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Efficacy of selective devices in reducing discards in the *Nephrops* trawl fishery in the Bay of Biscay

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The *Nephrops* fishery in the Bay of Biscay is an important commercial fishery which generates large amounts of discards owing to the use of small mesh trawls. To reduce discards, French trawlers were equipped with a variety of selective devices, from 2005 onwards. This study examines their efficacy using data from the French on-board observer programme, 2003–2010. Generalized linear models were built for catches, discards, and landings of *Nephrops* and hake, controlling for the other factors which drive the variability in these variables. A dorsal square-mesh panel meant to let small hake escape did not affect hake catch, but was found to decrease *Nephrops* catches and discards. Among the devices intended to reduce *Nephrops* discards, the flexible grid was the most efficient, as it decreased catches and discards in large proportions while increasing landings but this result was supported by a small number of observations; a larger mesh size in the codend (80 mm instead of 70) slightly decreased *Nephrops* discards; and a ventral square-mesh panel was not found to affect catch or discards of either species. The design of the on-board observer programme was meant to estimate discard amounts, which limited their utilization to investigate factors for discarding.

Keywords: analysis design, bycatch, hake, nephrops, observational study, on-board observer programme.

Introduction

Fisheries discards are an issue of increasing concern and there is a growing number of studies aiming at estimating discard amounts and characteristics since the 1980s (Rochet and Trenkel, 2005). World fisheries have been estimated to discard almost a third of their total catch (Alverson *et al.*, 1994). More recent estimates (Kelleher, 2005) suggest a decrease, often ascribed to the adoption of more selective fishing gears, changes in fishing practices to reduce bycatch, the decline of some fisheries, and a higher retention rate. This trend is not homogenous though, and some fisheries keep generating high levels of discards, including in European waters (Commission of the European Communities, 2009).

Many bottom trawls catch non-targeted fish and unwanted lengths of the targeted species, much of which are often discarded, with unknown mortality rates. Among bottom trawl fisheries, those which target crustaceans tend to generate high levels of discards (Alverson *et al.*, 1994). This includes the French bottom trawler fleet-targeting *Nephrops norvegicus* (hereafter *Nephrops*) in the Bay of Biscay (ICES Divisions, VIIIa,b), one of the most valuable French fisheries. Most of the *Nephrops* landed is caught with small mesh trawls (≤80 mm), consequently large quantities of small fish are also caught, and much of this bycatch is undersized and discarded.

Various ways of allowing juveniles to escape from trawls have been investigated by sea trials or simulations, such as larger mesh size (Briggs *et al.*, 1999), escape windows (Madsen *et al.*, 1999), square-mesh panels (Graham and Ferro 2004; Revill *et al.*, 2007), and a grid in the net (Dupouy *et al.*, 1997; Massart, 2000; Loaec *et al.*, 2006). Experiments in the Bay of Biscay demonstrated that the grid allowed juvenile benthic fish (Dupouy *et al.*, 1997; Massart, 2000) and juvenile *Nephrops* (Loaec *et al.*, 2006) to escape. While *Nephrops* discards were reduced by 50% with the grid (Graham and Ferro, 2004), a loss of marketable catch was also detected (Loaec *et al.*, 2006). Experiments in the Bay of Biscay with square-mesh panels dedicated to reduce the capture of juvenile hake decreased the retention of mature and juvenile hakes by a range of 30–50% (Graham and Ferro, 2004).

Partly based on these studies, technical regulations have been introduced to reduce bycatch in the Nephrops fishery in the Bay of Biscay. In 2002, the European Commission established a recovery plan for the Northern stock of European hake (*Merluccius merluccius*), under which the minimum codend mesh size (MMS) was raised from 70 to 100 mm to reduce the high level of hake discarding by *Nephrops* trawlers in the Bay of Biscay (EU Reg. 2341/2002). EU technical regulations in force in 2003 and 2004 are contained in Council Regulation (EC) No. 850/98 and its amendments. At the French government's request a 2-year derogation was granted to the industry to allow time for developing alternative solutions. Beginning in 2005, all vessels needed eventually to be equipped with a selective device for hake, a 100 mm square-mesh panel (dorsal square-mesh panel, DSM), instead of the 100 mm MMS. In addition, to decrease *Nephrops* discards of undersized specimens, since 2008 all vessels catching >50 kg of *Nephrops* per day must use at least one of three selective devices: a ventral square-mesh panel of minimum 60 mm (VSM), a flexible grid (13 mm spaced circular bars (GR)) at the bottom of the codend, or an 80 mm codend mesh size. Here, we examine whether these selective devices have fulfilled their role: have they contributed to reduce hake and *Nephrops* discards when introduced in the Bay of Biscay *Nephrops* fishery? More specifically, we expect that the catch of both the target and bycatch species were changed in amount and length-composition, and that the relationship between the amounts caught and discarded were modified by the selective devices. The latter only applies to the target species, as most of the bycatch species is discarded anyway. Besides, we also examine to what extent landings of the target species have been affected by the selective devices, as this might influence the uptake of these devices by fishers.

