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Improving codend selectivity in the fishery of the deep-sea red shrimp *Aristeus antennatus* in the northwestern Mediterranean Sea

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Summary: The deep-sea red shrimp *Aristeus antennatus* is one of the most valuable demersal resources in Catalonia (northeast Spain), and Palamós is the most important harbour for this fishery in the area. Here, a management plan published in 2013 established the use of a 40-mm square-mesh codend (40s), replacing the previously used 50-mm diamond mesh codend (50d). The objective was to decrease the amount of juveniles in the catches, but the regulation did not bring the expected results. In this study, we measured and compared the selectivity of the 40s and the 50d in this fishery. In addition, we experimented with the use of a 50-mm square-mesh codend (50s). According to our results, the 40s had a lower 50% selection length (L_{50}) than the 50d, while the 50s had a substantially higher L_{50} than the other two. A transition analysis showed an increase in yield per recruit after the second year from a hypothetical implementation of the 50s. Our conclusion is that the 40s does not have a higher selectivity than the 50d, which (at least partially) explains the failure to reach the management objective in Palamós. Conversely, the use of a 50s would significantly benefit the fishery, increasing gear selectivity and yield per recruit.

Keywords: codend selectivity; *Aristeus antennatus*; mesh configuration; yield per recruit; transition analysis; bottom trawling; NW Mediterranean Sea.

Mejora de la selectividad del copo en la pesquería de arrastre de la gamba roja, *Aristeus antennatus*, en el Mediterráneo noroccidental

Resumen: La gamba roja, *Aristeus antennatus*, es uno de los recursos demersales más valorados en Cataluña (noreste de España). Palamós es el puerto pesquero más importante para esta pesquería en la región. Una orden ministerial regulatoria y específica para este puerto, publicada en 2013, estableció la utilización de un copo de malla cuadrada con abertura mínima de 40 mm (40s), reemplazando el copo de malla romboidal de 50 mm (50d) utilizado hasta la fecha. El objetivo era disminuir la cantidad de juveniles en la captura, pero la regulación no consiguió los resultados esperados. En el presente estudio, se midió y comparó la selectividad del copo de 50d y 40s en esta pesquería. Además, se experimentó el uso de una malla cuadrada de 50 mm (50s). Los resultados mostraron que el copo de 40s presentaba una talla de retención del 50% (L_{50}) menor comparado con el copo de 50d, mientras que el de 50s tenía una L_{50} considerablemente mayor que los demás copos. El análisis de transición mostró un aumento del rendimiento por recluta (Y/R) después del segundo año desde la hipotética implementación del copo de 50s. Nuestra conclusión es que el copo de 40s no tiene una selectividad mayor que el copo de 50d, explicando (por lo menos en parte) la falta de consecución de los objetivos de gestión en la pesquería de gamba de Palamós. En cambio, el copo de 50s mejoraría significativamente a la pesquería, aumentando la selectividad del arte y el Y/R.

Palabras clave: selectividad del copo; *Aristeus antennatus*; configuración de la malla; rendimiento por recluta; análisis de transición; arrastre de fondo; Mediterráneo noroccidental.

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INTRODUCTION

Gear selectivity regulation is an important tool for fisheries management that can be efficiently implemented to maintain the catch within sustainable boundaries and to mitigate the overall impact of fisheries on the ecosystems (Sardà et al. 2006, Suuronen and Sardà 2007, Coll et al. 2008). In fact, through the regulation of size at first capture, improvements in gear selectivity are expected to reduce the capture of juveniles and increase the yield per recruit of targeted species, while reducing the total amount of discards (Armstrong et al. 1990, MacLennan 1992)

In bottom trawl fisheries, the main factors influencing gear selectivity are the codend mesh size and shape (Robertson and Stewart 1988, Reeves et al. 1992). In particular, a diamond-shaped mesh displays a tendency to stretch and close under tension, reducing its effective selectivity as the codend fills with the catch. Conversely, a square-shaped mesh tends to stay open during a tow, displaying an overall higher selectivity for most species than a diamond-shaped mesh of the same nominal size (Robertson and Stewart 1988, Sala et al. 2008).

