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From discard ban to exemption: How can gear technology help reduce catches of undersized *Nephrops* and hake in the Bay of Biscay trawling fleet?

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Abstract :

On January 1st, 2016, the French mixed *Nephrops* and hake fishery of the *Grande Vasière*, an area located in the Bay of Biscay, fell under the discard ban implemented as part of the new European Common Fisheries Policy. The fleet records historically high levels of discard despite numerous gear selectivity studies. Together with high discards survival, new technological solutions to minimize catches of undersized individuals could justify local exemptions from the discard ban. Our study focuses on the effects of two selective devices, a square mesh cylinder (SMC) and a grid, on the escapement of undersized individuals and discard reduction. Relative catch probability of the modified gear compared with the traditional gear was modelled using the catch comparison method. Potential losses from the commercial fraction of the catch were taken into account to assess their influence on the economic viability of fishing with the modified gears. The two devices had similar effects on undersized *Nephrops* escapement and on discard reduction, with median values of 26.5% and 23.6% for the SMC and of 30.4% and 21.4% for the grid, respectively. Only the grid was efficient for undersized hake, recording median values of escapement and discard reduction equal to 25.0% and 20.6%, respectively. Some loss from the commercial fraction of the catch was to be expected with both devices, which could be compensated for in the long term by the contribution of undersized individuals to the stock biomass. Our results support the use of selective gears technology as part of an integrated framework including control and management measures to mitigate the effect of the discard ban both for fishers and for the ecosystem. Further work is needed to quantify the effect of additional escapement from the gear on stock dynamics.

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Highlights

► A square mesh cylinder and a grid were tested to reduce *Nephrops* and hake discards. ► Both devices were efficient at letting *Nephrops* <30 mm cephalothoracic length escape. ► Only the grid allowed hake <23 cm total length to escape. ► Commercial losses may be compensated for in the long term by improved stock dynamics.

Keywords : *Nephrops*, European hake, Discard ban, Gear technology, Catch comparison, Selectivity

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2. Introduction

Article 15 of the new European Common Fisheries Policy (EU, 2013) imposes a discard ban for all species subject to either quota or minimum landing size (MLS) as specified in Regulation (EC) No 850/1998 (EC, 1998). The recently submitted discard plan for demersal species of the North-East Atlantic (Regulation (EU) 2015/2438) identifies both *Nephrops norvegicus* (hereafter *Nephrops*) and European hake (*Merluccius merluccius*) as falling under this regulation, with MLS thresholds of 28 mm Cephalothoracic Length (CTL) and 27 cm Total Length (TL), respectively.

Nephrops are crustaceans fished by bottom trawling. European *Nephrops* fisheries generate large amounts of demersal species bycatch, with high market value. Frequent bycatch species are cod, whiting, haddock and, for the French trawling fleet of the Bay of Biscay, European hake (Catchpole et al., 2006; Graham and Fryer, 2006; Madsen and Valentinsson, 2010; Nikolic et al., 2015). With 191 trawlers targeting the species in the area, it is one of the largest fishing fleet in France. In 2012, these vessels landed 2 175 tons of *Nephrops*, worth more than €29 million in market value (Leblond et al., 2014). Due to its economic importance, *Nephrops* fisheries have long been studied for trawl selectivity (Briggs, 2010; Catchpole and Revill, 2008; Frandsen et al., 2011). At the national level, the fishery has been the subject of the largest number of selectivity trials of any fishery (Vogel, 2016).

Early attempts to mitigate the effect of *Nephrops* trawling in ICES Area VIIIa focused on hake, following measured low levels of abundance at the end of the 1990s. Various technical measures were implemented to preserve juvenile fish including mesh size restrictions (Regulation (EC) 850/1998: art. 4), zoning for spawning grounds (Regulation (EC) 494/2002: art. 5 and 6), fishing effort limitation (Macher et al., 2008) and mandatory selective devices (Regulation (EC) 724/2001) (Nikolic et al., 2015). In 2010, further restrictive measures were adopted by the French national fishing committee (*Comité National des Pêches et des Elevages Marins*, CNPMEM) in the form of the mandatory implementation of one of four specified selective devices (French Republic (RF) arrêtés of 2011, and 2010). The selective devices were based on research conducted on trawl selectivity for *Nephrops* and round fish in the North-East Atlantic, with either a large mesh codend, a sorting grid, a square mesh panel (SMP) or a cylinder made of net tilted 45° sideways (CNPMEM, 2004; Fonseca et al., 1999; Krag et al., 2008; Madsen and Stæhr, 2005). Despite these measures, discards in the *Nephrops* fishery of the Bay of Biscay still accounted for 35.6 % of all *Nephrops* catches and for 55.3 % of all hake catches in weight in 2013, of which 85.1 % and 89.1 %, respectively, were undersized (Cornou et al., 2015).

The discard ban, which started on 1st January 2016, enforces the mandatory landing of all catches. Recent studies point out the ecological impacts of such a reduction in nutrients income for the ecosystem, with adverse effects foreseen for all components of the trophic food web (Heath et al., 2014; Sardà et al., 2015). In the Bay of Biscay, *Nephrops* and hake are the species which contribute the most to total discards in weight; their removal from the food web will induce a shift in the predation pressure exerted by top-predators on the different trophic groups of the area although it is difficult to assess its amplitude (Kopp et al., 2016). For example, sea birds target fishing vessels for food (Sommerfeld et al., 2016), consuming up to ¼ of all fish discarded by trawling in the Bay of Biscay (Depestele et al., 2016). Limiting bycatch therefore appears a prerequisite to limit the effects of the discard ban on the ecosystem and to the success of the new Common Fishery Policy (CFP) (Fauconnet and Rochet, 2016; Prellezo et al., 2016).

Achieving the sustainable management of *Nephrops* and hake stocks is a vital goal for maintaining commercial fishing in the Bay of Biscay. In the long term, the discard ban aims at rationalizing the fishing process, inducing a mind shift from "minimum landing size" to "minimum catching size"; selective gears and sustainable practices are different tools to achieve this aim (Gullestad et al., 2015). The discard ban will among other issues put a stop to high-grading practices and help to improve stock assessment (Batsleer et al., 2015; Catchpole et al., 2014). Exemptions from the discard ban are however possible based on two specific criteria: either when a high survival rate of discards has been demonstrated, or when all potential technical and management measures have been implemented to reduce catches of undersized individuals (EU, 2013: Art. 15). The mixed *Nephrops* and hake fishery of the Bay of Biscay presently benefits from a one-year exemption from the now enforced discard ban, until 1st January 2017 (Regulation (EU) 2015/2438), based on high survival rates of the discarded *Nephrops*

(Méhault et al., 2016). Further work is required by the STECF (Scientific and Technical European Council for Fisheries) to guarantee that the exemption can be pursued in the long term (Regulation (EU) 2015/2438).

