	16	0.09	0.04	0.15	0.07	0.002	0.000	0.005	21.1	30.0	1566	861	705
G2-1210-2	1210	21.1	24.28	1.15	0.136	23.41	17	0.09	0.04	0.14	0.07	0.002	0.000	0.004	21.1	31.0	1234	726	508
G2-1180-2	1180	21.1	24.36	0.99	0.983	6.44	16	0.08	0.04	0.12	0.05	0.001	0.000	0.003	21.1	30.0	1351	712	639
G2-1180-2	1180	21.1	24.26	1.50	0.842	11.28	17	0.11	0.05	0.21	0.10	0.003	-0.001	0.010	21.1	31.5	1080	611	469
G2-1230-3	1230	21.1	24.25	1.21	0.546	17.65	19	0.08	0.04	0.12	0.06	0.001	0.000	0.003	21.1	32.0	1757	1074	683
G2-1230-3	1230	21.1	24.25	1.13	0.033	30.50	18	0.08	0.04	0.13	0.06	0.002	0.000	0.004	21.1	31.0	2315	1424	891
G2-1210-3	1210	21.1	24.38	1.25	0.210	22.52	18	0.07	0.03	0.12	0.06	0.001	0.000	0.003	21.1	31.0	2025	1212	813
G2-1210-3	1210	21.1	24.69	0.93	0.155	24.01	18	0.07	0.03	0.10	0.05	0.001	0.000	0.002	21.1	33.0	1711	948	763
G2-1180-3	1180	21.1	24.36	1.13	0.613	15.71	18	0.07	0.04	0.11	0.05	0.001	0.000	0.003	21.1	32.0	1776	1016	760
G2-1180-3	1180	21.1	24.48	1.41	0.387	18.04	17	0.08	0.04	0.14	0.07	0.002	0.000	0.005	21.1	30.5	1836	1019	817

Table A3. Size selection parameters estimated for the 3rd sieve (G3). For details see caption of Table A1.

Code	Speed	Diam	L50	SR	<i>p</i> -value	Deviance	DOF	DeIL50	SdL50	DeISR	SdSR	<i>R</i>			MinL	MaxL	NrTot	NrTes	NrCov
<i>Sieve-Spe-Haul</i>	[RPM]	[mm]	[mm]	[mm]				[mm]	[mm]	[mm]	[mm]	R11	R12	R13	[mm]	[mm]			
G3-1230-1	1230	20.3	22.72	1.71	0.232	24.25	20	0.19	0.09	0.24	0.11	0.009	-0.008	0.013	20.3	32.0	1877	1644	233
G3-1230-1	1230	20.3	22.38	1.89	0.741	14.71	19	0.22	0.10	0.25	0.12	0.011	-0.010	0.014	20.3	32.0	2399	2124	275
G3-1210-1	1210	20.3	22.96	1.74	0.981	7.83	18	0.20	0.10	0.27	0.13	0.009	-0.009	0.016	20.3	31.0	1422	1206	216
G3-1210-1	1210	20.3	22.77	1.92	0.158	25.07	19	0.21	0.10	0.27	0.13	0.011	-0.010	0.017	20.3	33.0	1827	1573	254
G3-1180-1	1180	20.3	22.80	1.75	0.096	27.40	19	0.20	0.10	0.25	0.12	0.010	-0.009	0.014	20.3	32.5	1868	1627	241
G3-1180-1	1180	20.3	22.95	1.89	0.695	15.43	19	0.22	0.11	0.28	0.13	0.011	-0.011	0.018	20.3	31.5	1710	1468	242
G3-1230-2	1230	20.3	22.88	1.55	0.275	18.87	16	0.19	0.09	0.24	0.12	0.008	-0.007	0.013	20.3	30.0	1275	1076	199
G3-1230-2	1230	20.3	23.24	1.52	0.989	6.50	17	0.19	0.09	0.26	0.12	0.008	-0.006	0.015	20.3	31.0	900	732	168
G3-1210-2	1210	20.3	22.99	1.47	0.930	8.56	16	0.15	0.07	0.20	0.09	0.005	-0.004	0.009	20.3	30.0	1566	1298	268
G3-1210-2	1210	20.3	21.26	2.39	0.622	14.64	17	0.66	0.31	0.62	0.29	0.099	-0.084	0.086	20.3	31.0	1234	1149	85
G3-1180-2	1180	20.3	22.61	1.79	0.338	17.76	16	0.21	0.10	0.27	0.13	0.009	-0.009	0.017	20.3	30.0	1351	1129	222
G3-1180-2	1180	20.3	22.99	1.89	0.917	9.67	17	0.22	0.10	0.32	0.15	0.011	-0.011	0.023	20.3	31.5	1080	858	222
G3-1230-3	1230	20.3	22.70	1.73	0.868	12.39	19	0.19	0.09	0.24	0.12	0.008	-0.008	0.013	20.3	32.0	1757	1508	249
G3-1230-3	1230	20.3	22.34	2.11	0.087	26.58	18	0.24	0.11	0.29	0.14	0.013	-0.013	0.019	20.3	31.0	2315	2022	293
G3-1210-3	1210	20.3	22.66	1.85	0.994	6.43	18	0.21	0.10	0.26	0.12	0.010	-0.009	0.015	20.3	31.0	2025	1755	270
G3-1210-3	1210	20.3	22.72	1.88	0.281	20.98	18	0.22	0.11	0.28	0.13	0.011	-0.011	0.017	20.3	33.0	1711	1481	230
G3-1180-3	1180	20.3	22.67	1.72	0.818	12.54	18	0.18	0.08	0.23	0.11	0.007	-0.007	0.012	20.3	32.0	1776	1512	264
G3-1180-3	1180	20.3	22.65	1.74	0.978	7.41	17	0.20	0.10	0.25	0.12	0.009	-0.009	0.014	20.3	30.5	1836	1592	244