The deep-sea red shrimp *Aristeus antennatus* (Risso, 1816) is one of the most economically important demersal resources in the Northwest Mediterranean Sea. In Catalonia (northeast Spain), this resource is fished exclusively by bottom trawling and makes up to 50% of the income of the local fishermen's associations (Maynou et al. 2006, DGPAM 2017). In particular, medium- and large-size individuals [≥30 mm cephalothorax length (CL)] reach a much higher price in the market than smaller individuals, i.e. €42 kg^{-1} vs. €16 kg^{-1}, respectively (average values for 2010-2015; data from sales bills of the Fishermen's Association of Palamós, Catalonia). Size at first maturity for the red shrimp was estimated at 27 mm CL for females and 24 mm CL for males (Sardà and Demestre 1987). However, there is no official minimum landing size for this fishery.

Starting in 2008, the total amount (as well the proportion) of small individuals in the catches increased dramatically in several harbours of Catalonia. In Palamós, the most important harbour for this fishery in the area, yearly catches of small individuals exceeded those of large individuals and remained particularly high in almost all years (Fig. 1, data from landing statistics of the Fishermen's Association of Palamós). The process behind this sudden shift in the catch composition of red shrimp is still unclear. The main hypothesis is that it derives from a combination of unusually high recruitment events triggered by specific environmental conditions, i.e. particularly strong dense shelf water cascading events (Company et al. 2008), and growth overfishing (Gorelli et al. 2016a).

In 2013, the Fishermen's Association of Palamós adopted a long-term management plan for the fishery of the red shrimp, with the collaboration and approval of the Catalan regional government and the Spanish central government (BOE 2013). The objective of the plan was to increase the sustainability of the fishery

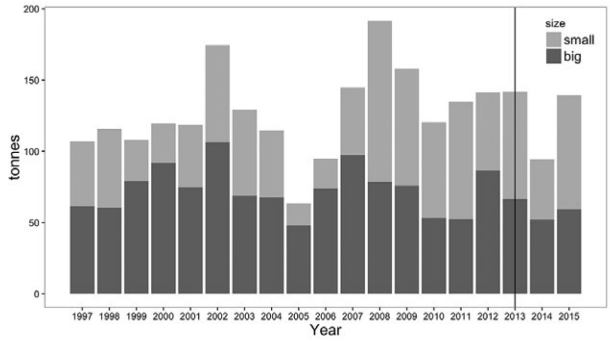

Fig. 1. – Red shrimp catches (tonnes) for the trawling fleet of Palamós shown per commercial size class: small individuals (<30 mm cephalothorax length) in light grey and medium/big individuals (≥30 mm cephalothorax length) in dark grey. The vertical line indicates the starting year of full implementation of the 40-mm square mesh codend, i.e. 2013. Previously, the 50-mm diamond mesh codend was used. Note that from 2008 onwards the proportion of small individuals in the catches was above 50% in almost all years.

(both economic and biological), with particular attention to reducing fishing pressure on the smallest individuals of the targeted stock. The new regulation established the use of a 40-mm square-mesh codend instead of the 50-mm diamond-mesh codend previously used in the fishery. Other measures in the management plan included a two-month fishery closure in winter/spring (when shoals of juveniles appear in the fishing grounds) and a 20% reduction (during the 5-year duration of the management plan) in the number of vessels operating in the red shrimp fishing grounds. The plan came officially into force in May 2013, but the fleet started self-regulating more than a year in advance. In fact, the transition from the 50-mm diamond mesh to the 40-mm square mesh started in March 2012 and was completed by May 2013. It is worth noting that the whole management plan was established without any previous scientific evaluation of the fishery. Thus, the measures were adopted as a precaution in order to avoid severe overfishing and to increase the average size of individuals in the catch. The expected outcomes were, in the short term, a reduction in the amount of small individuals in the catches and, in the medium and long term, an increase in the yield per recruit and the overall profitability of the fishery.

In this study, we measured and compared the selectivity of three different codend mesh configurations in the fishery of the deep-sea red shrimp: a) the 50-mm diamond mesh (hereafter 50d), used prior to the implementation of the management plan; b) the 40-mm square mesh (hereafter 40s), fully implemented from mid-2013 and used to date, and c) the 50-mm square mesh (hereafter 50s), not used at present in the fishery and included in the analysis to assess the potential improvements in gear selectivity. Furthermore, we simulated the evolution of yield per recruit (Y/R) and biomass per recruit (B/R) after a hypothetical implementation of the 50s. Our objective was to assess the effectiveness of the selectivity regulation adopted in Palamós and to provide the necessary scientific evidence to support any future management decision regarding gear selectivity in this fishery.