In the English *Nephrops* fishery, selective gear technology was identified as the best solution to limit discards while preserving fishing (Catchpole et al., 2006). Reducing catches of undersized individuals according to their MLS through the use of selective devices improves stock exploitation diagrams by reducing fishing mortality of young individuals (Macher et al., 2008). Effects on the recruitment process due to increased spawning biomass of both *Nephrops* and hake would be immediate and stabilize within 5 to 10 years (Raveau et al., 2012); Potential short-term economic loss due to some reduction of the commercial fraction of the catch would be compensated for in the long term (Raveau et al., 2012).

The present study focuses on technical solutions to reduce catches of undersized individuals of both *Nephrops* and hake. We present new results on two potential selective devices: a square mesh cylinder (SMC) and an inverted selective grid, which were tested onboard commercial vessels in 2010 and 2011. Both the SMC and the grid tested were developed on the basis of existing devices whose use is enforced in the area: the SMC of the present study provides larger mesh openings than the imposed appliance made of diamond mesh tilted 45° sideways (Frandsen et al., 2010a), and the grid located on the dorsal part of the extension section provides greater chances of contact for undersized hake than a ventral grid (Frandsen et al., 2010b; Graham and Fryer, 2006).

Our aims were (1) to quantify the escapement rate of undersized *Nephrops* and hake associated with the use of each device, compared with the control trawl, and to estimate the corresponding discard rate reduction; (2) to model the catch probability of the test gears relative to the control gear for each species; and (3) to establish whether professional fishers would experience a loss of commercially valuable individuals if they put these devices to use. On the basis of these findings we discuss how much these selective devices would contribute to improving management for the mixed *Nephrops* and hake fishery in the Bay of Biscay, in the context of the new CFP and its associated discard ban. The potential ecological effects of different management options are discussed in views of the existing literature for this fishery and for other mixed fisheries targeting *Nephrops* in the North-East Atlantic.

3. Material and methods

3.1. Fishing gear characteristics

All fishing vessels involved in the trials were twin-rigged with identical trawl bodies and codends. For the control trawl, the configuration was designed to be representative of professional fishing conditions and to comply with regulations currently in force in the area. A mandatory 100-mm SMP, 3m by 1 m, was inserted in the tapered section of each, 12 meshes ahead of the extension section. The extension section was 100 meshes long, made of single-twine polyethylene fibre (PE), 3 mm in diameter and of 80-mm mesh-size (gauge). Codends were 33 meshes deep, 120 meshes in circumference and made of single-twine PE with a mesh-size of 75 mm (gauge). Aside of the selective devices, selective trawls were identical to the control trawls. The selective devices used are shown in figure 1:

(i) The SMC is located in the extension section of the trawl, five meshes down from the tapered section. Mesh size is 70 mm at the gauge (37 mm mesh bar). The SMC is made of PE, has 120 meshes in circumference and is 85 meshes long (3.15 m). Fitting of the SMC to the diamond mesh trawl body is done by joining two diamond meshes to one square mesh. The lower side of the SMC is located 60 meshes up from the codend (Figure 1A).

(ii) The inverted selective grid, hereafter referred to as 'the grid', is also located in the extension section of the trawl, on the ventral part, five meshes away from the tapered section. The grid is made of soft polyurethane (EVAFLEX), with 13 mm vertical bar spacing. Bars have a round cross section; five horizontal bars ensure the grid's rigidity. The lower side of the grid is located 60 meshes up from the codend (Figure 1B).

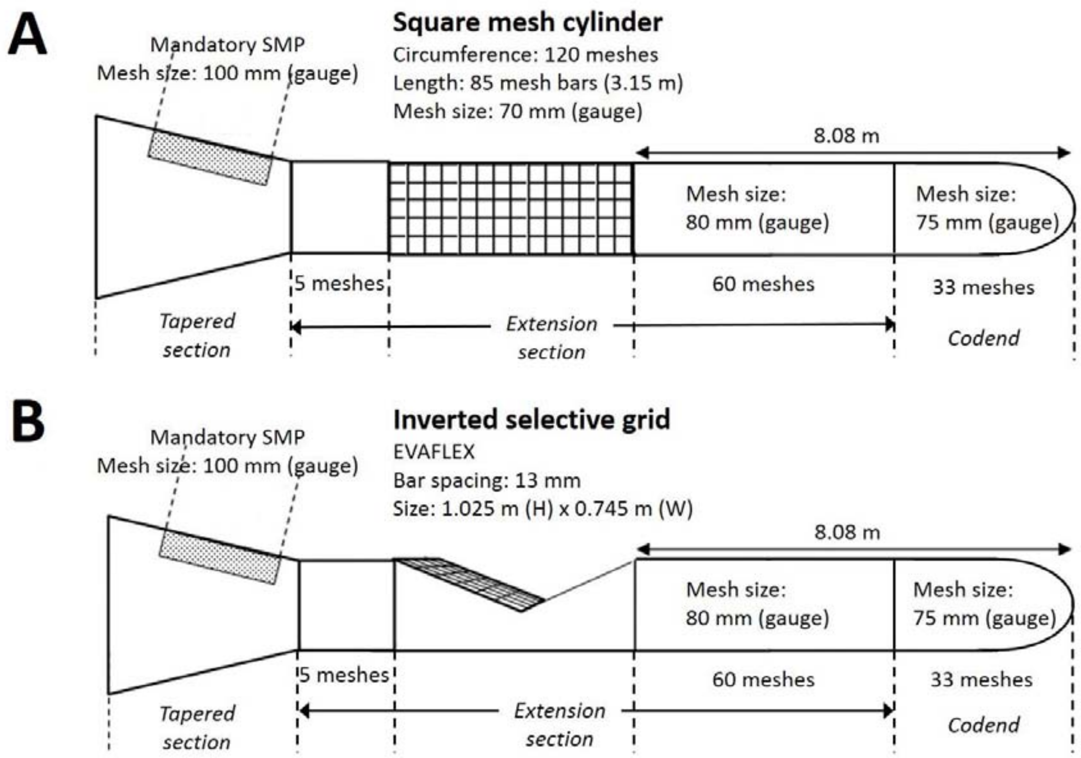

Figure 1. Diagram of the square mesh cylinder (A) and inverted selective grid (B), with location details within the trawl body.

3.2. Sea trials

Sea trials were performed during the periods April–August 2010 and May–June 2011 for the square mesh cylinder, and April–September 2011 for the grid. Trials were carried out on the "*Grande Vasière*", an area of the Bay of Biscay starting at the latitude of the Gironde estuary and stretching up to the south-west point of Brittany (Lat. 47.856 N, 45.833 S, Long. -5.129 O, -2.082 E) (Macher et al., 2008). Ten vessels of similar length and horse power belonging to the *Nephrops* fishing fleet were involved in the trials of the SMC, and 13 for the grid. Each vessel was equipped with a control trawl on one side and a selective trawl on the other side, to allow paired tows. In total, 113 valid hauls (i.e., no operating damage while trawling) were run for the SMC and 74 for the inverted grid, for a mean haul duration of 186 min and 193 min respectively (Table 1). Average trawling speed was 3.56 knots (SD: 0.34), sea state varied from calm to rough with median wave height equal to 0.75 m and a maximum of 3.00 m.