On-board observer programmes provide data to examine this question. These programmes consist in embarking scientific observers on-board fishing vessels during commercial trips; observers sample and record the whole catch, including the discarded fraction. These data are collected under sampling plans designed to estimate total catch and discards, thus, they should be representative of the fishing activity. The wide fluctuations in catch and discards are driven by multiple and interacting factors (Rochet and Trenkel, 2005; Feekings *et al.*, 2012). These factors can be social such as fishers' perceptions, which determine their level of compliance (Matić-Skoko *et al.*, 2011), biological such as the recovery of a target stock (Matić-Skoko *et al.*, 2011), or economic such as market and fuel prices (Catchpole *et al.*, 2008). Gear efficacy is the result of fish behaviour (avoidance or herding), mesh size, factors related to gear rigging and fishing vessel characteristics (power, length, crew experience, etc.), and seasonal variations (Trenkel *et al.*, 2008). The potential influence of these factors has to be controlled for when investigating the efficacy of selective devices. But this is not straightforward because the data are not balanced across all factors. Lack of balance may lead to spurious conclusions. For example, a hypothetical selective device could be found to catch smaller fish, just because this device was mostly deployed during the recruitment season, when smaller fish are caught by all gears anyway. An analysis including all data without checking for these potentially confounding factors might produce false results. A balanced analysis design is a key step for obtaining causal inferences in observational studies (Rubin, 2008). This can be done in two ways: by extracting subsets of data in which potentially confounding factors are homogeneous and by ensuring that the data are sufficiently balanced across the combinations of the potentially confounding factors and the factor of interest—here, the selective devices.

In this study, we investigated the efficacy of the selective devices added to bottom *Nephrops* trawls to reduce the discards of hake and *Nephrops* in the Bay of Biscay, and examined whether they affect total catch, discards, and landings. To that aim, we used on-board observer data on commercial fishing vessels from the national programme carried out under the European Union Data Collection Framework (DCF; European Union, 2001, 2008). Generalized linear models were used on appropriate subsets of these data to examine whether (i) selective devices changed the catch of the target (*Nephrops*) and main bycatch species (hake), either in number or weight; (ii) selective devices changed the relationship between catch and discards, or catch and landings, for the target species *Nephrops*; and (iii) selective devices changed the average length of the catch, for the bycatch species hake. In addition, we also examined whether changes in hake and *Nephrops* discards at the fleet level could be observed when the selective-device-related regulations entered into force—namely, in 2005 and 2008.

Material and methods

The fishery

The traditional *Nephrops* trawl has a low headline, typically <2 m, with short wings, and a minimal 70 mm mesh throughout (since 2000). The use of multiple trawl rigs started in the mid-1980s and has expanded since the late-1980s throughout the European *Nephrops* fleet in the Atlantic (Bell *et al.*, 2006). Two categories of trawls are currently used: otter twin (OTT) and bottom otter trawls (OTB). In the North of the Bay of Biscay the fishery operates mainly twin trawls targeting *Nephrops* species throughout the year while in the South single trawls are more often used, mostly in summer. There is currently a fleet of 200 vessels (*numerus clausus* licence system), 11–22 m long with a typical crew of three seamen. *Nephrops* trawlers spend ~200 days at sea per year with the time spent per trip varying from 12 h to 3 days (Dubé *et al.*, 2012). In 2010 3398 tons of *Nephrops* were landed (ICES, 2010). Since December 2005, a minimum landing size (MLS) of 26 mm carapace length (CL), i.e. 9 cm total length, has been agreed by French Producers' Organizations for marketing reasons, above the European regulatory MLS (21 mm CL), i.e. 7 cm total length. Spawning biomass and fishing mortality were relatively stable until 2005; recently fishing mortality decreased and spawning biomass increased (ICES, 2012). Legal hake MLS has been 270 mm total length since 1998 (Council Reg. No 850/98) and a plan is implemented for the recovery of the Northern hake stock (European Union, 2004).