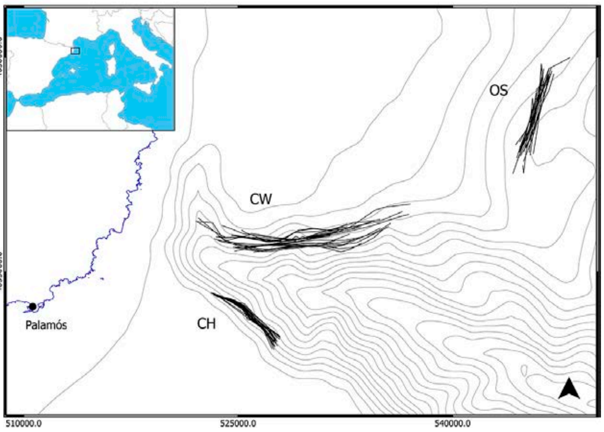

Fig. 2. – Map of the study area, i.e. the main fishing grounds for red shrimp exploited by the trawling fleet of Palamós (Catalonia, NE Spain). The fishing grounds are located on the margins of a submarine canyon (CH, canyon head; CW, canyon northern wall; OS, open slope). Tracks of the experimental tows are shown on the map.

MATERIALS AND METHODS

Sampling was carried out onboard a commercial shrimp trawler of the Palamós fleet, with 68.5 t GT and 700 hp engine power. The standard covered codend method (Wileman et al. 1996) was employed to assess the selectivity of the three mesh configurations. The cover had a mesh size of 12 mm (stretched), and was attached directly to the funnel end of the net. In order to maintain a good flow of water and avoid masking the codend meshes, the cover was 1.5 m wider and longer than the codends. The three codends were made of a 3-mm-thick nylon twine. Experimental tows with the three codends were carried out on the commercial fishing grounds for red shrimp traditionally exploited by the Palamós fleet (Fig. 2), which are located at depths of between 300 and 900 m. The average towing speed was two knots. The overall performance of the gear (door spread, mouth opening and towing depth) was monitored using acoustic sensors (Scanmar AS, Asgardstrand, Norway). The mean effective towing duration was 1 hour 40 minutes. Catch sampling focused on *A. antennatus*, which is the only target species in this fishery and constitutes the majority of the catches (Gorelli et al. 2016b). The CL of individuals in the codend and cover was measured with a precision of 0.1 mm. When catches were too large to measure each individual, representative subsamples were measured instead. Experimental tows with the 50d were performed from January 2012 to March 2012, and experimental tows with the 40s were carried out from May 2012 to December 2013 (these data were part of a catch sampling for stock assessment). In May-June 2016, the 50s was tested and a few more tows using the 50d were performed. Although the landings of red shrimp display a yearly peak in summer, the species is targeted during the whole year and its abundance in the fishing grounds at all times allowed a representative sampling for the three codends tested.

The size selectivity of the three mesh configurations was modelled using a standard logistic curve:

Table 1. – Parameters used for the pseudo-cohort analysis for red shrimp females. Parameters of the Von Bertalanffy relationship (L_{inf}, k, t_0) are from Sardà and Demestre (1987); parameters of the length-weight relationship (a, b) are from Demestre (1990); natural mortality (M) is from Demestre and Martín (1993). Fterm is the terminal fishing mortality for the pseudo-cohort analysis, assumed as in Demestre and Lleonart (1993).

L_{inf}	k	t_0	a	b	M	Fterm
76	0.3	–0.07	0.00264	2.46604	0.5	2

$$r(l) = \frac{e^{(a+b\times l)}}{1+e^{(a+b\times l)}}$$

where r(l) is the probability that a fish of length l, if contacting the gear, will be retained.