Table 1. Basic haul information on sea trials run with the square mesh cylinder and the inverted grid in 2009-2010 in the Bay of Biscay.

Selective devices	*Total number of hauls*	*with* Nephrops	*with hake*	*Mean haul duration in min (SD)*
SMC	113	62	87	186 (35)
Grid	84	74	84	193 (40)

3.3. Data collection

For each haul, both commercial catches and discards of *Nephrops* and hake were weighed and measured. Total length was measured in cm for fish, and cephalothoracic length was measured in mm for *Nephrops*. When the total catch was too large to allow measurement of every individual, random sub-sampling was performed and the weight ratio between total catch and subsample was recorded for the subsequent data processing. Estimated total numbers of individuals of each species and size per haul were computed as the product of the number of individuals sampled, using the recorded weight ratio. They are hereafter referred to as "scaled-up count data". Hauls lasting less than one hour were removed from the data set as non-representative of commercial fishing operations. Data selection was made based on the number of individuals recorded per length class: when less than five individuals had been caught for the control and test gear combined for a given haul, the length class was removed as non-representative.

3.4. Data analysis

3.4.1. Sampling scheme validation

All statistical analyses were run in 'R' (R Core Team, 2014). Pooled scaled-up count data were plotted for each selective device against the corresponding control gear, creating catch comparison graphs. Size distributions of catches by the test and control gears were compared using the Kolmogorov-Smirnov test (Wilcox, 2005). Proportions of fish retained per length class, $\mathrm{P(l)}$, were computed and displayed on the graph, such that:

$$\mathrm{P\ (l)} = \frac{\mathrm{N_{l,t}}}{\mathrm{N_{l,c}} + \mathrm{N_{l,t}}}$$

where $\mathrm{N_{l,t}}$ is the sum of scaled-up count data of fish of length l in the test gear and $\mathrm{N_{l,c}}$ the sum of scaled-up count data of fish of length l in the control gear across all hauls. A weighted spline regression with four degrees of freedom was run on the observed proportions and added to the graph. A horizontal line was drawn at 0.5 to indicate the level at which the two gears showed equal fishing performance.

3.4.2. Escapement rates

Escapement rates in numbers, r_{esc}, due to the implementation of the different selective devices for undersized individuals were estimated for each device and species, as:

$$r_{esc} = 1 - \frac{n_{l<MLS,t}}{n_{l<MLS,c}}$$

where $n_{l<MLS,t}$ is the number of undersized individuals in the test gear and $n_{l<MLS,c}$ the number of undersized individuals in the control gear. A positive escapement value is returned when less fish are captured by the test gear than by the control gear; this is equal to zero if there is the same number of fish in both gears and negative if more fish are captured by the test gear than by the control gear. Escapement rates for each haul were plotted as violin plots (Hintze and Nelson, 1998), which provide a visual representation of the data distribution; outliers were kept to give a full representation of the variability observed during the sampling process. The descriptive statistics median escapement, mean escapement and associated standard deviation were calculated for undersized and for market-sized individuals.

3.4.3. *Modelling*

Relative catch probability of the test gear compared with the control gear was modelled according to Holst and Revill's method (2009) and traditional data analysis of binomial type data (Agresti, 2010). A logistic regression was run on the observed proportions of fish retained in the framework of generalized linear mixed models (GLMM), which made it possible to account for variability arising from the experimental design by adding random terms to the model's structure that would affect either or both the intercept and the slope parameter estimates (Pinheiro and Bates, 2000).

Fish length was considered in terms of explanatory variable. The use of absolute catch values induces some variability owing to differences in tow duration between hauls; additional variability arises from differences in experimental conditions between hauls, such as sea state, water temperature or turbidity. This environmental variability is accounted for in the modelling process by implementing "haul" as the random term. Fish length was standardized to facilitate model convergence. Centring (L-mean) and scaling (L-sd) parameters for length were reported to make estimate interpretation in GLMM results easier.

GLMM were set using the lme4 'R' package with the *glmer()* function (Bates et al., 2014). By this method, model selection is based on the AIC score of each model (Burnham and Anderson, 2002). Two models were considered. The first one was set with a random intercept, which takes into account that the baseline escapement probability varies from one haul to another:

$$logit(p) = (\beta_0 + \beta_{0L}) + \beta_1 L + \beta_2 L^2 + \varepsilon_L$$

The second model includes both a random slope and a random intercept. The former implies that escapement probability varies for fish of the same length class between hauls. Size variability of fish and crustacean caught by the gear is associated with individual's swimming abilities and resilience to effort, which affect escapement probability (Killen et al., 2015) and justify the use of a random term associated with length:

$$logit(p) = (\beta_0 + \beta_{0Lj}) + (\beta_1 + \beta_{1j})L + (\beta_2 + \beta_{2j})L^2 + \varepsilon_{Lj}$$

For both models, Ls is the constant term in its quadratic form and js is the different levels of the random factor. GLMM parameter estimates and statistical significance are presented in the results section. As for splines, a horizontal was line drawn at 0.5 to indicate the level at which the two gears showed equal fishing performance. An efficient selective device will hereafter designate a device for which the 0.5 level was not reached for small sized individuals (<MLS) but was either equal to or greater than 0.5 for individuals larger than the MLS. Such a pattern corresponds to an escapement of undersized individuals without commercial losses from the catch. Some tolerance was allowed around the length at which the model reached the 0.5 level when qualifying a device as efficient.

3.4.4. *Discard and commercial catch rates reduction*

Estimated discard rate reduction in weight, r_{disc}, and estimated commercial losses in terms of weight, r_{cc} – hereafter referred to as commercial catch rate reduction, associated with the use of the selective devices compared to the traditional gear were computed for simulation, based on length–weight relationships for each species in the Bay of Biscay (Mahe et al., 2007) and using MLS as the discarding criterion:

$$r_{disc} = 1 - \frac{\hat{m}_{disc,t}}{\hat{m}_{disc,c}} \quad \text{and} \quad r_{cc} = 1 - \frac{\hat{m}_{cc,t}}{\hat{m}_{cc,c}}$$

where $\hat{m}_{disc,t}$ is the estimated weight of discards in the test gear and $\hat{m}_{disc,c}$ the estimated weight of discards in the control gear, while $\hat{m}_{cc,t}$ is the estimated weight of commercial catches in the test gear and $\hat{m}_{cc,c}$ the estimated weight of commercial catches by the control gear. As for escapement, a positive value expresses a reduction in discards or, respectively, a reduction in commercial catches in the test gear compared with the control gear.