Sampling design and protocol

Since 2003, France has implemented a programme of data collection on-board fishing vessels, as part of the DCF. Sampling is stratified by combination of gear and target species, quarter, and ICES area. For each trip, samples (one or more baskets) were taken from the discards, sorted and weighed by species, and length measured. Either the sampling fraction or the total amount of discards was estimated by weight, volume, or visually, depending on working conditions onboard. Landings were weighed by species and individually measured. Total catch per trip was estimated as the sum of landings and discards. The data consisted of the estimated total catch, landings and discards per species per trip, with information on vessel, fishing methods, rectangles, depth, and time and duration for each trip and fishing operation (FO). The sampling protocol is available online (Ifremer, 2012).

For the Bay of Biscay *Nephrops* trawler fleet, the duration of sampled trips was generally 1 or 2 days, and 2.6 FOs were sampled per trip on average. There was no trend in the duration of fishing trips nor FOs over the study period (Supplementary Table S1). The fraction of *Nephrops* FOs sampled within observed trips varied between 40 and 90% from 2003 to 2010, for a total of 739 FOs sampled in ICES divisions VIIIa and VIIIb (Table 1). Trips carried out from 2003 to 2010 in division VIIIa were selected, which represented a total of 687 FOs sampled (Figure 1).

Model analysis

Many environmental and vessel- or gear-specific parameters influence discard rates (Rochet and Trenkel, 2005; Krag *et al.*, 2008; Madsen and Valentinsson, 2010). These factors vary between species, vessels and métiers, and over time and space (Rochet *et al.*, 2002; Bell *et al.*, 2008; Trenkel *et al.*, 2008; Catchpole *et al.*, 2011). *Nephrops* emerge from burrows at different times depending

Table 1. Number of fishing operations sampled and trips observed per year, and fraction (%) of fishing operations (FO) sampled within observed trips on-board *Nephrops* trawlers in the Bay of Biscay (VIIIa–b).

			2003	2004	2005	2006	2007	2008	2009	2010	2003–2010	
Nephrops	Discards	Fishing operations	113	92	125	74	81	50	116	88	Total	739
		Trips	43	43	51	30	26	20	35	40		288
		% FO sampled	70	70	60	70	80	80	50	40	Mean	65
	Landings	Fishing operations	116	94	124	74	79	49	111	89	Total	736
		Trips	44	43	50	30	25	20	35	41		288
		% FO sampled	70	70	60	70	90	80	40	40	Mean	65
Hake	Discards	Fishing operations	105	90	126	73	78	51	115	91	Total	729
		Trips	43	42	51	30	26	20	35	42		289
		% FO sampled	70	70	60	70	80	80	50	40	Mean	65
	Landings	Fishing operations	116	94	125	73	73	51	76	78	Total	686
		Trips	44	43	51	30	25	20	34	38		285
		% FO sampled	70	70	60	70	80	80	30	40	Mean	63