The logistic parameters (a, intercept; b, slope) were estimated using a mixed-effects logistic model (Fryer 1991). The mixed-effects model takes into account both within- and between-haul variability. The latter occurs between deployments of the same fishing gear and is due to the effect of uncontrolled variables (Millar and Fryer 1999, Reeves et al. 1992). This method ensures the proper estimation of parameter uncertainties, avoiding spurious statistical significance. In order to fit the mixed-effects logistic model, we used the *glmer* function in the *lme4* R package. The 50% selection length (L_{50}, i.e. the length at which 50% of the fish contacting the gear will be retained) and the selection range (SR) with associated standard errors were calculated as in Wileman et al. (1996). In particular:

$$L_{50} = -\frac{a}{b}$$

$$SR = L_{75} - L_{25} = -\frac{2\times \ln(3)}{b}$$

In order to simulate the effect of changing mesh configuration from 40s to 50s, a transition analysis using the software VIT was performed (Lleonart and Salat 1997). First, we ran a pseudo-cohort analysis using the length frequencies obtained with the 40s and the 50s separately. Parameters used in the analysis are shown in Table 1. Then, we ran a transition analysis to simulate the effect on Y/R and B/R of shifting current fishing mortalities obtained with the 40s to fishing mortalities obtained with the 50s. Details on the pseudo-cohort analysis and the transition analysis are described in Lleonart and Salat (1997). Females and males of red shrimp have very different biological parameters (Sardà and Demestre 1987, Demestre 1990, Demestre and Martín 1993). Females grow larger than males and are more abundant in the fishing grounds. In our sampling, females made around 80% of total catch weights, while constituting nearly 100% of individuals in the medium/big size class. Adult males fell almost completely in the small size class. For these reasons, the transition analysis was performed on females only.

RESULTS

A total of 99 valid experimental tows were performed in this study: 16 using the 50d, 66 using the 40s, and 17 using the 50s (Table 2). The average catch

Table 2. – Number of valid hauls per mesh configuration (50d, 50-mm diamond; 40s, 40-mm square; 50s, 50-mm square). Total number of individuals retained in the codend and cover per mesh configuration are also displayed.

	50d	40s	50s
N of valid hauls	16	66	17
N of individuals in codend	21462	87899	27750
N of individuals in cover	17913	31378	41399

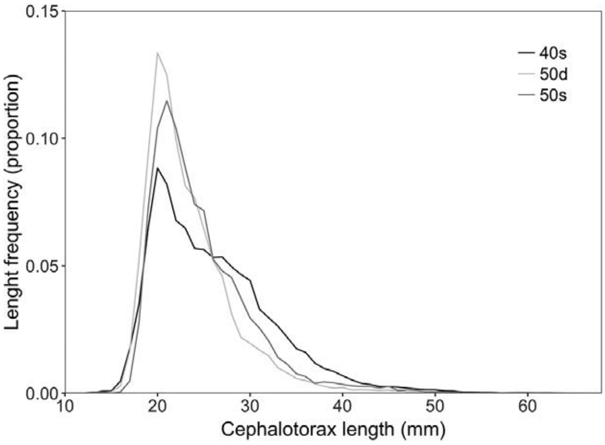

Fig. 3. – Length frequency of individuals encountering the gear in the experimental tows for the three mesh configurations: 50-mm diamond (50d), 40-mm square (40s) and 50-mm square (50s).

weight of *A. antennatus* in the experimental hauls was 11.5 kg for the 50d, 15.3 for the 40s and 17.5 for the 50s. The length range and frequency of individuals encountering the gear during the tows was very similar for the three mesh configurations (Fig. 3). Selectivity curves for individual hauls carried out with the three different codends are shown in Figure 4. Mean logistic parameters, *a* and *b*, displayed significant differences among mesh configurations (Table 3, Fig. 5). In particular, the pairwise test showed that significant differences in the steepness occurred between the 40s and the other two. As for the intercept, significant differences occurred between the 50d and the other two (Table 3). Significant logistic parameters allowed the estimation of mean SR and L_{50} (Table 4). The 40s displayed the lowest L_{50} among the three mesh configurations (21.1 mm). In particular, the difference between the 40s and the 50d was minimal (1.5 mm), while the

Table 3. – Logistic parameters (a and b) estimated by the mixed-effects model for the three mesh configurations (50d, 50-mm diamond; 40s, 40-mm square; 50s, 50-mm square), standard errors (se) and pairwise comparison between mesh configurations. The asterisk indicates significant P values, i.e. <0.05.