4. Results

4.1. Effects of the selective devices on *Nephrops* catches

4.1.1. Catch composition from sampling

Nephrops captured through the different trials ranged from 10 mm to more than 50 mm in carapace length. No cohort-like structure could be identified from the pooled scaled-up catch data (Figure 2). Size structure of the *Nephrops* population sampled through the use of selective gears is different to the control gear for both selective devices, with highly statistically significant t-values (p<0.001) (Table 2), indicating an effect of the devices. 0verdispersion in the proportions of *Nephrops* retained is observed for length values greater than 45 mm in both cases (Figure 2), limiting our ability to infer the effect of the devices over this size.

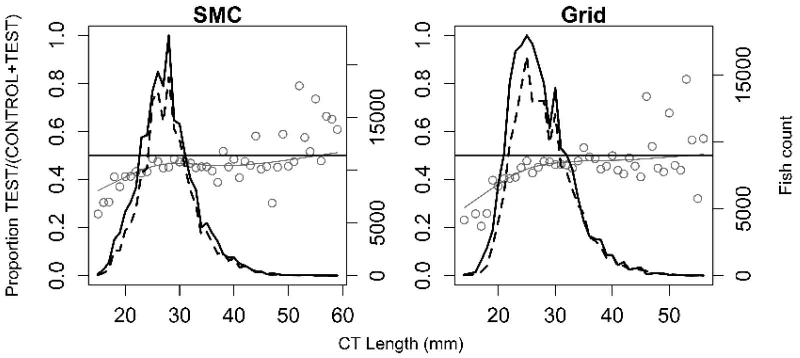

Figure 2. Pooled scaled-up catches of *Nephrops* from trials of the SMC (left) and of the grid (right). Catches from the control gear (thick black line), catches from the test gear (thick broken line), proportions (dots) and a regressive spline with four degrees of freedom run on weighted proportions (thin grey line) are shown.

Table 2. Descriptive statistics and t-value with level of statistical significance of *Nephrops* sampled with the different trawl designs. (L: length; SD: standard deviation; ***p<0.001)

	SMC		*Grid*	
	Control	*Test*	*Control*	*Test*
L – mean (mm)	30.9	31.2	31.9	32.2
L – median (mm)	30.0	30.0	31.0	32.0
L – sd (mm)	8.7	8.5	8.6	8.4
t-value	7.41***		8.29***	

Nephrops caught during the SMC trials were smaller on average than *Nephrops* caught during the grid trials (Welsh's t-test on catches of the control gears: $t = 5.69$, $p<0.001$) (Table 2). Standard deviation around the mean was similar for both selective devices and for the test and control gears (Table 2), which can be attributed to the effect of environmental variability alone.

4.1.2. Escapement of undersized Nephrops

Undersized *Nephrops* escaping through the SMC display a distribution that is close to normal (Figure 3A). Escapement values range from -54.1 % to 100 %. Standard deviation is greater than mean escapement value; the difference between mean and median escapement values is negligible for this device (Figure 3A).

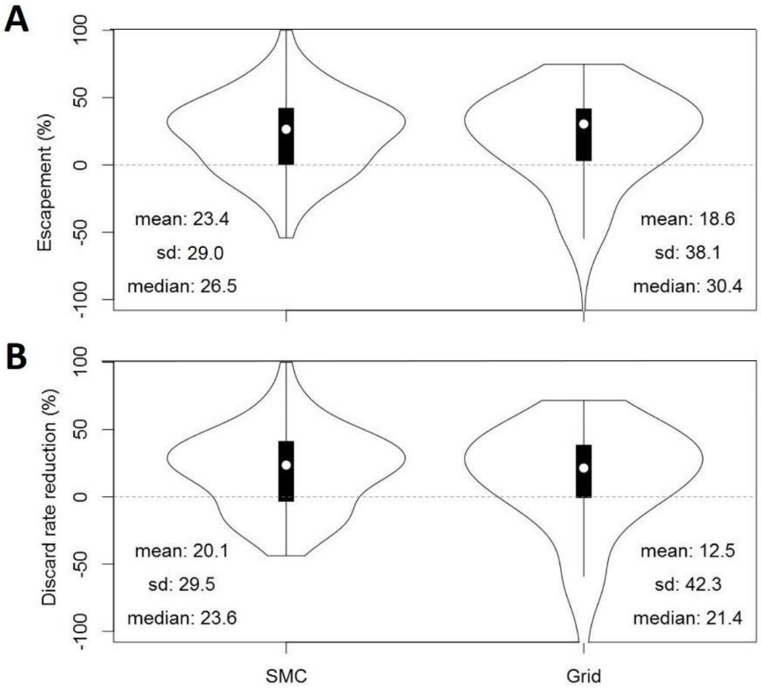

Figure 3. Escapement levels of undersized *Nephrops* in numbers (A) and discard rate reduction of undersized *Nephrops* based on estimated discard weights (B) for the implementation of the SMC (left) or of the grid (right) compared with the control gear. Violin plots display the median (white dots), 25th to 75th percentiles (black-filled rectangle) and extreme 5th and 95th percentiles (straight black line), the black curves illustrate the data distribution. Mean, SD and median values are given.

Outliers are recorded for undersized *Nephrops* escaping through the grid: distributions of escapement values are skewed towards negative values (Figure 3A), with a minimum value of -139.4 %. The maximum escapement observed was 74.8 %. The grid shows a lower mean escapement value of undersized *Nephrops* than the SMC and its results are more variable. There is an 11.8 % difference between mean and median escapement values for this device, showing the influence of outliers on the arithmetic mean value (Figure 3A).

4.1.3. Discard rate reduction

Discard rate reduction in terms of weight of *Nephrops* from the SMC trials ranges from -43.8 % to 100 %, with a bimodal distribution (Figure 3B). Standard deviation is 1.5 times greater than mean escapement value; mean and median values are similar (Figure 3B).

Distribution of discard rate reduction from the grid trials is skewed towards negative values (Figure 3B), although only two records are inferior to -100 %, at -107.4 % and -158.9 %. The 5^{th} quantile is equal to -66.8 %. Standard deviation is 3.4 times larger than the mean value; the median value 1.7 larger than the mean value (Figure 3B). The maximum discard rate reduction recorded was 71.5 %.

4.1.4. Relative catch probability

Catch probability of the test gear relative to the control gear was modelled on the 5-45 mm CTL interval to guarantee homogeneity of the variance in the dataset of predicted values. Models including both a random intercept and a random slope returned the best fit, with the lowest AIC value for both selective devices tested (Table 3). All the parameters included made a statistically significant contribution to the model, with size effect being different from zero.

Table 3. Parameter estimates for fixed effects and standard deviation associated with random effects for *Nephrops* relative retention models (RI: model with random intercept; RIRS: model with random intercept and random slope; SD: standard deviation; * p<0.05, **p<0.01, ***p<0.001).