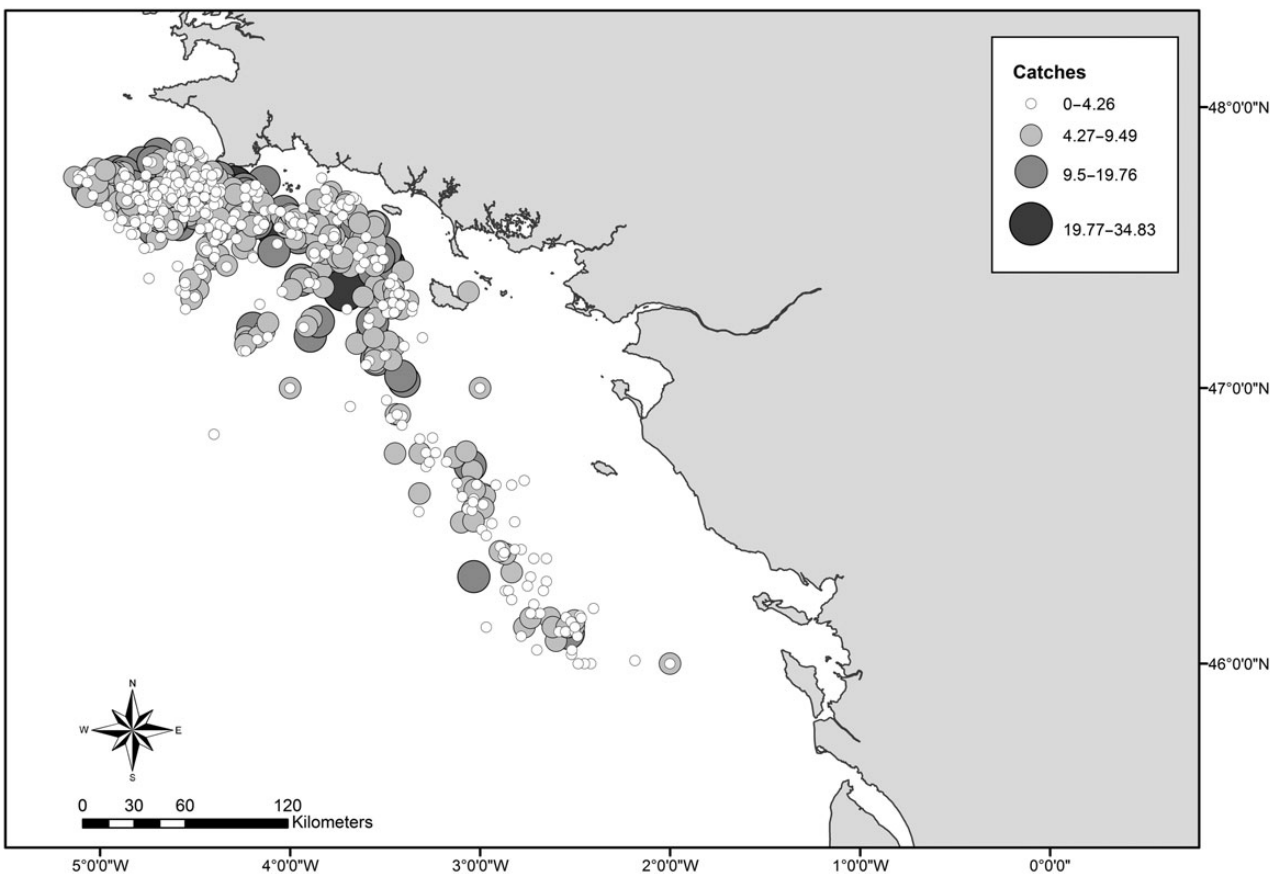

Figure 1. Locations of the *Nephrops* trawlers fishing operations sampled in the on-board observer programme from 2003 to 2010 in the Bay of Biscay with the corresponding catch weight (kg).

Table 2. Variables included in the generalized linear models of hake and *Nephrops* catch and discards.

Variable name	Unit or levels	Definition	Comment
Dependent variables			
CatchN	No individuals	Number caught per FO	
CatchW	g	Weight caught per FO	
DiscardN	No individuals	Number discarded per FO	
DiscardW	g	Weight discarded per FO	
LandN	No individuals	Number landed per FO	
LandW	g	Weight landed per FO	
MeanLength	mm	Average length of the FO catch	Only used for hake
Explanatory variables			
CatchN	No individuals	Number caught per FO	Only for numbers discarded or landed
CatchW	g	Weight caught per FO	Only for weights discarded or landed
FishingTime	Minutes	Duration of FO	
Latitude	Decimal degrees	Latitude at the FO start	
Depth	m	Depth at the FO start	
VesselPower	[0–210], [211–241], [242–293], [294–551] kW	Vessel horse power	Proxy for vessel effect. Categorized
Year	2003–2010	Year of FO	Categorized
Quarter	Q1, Q2, Q3, Q4	Quarter of FO	
DayTime	Morning, evening	Time since sunrise at FO beginning	Categorized
DSM	DSM, None	Presence of dorsal square-mesh panel (against no device at all)	
GR	DSM-GR, DSM	Presence of flexible grid combined with dorsal square-mesh panel (against dorsal panel alone)	
VSM	D + VSM, DSM	Presence of ventral square-mesh panel combined with dorsal panel (against dorsal panel alone)	
MeshSize	70 mm, 80 mm	Mesh size in the codend	
VSM × Mesh size	(D + VSM—70 mm), (DSM—80 mm)	Combinations of codend mesh size with ventral square-mesh panel and/or dorsal panel	The other combinations (D + VSM—80 mm) (DSM—70 mm) were too rarely used

Continuous variables are *italicized*, all other variables are categorical. The continuous variables that were categorized to allow simple modelling of non-linear effects are mentioned as "Categorized" in the "Comment" column.

Table 3. Variables included in the generalized linear models of hake and *Nephrops* catch, discards, and landings, selected in a stepwise forward approach using analysis of deviance, for each selective device.