	Estimate	se	P value
a 50d	–6.45	0.54	<0.001*
b 50d	0.29	0.02	<0.001*
a 40s	–8.11	0.27	<0.001*
b 40s	0.38	0.01	<0.001*
a 50s	–8.02	0.51	<0.001*
b 50s	0.31	0.02	<0.001*
a 40s - a 50d	–1.66	0.60	<0.01*
a 50s - a 50d	–1.57	0.74	<0.05*
a 40s - a 50s	–0.09	0.58	>0.1
b 40s - b 50s	0.08	0.02	<0.001*
b 50d - b 50s	–0.02	0.03	>0.1
b 40s - b 50d	0.1	0.02	<0.001*

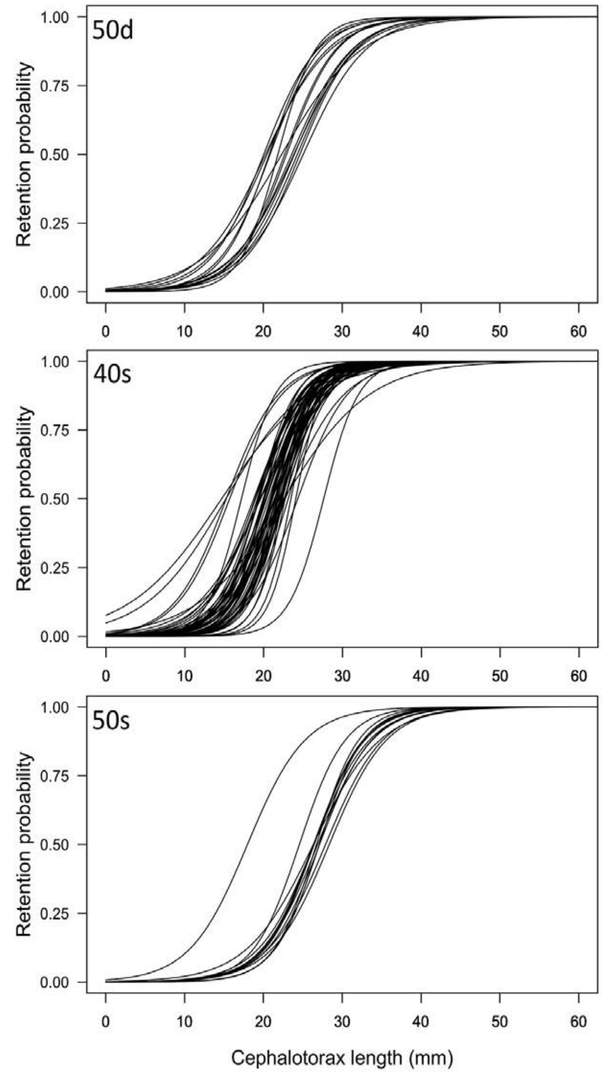

Fig. 4. – Selectivity curves of individual hauls for the 50-mm diamond mesh (50d), 40-mm square mesh (40s) and 50-mm square mesh (50s).

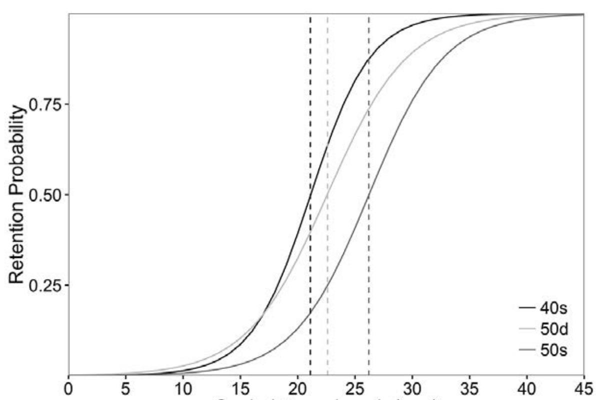

Fig. 5. – Mean selectivity curves for the 50-mm diamond mesh (50d), 40-mm square mesh (40s) and 50-mm square mesh (50s), obtained taking into account between-haul variability. The vertical dashed lines indicate the L_{50} for the three mesh configurations (black, 40s; light grey, 50d; dark grey, 50s).

Table 4. – Mean estimates of 50% selection length (L_{50}), selection range (SR) and associated standard errors (se) for the three mesh configurations (50d, 50-mm diamond; 40s, 40-mm square; 50s, 50-mm square).