	Square Mesh Cylinder		*Inverted Grid*	
	RI	*RIRS*	*RI*	*RIRS*
AIC	54257	51069	53938	51150
Fixed effects : estimates (SD)				
(Intercept)	- 0.16 (0.03) ***	- 0.16 (0.03) ***	- 0.09 (0.03) **	- 0.09 (0.03) **
Length	0.10 (0.01) ***	0.15 (0.05) **	0.12 (0.01) ***	0.14 (0.04) **
Length²	- 0.10 (0.01) ***	- 0.15 (0.01) ***	- 0.13 (0.01) ***	- 0.17 (0.01) ***
Random effects : SD				
Haul	0.27	0.27	0.26	0.26
Length	-	0.39	-	0.35

Conclusions drawn from graphical representations of the models outputs as relative catch probability are identical for the two selective devices (Figure 4). The random effect associated with length has either a larger or an equivalent influence on the odds ratio of the retention than does the random effect associated with haul

(Table 3); both selective gears reduce catches over the whole range of sizes sampled, from 15 mm to 45 mm CTL (Figure 4). The effect of the selective devices is, however, weak for individuals between 27 mm and 39 mm CTL, while it is stronger for small sized individuals (<25 mm CTL). The 95 % confidence intervals (CI) are small over the whole size range considered in the modelling process (Figure 4).

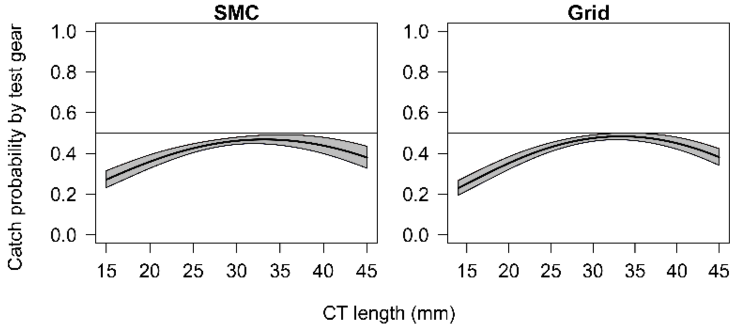

Figure 4. GLMM output representing *Nephrops* relative catch probability by the test gear relative to the control gear from the implementation of the SMC (left) and grid (right), with 95 % confidence intervals around the mean.

4.2. Effects of the selective devices on hake catches

4.2.1. Catch composition from sampling

Hake captured during the trials ranged from 10 to 80 cm in length, and less catches of hake were recorded from trials with the SMC than from trials with the grid (Figure 5). Population structure of individuals sampled through the use of selective gears is different to the control gear for both selective devices, with statistically highly significant t-values (p<0.001) (Table 4), indicating an effect of the devices. However, overdispersion in the proportions of fish retained are observed for length values greater than 40 cm for the SMC and greater than 35 cm for the grid (Figure 5), limiting our ability to infer the effect of the devices above these sizes.

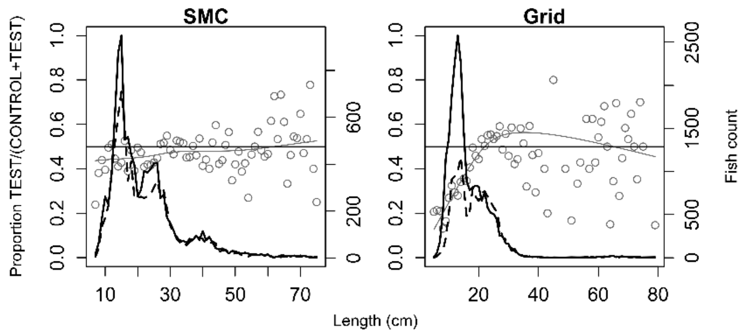

Figure 5. Pooled scaled-up catches of hake from trials of the SMC (left) and of the grid (right). Catches from the control gear (thick black line), catches from the test gear (thick broken line), proportions (dots) and a regressive spline with four degrees of freedom run on weighted proportions (thin grey line) are shown.

Table 4. Descriptive statistics and t-value with level of statistical significance of hake sampled with the different trawl designs. (L: length; SD: standard deviation; ***p<0.001)

	SMC		*Grid*	
	Control	*Test*	*Control*	*Test*
L – mean (cm)	32.4	32.6	26.0	27.9
L – median (cm)	31.0	31.0	22.0	24.0
L – sd (cm)	15.2	15.4	16.2	16.8
t-value	3.94***		7.97***	

Hake caught during the SMC trials were larger on average than those caught during the grid trials (Welsh's t-test on catches of the control gears: $t = -13.33$, $p<0.001$) (Table 4). Standard deviation around the mean was similar for the two selective devices and for the test and control gears (Table 4), which can be attributed to the effect of environmental variability alone.

From the SMC trials, data structure in length indicates three cohorts with modes at 15 cm, 27 cm and 40 cm (Figure 5). From the grid trials, only two cohorts, with modes at 15 cm and 25 cm, could be identified; few individuals of length greater than 35 cm were encountered during the grid trials (Figure 5).

4.2.2. Escapement of undersized hake

Undersized hake escapement values from the SMC display a quasi-normal distribution, with a longer tail toward negative values; the 5th quantile is -60.8 % (Figure 6A) and the recorded minimum value is -118.9 %. The maximum escapement value recorded was equal to 100 %. Standard deviation is 2.5 times larger than the mean escapement value for undersized hake; the difference between mean and median escapement values is negligible for this device.

Distribution of undersized hake escapement values from the grid is skewed towards negative values, with a recorded minimum value of -174.6 %. However, 75 % of the data are positive (Figure 6A) and the maximum escapement value is equal to 88.5 %. Median escapement value is greater than the average value; standard deviation is 2.9 times larger than the mean value (Figure 6A).

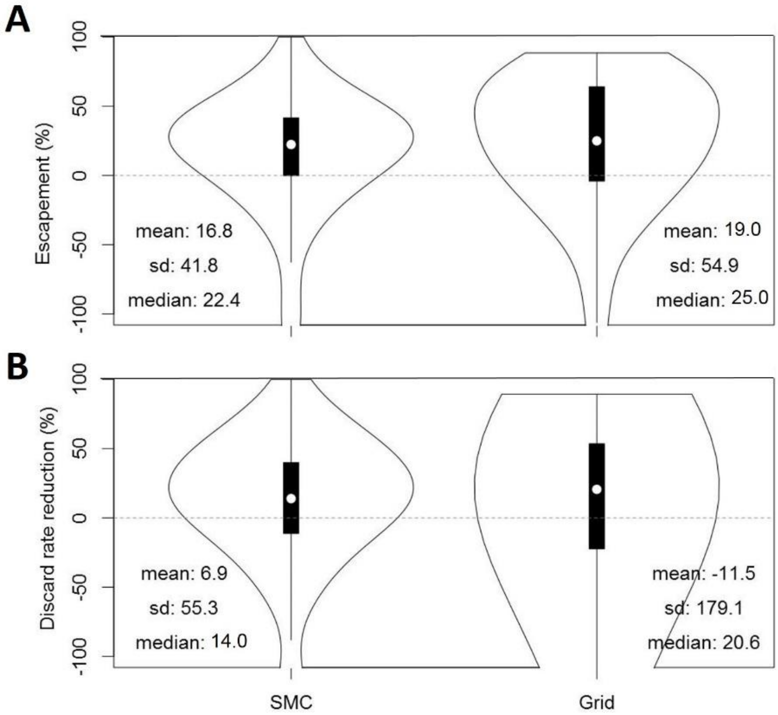

Figure 6. Escapement levels of undersized hake in numbers (A) and discard rate reduction of undersized hake based on estimated discard weights (B) for the implementation of the SMC (left) and of the grid (right) compared with the control gear. Violin plots display the median (white dots), 25th to 75th percentiles (black-filled rectangle) and extreme 5th and 95th percentiles (straight black line), the black curves illustrate the data distribution. Mean, SD and median values are given.

4.2.3. Discard rate reduction

Hake discard rate reduction in terms of weight from the use of the SMC displays a quasi-normal distribution, with six records having strongly negative values, from -113.8 % to a minimum of -202.0 % (Figure 6B). Maximum discard rate reduction recorded reached 100 %. The median value is greater than the mean value, and standard deviation is 8 times larger than the mean value (Figure 6B).

Hake discard rate reduction from the use of the grid is heterogeneous, with no distinctive pattern in the data distribution (Figure 6B). Discard rate reduction observed ranged from an extreme negative value at -1422.4 % to a maximum of 89.4 %, with eight records inferior to -100 % of which seven lie between -147.3 % and -107.0 %. The 5th quantile has a value of -122.1 %. Mean and median values are very different, the former being negative, which would mean that the selective device increases discards in terms of weight, and the latter positive (Figure 6B). The standard deviation is 179.1 % due to an extreme outlier.

4.2.4. *Relative catch probability*

Relative catch probability of the test gear compared with the control gear was modelled for the 5–45 cm TL range for the SMC, and on the 5–35 cm TL range for the grid, to guarantee homogeneity of the variance in the data set of predicted values. Models including both a random intercept and a random slope returned the best fit, with the lowest AIC value (Table 5).

Table 5. Parameter estimates for fixed effects and standard deviation (SD) associated with random effects for hake relative retention models (RI: model with random intercept; RIRS: model with random intercept and random slope; SD: standard deviation; * p<0.05, **p<0.01, ***p<0.001).

	SMC		*Grid*	
	RI	*RIRS*	*RI*	*RIRS*
AIC	6629	6320	10347	9911
Fixed effects : estimates (SD)				
(Intercept)	- 0.03 (0.09)	- 0.10 (0.09)	- 0.19 (0.07)**	- 0.26 (0.07)***
Length	0.08 (0.02)**	- 0.03 (0.12)	0.36 (0.02)***	0.31 (0.07)***
Length²	0.01 (0.02)	0.04 (0.03	- 0.20 (0.02)***	- 0.28 (0.02)***
Random effects : SD				
Haul	0.70	0.73	0.58	0.63
Length	-	0.92	-	0.57

Models configured for hake selectivity from the use of a SMC appear poorly fitted, with statistical significance of the different parameters being larger than 0.1 for all parameters, except length in the random intercept model, and larger than 0.1 for all parameters in the random intercept and random slope model (Table 5). Random factors have greater effects than fixed factors on the predicted relative retention's odds ratio, with associated standard deviations being one order of magnitude larger. When included, the random factor "length" had greater influence on the relative retention's odds ratio than the random factor "haul" (Table 5). There is no significant effect of the SMC over the size range considered, with the relative catch probability ranking from a minimum for individuals 24 cm TL, with 95 % CI [0.43; 0.52], to a maximum for individuals of 45 cm TL, with 95 % CI [0.35; 0.69] (Figure 7).

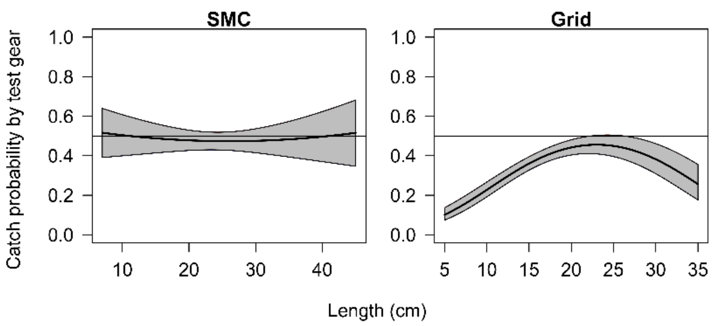

Figure 7. GLMM output representing hake relative catch probability by the test gear relative to the control gear following the implementation of the SMC (left) and grid (right), with 95 % confidence intervals around the mean.

Models set for hake selectivity from the use of the grid showed a statistically significant effect of all parameters included (Table 5). As for the SMC, random factors have a greater effect on the relative retention's odds ratio than fixed factors. Effects of the two random factors considered are of a similar order of magnitude. The random factor associated with haul is unaffected by the addition of a length associated random factor (Table 5). Relative catch probability is significantly smaller than 0.5 for fish under 22 cm and over 27 cm TL, reflecting an escapement through the grid (Figure 7). Relative catch probability for this gear decreases with fish size below 22 cm TL; 95 % CI around the mean is small over the whole size range considered, with a minimum for fish of 17 cm TL, with 95 % CI [0.36, 0.43], and a maximum for fish of 35 cm TL, with 95 % CI [0.18, 0.36].

4.3. Effect of the selective devices on the commercial fraction of the catch

4.3.1. Nephrops commercial catch rate reduction

Both selective devices induce losses in the commercial fraction of the catch (Figure 8A). For the SMC, commercial catch rate reduction in weight of *Nephrops* displays a quasi-normal distribution of the data around the mean value (Figure 8A). Maximum reduction of commercial catch rate is 67.2 %, and the minimum recorded value -65.2 %.

The distribution of commercial catch rate reduction values for the grid was quasi-normal around the mean value (Figure 8A). Reduction of the commercial catch rate did not exceed 66.4 %, the minimum recorded value is equal to -29.7 %.