	50d	se	40s	se	50s	se
L_{50}	22.6	0.4	21.1	0.3	26.2	0.5
SR	7.7	0.4	5.7	0.2	7.2	0.2

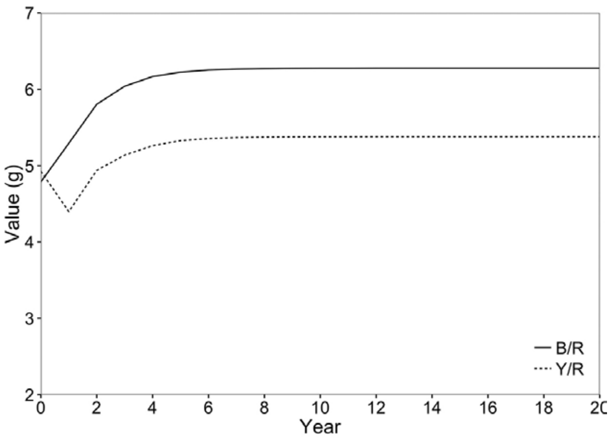

Fig. 6. – Simultated effects on the yield per recruit (Y/R, dotted line) and biomass per recruit (B/R, black line) in the red shrimp fishery after shifting mesh configuration from 40-mm square mesh to 50-mm square mesh. The y-axis represents the values in grams of yield per recruit and biomass per recruit.

difference between 40s and 50s was more substantial (5.1 mm) (Table 4, Fig. 5). The 40s displayed the narrowest selection range (5.7 mm), while the other two mesh configurations had a similar SR (7.7 and 7.2 for the 50d and 50s, respectively).

The expected Y/R after a hypothetical implementation of the 50s showed an initial decrease of 10.75%, falling from 4.93 g to 4.40 g after one year. Starting from the second year, the model suggested a recovery and a subsequent increase in the Y/R, reaching a maximum value of 5.38 g after 9 years (corresponding to an increase of 9.13% compared with the initial value) (Fig. 6). As shown in Figure 6, after five years the Y/R was already very close to the maximum. The B/R showed a gradual increase, rising from an initial value of 4.79 g to a maximum value of 6.28 g after nine years from the hypothetical 50s implementation. This corresponded to a percentage increase of 31. Like the Y/R, after five years the B/R was already very close to the maximum.

DISCUSSION

In this study, we found that shifting from a diamond to a square mesh does not assure a higher selectivity regardless of the nominal mesh size. In fact, the 40s displayed a smaller L_{50} than the 50d. Similar results were obtained for other species in the eastern Mediterranean Sea (Aydin et al. 2011). This finding might explain (at least partially) the failure to reduce the catch of small individuals attempted in Palamós by replacing the 50d with the 40s. In fact, the annual series of catches per commercial size (Fig. 1) shows that the catch of small individuals was not significantly reduced after 2013, when the 40s was fully adopted by the trawling fleet. On the other hand, the 50s was found to be significantly more selective than the 50d (higher L_{50} and smaller SR). Square mesh codends were proven significantly more selective than diamond mesh codends of the same nominal size in several other Mediterranean fisheries and for a diversity of species (Guijarro and Massutí 2006, Sala et al. 2008, Tosunoglu et al. 2009).

The improvement in selectivity associated with the 50s is substantial in terms of L_{50}. The initial decrease in the simulated Y/R after the adoption of this codend was recovered relatively rapidly (after only two years), and Y/R continued to improve in the following years. At the same time, the simulated B/R started to increase immediately after the implementation of the 50s, and continued increasing in the following years. It is important to highlight that an increase in the average size of individuals in the catch might translate into a substantial economic advantage (given the high price of big red shrimp individuals) even without a significant increase in the total yield. Thus, the adoption of the 50s might improve the overall economic and biological sustainability of the fishery, helping achieve the management objectives set in Palamós. It must also be noted that the L_{50} of the 50s is still slightly below the size at first maturity of females. In this context, other measures to protect juveniles (such as the fishery closure already in place in Palamós during two months in winter/spring) should be implemented to complement the selectivity increase. Further experimentation of other mesh configurations is also recommended.

Finally, our study highlights the importance and the need for scientific evidence to support the adoption of management measures. The investment made by the Fishermen's Association of Palamós to change the codend mesh configuration from 50d to 40s did not bring any beneficial effect to the fishery. A previous evaluation and comparison of the selectivity of the two mesh configurations would have prevented this loss of economic resources. In fact, the implementation of management measures without previous knowledge or estimate of their effects might result in unexpected outcomes, such as potential disadvantages for the fishery, economic loss and no contribution to the achievement of the established management objectives.

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