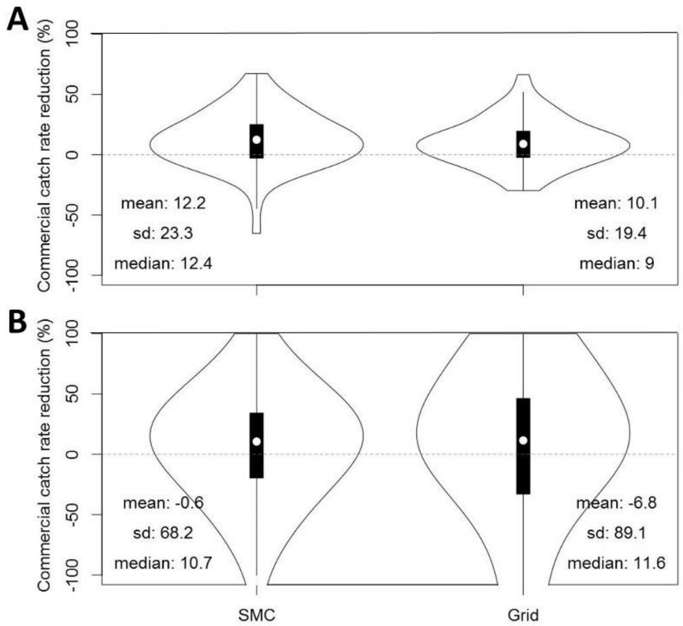

Figure 8. Commercial catch rate reduction of *Nephrops* (A) and hake (B) based on estimated commercial catch weight following the implementation of the SMC (left) and grid (right) compared to the control gear. Violin plots display the median (white dots), 25th to 75th percentiles (black-filled rectangle) and extreme 5th and 95th percentiles (straight black line), the black curves illustrate the data distribution. Mean, SD and median values are given.

4.3.2. Hake commercial catch rate reduction

Levels of losses from the commercial fraction of hake in terms of weight following the implementation of the SMC displayed a quasi-normal distribution, with 3 records in the strongly negative values, at -112.4 %, -175.7 % and -384.6 %. This variability causes a large standard deviation and the median to be greater than the mean value (Figure 8B). The maximum discard rate reduction recorded is 100 % (Figure 8B).

Commercial catch rate reductions for hake from the use of the grid were heterogeneous. Values recorded ranged from -290.0 % to 100.0 %, with 9 records of rates inferior to -100 %. The 5th quantile had a value of -188.3 %. The mean commercial catch rate reduction is negative while the median is positive; the standard deviation is 13.1 times larger than the mean value (Figure 8B).

4.4. Results summary

The occurrence of extreme negative values of discard rate reduction, escapement of undersized individuals or commercial catch rate reduction caused median values to be more reliable than the means throughout our results. These extreme values were kept in the analysis process to reflect the randomness inherent to the fishing process, which is associated with herding effects of fish when confronted to trawling (Catchpole and Revill, 2008; Wardle, 1986).

The 68-mm gauge size SMC appears efficient at letting undersized *Nephrops* escape with little variability in the results. From the modelling outputs, length is a statistically significant parameter for explaining the variability in relative catch probability, although randomness arising from environmental conditions and from characteristics of individual fish contribute equally to the overall variability observed (Table 3). Median loss associated with this device was 12.4 % in terms of weight of market-sized *Nephrops* (Figure 8A). The device is, however, not effective at letting hake of 5 to 45 cm TL escape when taking into account random variability. Compared to median values obtained for escapement and discard rates reduction for undersized hake (Figure 6), the model outputs emphasize the dominant influence of individual variability and of environmental conditions on the expected catch probability, with the influence of length being null (Table 5). Observed loss from the commercial fraction of the catch could reach 10.7 % but variability is high (Figure 8B).

Median escapement and discard rate reduction of undersized *Nephrops* from the grid is greater than from the SMC (Figure 3). Variability is also greater with this device than observed with the SMC. Loss from the commercial fraction reaches 9 % median weight (Figure 8A). Models of relative catch probability return similar results as for the grid, with a statistically significant effect of size on the catch and variability being equally attributed to individual characteristics and environmental conditions (Table 3). For hake, the grid appears more effective than the SMC at letting undersized individuals escape, which is in agreement with grid studies carried out on other *Nephrops* fisheries of the North-East Atlantic (Madsen and Valentinsson, 2010; Valentinsson and Ulmestrand, 2008). The most stable relative catch probability values are obtained for fish of 17 cm TL while the largest variability is associated with the maximum length considered for modelling, at 35 cm TL (Figure 7). Median escapement of undersized individuals is 25 %, corresponding to a 20.6 % discard rate reduction in weight (Figure 6). However, variability is very large for the latter. Median loss from the commercial fraction represents 11.6 % of the commercial catches (Figure 8B). Despite the variability observed, relative catch probability modelling identified the grid as an efficient device for undersized hake selectivity. Although variability due to environmental conditions and individual characteristics is still important, length is a good predictor of fish catch probability (Table 5).

5. Discussion

5.1. Sampling conditions and methods

Different population structures for hake were observed during the SMC trials and during the grid trials, with very few fish larger than 40 cm captured during the grid trials (Figure 3A). Such a difference may arise from the sampling scheme used, with trials conducted at slightly different periods of the year. While *Nephrops* is sedentary and its abundance unaffected by this parameter, hake populations will migrate from feeding sites to reproduction sites over the year. The absence of large, sexually mature, individuals is the signature of such migratory patterns (Casey and Pereiro, 1995; de Pontual et al., 2013). When modelling the relative catch probability, this lack of information impaired our ability to analyse the effect of the grid on a potential loss of larger individuals, which have a higher market value.

When comparing relative proportions of hake retained per length class with catch probability graphs, the trends underpinned for fish larger than 25 cm TL by the spline seem to be further accentuated in the models. However, escapement of large fish through the grid appears unrealistic from a mechanical point of view (Valentinsson and Ulmestrand, 2008). Although there is a general consensus on the method (Holst et al., 2009), further methodological development would be necessary to evaluate if the use of a higher order polynomial may be more appropriate to limit the dome-shaped effect arising from the quadratic form used here; this is however beyond the scope of this study. One would thus recommend caution when interpreting model results for fish larger than 25 cm TL.

Our estimations of discards and of commercial catch rate reduction are based on MLS as discarding criterion. However, data from an on-board observer program on the percentage of undersized individuals in the discards clearly show some high-grading practices taking place. The weight of discards arising from high-grading of the commercial fraction of the catch could represent up to 15 % of all discards for *Nephrops* and up to 11 % for hake (Cornou et al., 2015). Moreover, on-board observer programs only provide a limited picture of fishing practices (Benoît and Allard, 2009), meaning that high-grading practices may be underestimated. Such phenomena would affect both the total weight of the discards and the commercial catch. Values presented here are therefore to be considered with caution: the predicted loss from the commercial fraction of the catch may be overestimated, as well as discard rate reduction.

5.2. Selective gear technology and development

Previous studies identified uneven effects of the currently mandatory selective devices for the *Nephrops* and hake trawling fleet of the Grande Vasière (Nikolic et al., 2015). With the discard ban now enforced and the strong incentive to gain exemptions, the results of our trials provide managers with new, more efficient devices to submit to professional fishermen. Taking into account the historical background of the mixed fishery for *Nephrops* and hake on the *Grande Vasière*, selectivity studies aimed primarily at reducing hake bycatch for biological reasons. Only the grid would provide an efficient tool to help and reduce catches of undersized individuals for this species. Undersized *Nephrops* would benefit from the implementation of any of the two devices tested here.

The switch from a ventral position, as currently enforced (Nikolic et al., 2015), to a dorsal position improves the efficacy of the grid for hake escapement; it may also reduce mending costs by limiting friction with the bottom, making the grid more attractive to fishermen. However, our analysis emphasized the importance of random factors in escapement success, such as environmental conditions and individual fitness (Killen et al., 2015). These results support an opportunistic escapement behaviour for hake, for which contact probability with the device would be the best predictor of escapement as documented for other round fish species in the North-East Atlantic such as cod and whiting (Jones et al., 2008; Krag et al., 2016; Vogel et al., in review).

Based on the SMC trials, increasing mesh opening by modifying its geometry is efficient for *Nephrops*, whose escapement is considered passive. Its influence on hake, a fish with active escapement behaviour, is null but not detrimental. Increasing mesh size for the SMC should be tested, as the device is easier to integrate into the extension part of the trawl, and requests less care and handling at sea than the grid in case of commercial application. Other mesh sizes and geometries could be considered to identify those best suited to the morphology of hake and to improve escapement of undersized individuals (Herrmann et al., 2009; Krag et al., 2011).

5.3. Implications for fisheries management

Favouring selective practices and gears is one of the incentives of the discard ban to reduce the overall fishing pressure on stocks and improve exploitation patterns. In another mixed fishery targeting prawns Zhou *et al.* (2014) identified discards as an element of sustainable fishing: with reduced fishing mortality rates, individuals returned to the sea contribute to stock dynamics. The implementation of selective devices may foster the process as individuals escaping through the selective device may display higher survival rates than discarded individuals due to reduced stress conditions (Suuronen, 2005). *Nephrops* escaping through the selective devices would contribute to the future reproductive biomass and, despite losses on the commercial part of the catch, will benefit the population dynamics in the long term (Macher et al., 2008). The additional discard reduction provided by the grid and the SMC, associated with the recent results published on *Nephrops* survival from the discarding process (Méhault et al., 2016), need to be implemented in broader simulation models for stocks dynamics to re-evaluate Maximum Sustainable Yields in terms of biomass and effort for the fishery and its effect on near-by fleets (Guillen et al., 2014, 2013).

From our results, any device that has a positive effect on reducing catches of undersized individuals and the amount of discards will also affect commercial catches. The choice of one device over another will be guided by commercial practices, fishing strategies and targeted species (Eliasen et al., 2014; Sigurðardóttir et al., 2015). *Nephrops* being the species with the greatest market value, the SMC and grid would affect fisher's income equally in the short term. However, as escapement of undersized individuals is greater than commercial loss, the subsequent increase in recruitment could be beneficial both in terms of population dynamics and financial incomes for fishers in the long term (Raveau et al., 2012). Some short-term benefits may also occur if commercial sized individuals escaping from the gear remain available for capture on a later occasion upon survival, although additional costs associated with time at sea would need to be considered. Predictions also need to be made on the additional time at sea required to level off commercial catches, to estimate the amount of unwanted catches that may be generated, and to evaluate the part of TACs that will be lost to these unwanted catches.

5.4. Ecological impacts of the discard ban for the Bay of Biscay

From a food web perspective, the implementation of the discard ban for the *Nephrops* fishing fleet in the Bay of Biscay represents the loss of 1208 tons of *Nephrops* and of 1252 tons of hake on average every year (Kopp et al., 2016), both to the benthic communities and to top-predators (Depestele et al., 2016). Reducing catches of undersized individuals by technological measures in the form of selective devices implemented in the body of commercially used trawls is a way to limit the consequences of the discard ban for the ecosystem.

Assuming that discards are exclusively composed of undersized individuals, the implementation of the SMC would reduce discards to 923 tons of *Nephrops* and 1077 tons of hake, and the implementation of the grid to

949 tons of *Nephrops* and 994 tons of hake, on annual average. In the case of an exemption being granted to the fleet, selective gears will help to maintain the marine food webs of the Bay of Biscay, by limiting the changes in nutriment incomes, and to ensure the resilience of their trophic dynamics under the new CFP (Fondo et al., 2015; Kopp et al., 2016). However, in case of the landing obligation being pursued, understanding the effects on the ecosystem of such a drastic reduction in food incomes would require further analyses to be carried out (Sardà et al., 2015).

6. Conclusion

Many questions still remain regarding the implementation of the discard ban for the mixed fishery for *Nephrops* and hake of the *Grande Vasière.* Previous experiments of discard ban in the North-East Atlantic took almost 30 years to reach a state of equilibrium and required strong controls of the fishing activity to ensure the compliance of professional fishermen with the implemented measures (Gullestad et al., 2015). However, these drastic measures paved the way to the development and extended use of selective fishing gears (Gullestad et al., 2015).

If gear selectivity cannot be considered as an objective towards the sustainable management of fisheries (Fauconnet and Rochet, 2016), it is an essential element in the development of sustainable fishing practices at a larger scale (Condie et al., 2014). However, results from the SMC trials carried out in this study highlight the difficulty to provide selective devices for vessels targeting multiple species. Moreover, economical drivers leading to high-grading and other quotas-related discarding practices will also need to be addressed. Therefore, the success of the new CFP relies on the implementation of new selective devices within an integrated framework, including renewed management measures and strong incentives to adopt them (Condi et al., 2013).

If our findings together with the high survival of discarded *Nephrops* (Méhault et al., 2016) indicate that an exemption from the discard ban based on the mandatory implementation of selective gears would benefit the ecosystem, the stocks and the fishermen, the long term benefits of the discard ban and associated exemptions are debatable. From an economical point of view, potential adverse effects of the discard ban following previous measures to reduce hake bycatch in the *Nephrops* and hake fishery of the *Grande Vasière* include hake becoming a “choke species” (Schrope, 2010; Ulrich et al., 2011). TACs for hake remain low despite the stock being back to acceptable levels of abundance following the emergency plan put into force in 2001 (Baudron and Fernandes, 2014). As such, an exemption granted to the fishery would guarantee that fishermen can keep targeting

Nephrops once hake quotas have been exceeded. However, in a socio-economic study of the different trawling fleets of the Bay of Biscay, Prellezo et al. (2016) simulate the effects of flexibilities and exemptions associated with the discard ban policy. They identified a strict discard ban as a more efficient management measure due to redistributive choke effect between the different fleets of the southern part of the Bay of Biscay (Prellezo et al., 2016).

To conclude, adding ecological considerations to the needs of the fishing sector in the context of the new Common Fisheries Policy, our results emphasize the on-going role of gear technology research towards achieving sustainable fishing practices and obtaining exemptions based on the demonstrated interests of selective discards (Heath et al., 2014).

7. Acknowledgments

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