Nephrops				
Selective device	DSM	GR	VSM	Mesh size
Year(s)	2005	2007	2009–10	2007–10
Subset	Mesh size 70 mm	Quarters 2–3		DSM or D + VSM
n	95	44	163	259
Catch	*CatchN* ~ **DSM** + *FishingTime* + VesselPower + quarter *CatchW* ~ *FishingTime* + VesselPower + quarter	*CatchN* ~ **GR** + DayTime + *Depth*	*CatchN* ~ VesselPower + *Latitude*	*CatchN* ~ VesselPower + *Latitude* + quarter
% Dev. explained	*CatchN*: 21% *CatchW*: 19%	67%	7%	9%
Discards	*DiscN* ~ **DSM** + quarter + log(*CatchN*)	*DiscN* ~ Mesh + **GR** × log(*CatchN*)	*DiscN* ~ year + quarter + log(*CatchN*)	*DiscN* ~ year + quarter + **Mesh** + log(*CatchN*)
% Dev. explained	89%	89%	77%	80%
Landings	*LandN* ~ quarter + log(*CatchN*)	*LandN* ~ Mesh + **GR** × log(*CatchN*)	*LandN* ~ year + quarter + log(*CatchN*)	*LandN* ~ year + quarter + **Mesh** × log(*CatchN*)
% Dev. explained	78%	86%	81%	78%
Hake				
Selective device	DSM	VSM × Mesh size	VSM	Mesh size
Year(s)	2005	2009–10	2009–10	2007–9
Subset	Mesh size 70 mm	(D + VSM—70 mm) or (DSM—80 mm)		DSM (without VSM)
n	95	124	163	149
Catch	*CatchW* ~ *FishingTime* + VesselPower + quarter	*CatchW* ~ *Latitude* + year + quarter	*CatchW* ~ *Latitude* + year + quarter	*CatchW* ~ *Latitude* + year + quarter
% Dev. explained	44%	46%	*CatchW*: 55%	39%
Catch mean length	*MeanLength* ~ VesselPower + *FishingTime* + quarter	*MeanLength* ~ *Latitude* + quarter	*MeanLength* ~ quarter	*MeanLength* ~ year + quarter
% Dev. explained	29%	38%	33%	32%

Only one model is reported when results for weights and numbers were similar. Continuous variables are *italicized*, all other variables are categorical. n = number of fishing operations included in analysis. Selective device effect that were the focus of each analysis are reported in bold when they were retained in the selected model.

on depth, meaning that *Nephrops* availability is expected to vary throughout the day (Trenkel *et al.*, 2007).

Since observations were not balanced across all these explanatory variables, the effect of selective devices could not be tested directly. Rather, the effect of potentially confounding explanatory variables needed to be estimated, to examine selective-device effects on discards, landings, and catch independent of the other explanatory variables. To this effect, generalized linear models (with Gamma distribution and a log link) were built for each variable of interest, using a stepwise forward approach. Terms (candidate variables or interactions) were added one at a time and retained if they significantly reduced the residual deviance (F-test, α-value = 0.05). All candidate explanatory variables (Table 2) were used in the process. The exceptions are water depth and latitude, which are correlated (more shallower FOs were hauled in the North); the variable with the least missing observations for a given subset of data was used. Some continuous variables (vessel power, year, time of the day) had to be categorized to account for potentially non-linear effects while keeping the number of parameters to be estimated low.

Data subsetting for modelling discards

To analyse the effect of selective devices while minimizing the influence of confounding variables on a year-to-year scale, 4-year groups were set up (Table 3). The main purpose of these data subsetting is to avoid the effect of the variables of interest (here, the selective devices) being confounded with other factors. Among these factors, catch and discards are known to be strongly influenced by year and season effects. Therefore, subsets of data used to analyse the effect of a given device should ideally include just 1 year or season. As such subsets may not provide sufficient numbers of FOs to be analysed, an alternative is to design subsets that are approximately balanced across several years and/or seasons. A balance has to be found between the power of the analysis, that is, a enough observations, and potentially dubious conclusions muddled with confounding effects. The DSM, a device designed to let hake escape, was introduced in 2004 and became mandatory in 2005; compliance reached 100% only in 2007 (Figure 2). To analyse the efficacy of DSM, we used 2005 data, the only year with a reasonably balanced proportion of sampled FOs with and without DSM (Figure 2, Table 3). The flexible grid, the VSM, and the 80 mm codend mesh size were designed to avoid small *Nephrops*, thus decrease *Nephrops* discards. Since the DSM was already mandatory, these devices were generally used combined with DSM (DSM-GR, D + VSM). The grid GR was introduced and used in a significant number of FOs only in 2007; therefore, we used 2007 to analyse its effect (Figure 2, Table 3). The VSM panel was introduced in 2008 and significantly used in 2009 and 2010 with 44 and 35% of sampled FOs, thus we used data from 2009 and 2010 (Figure 2, Table 3). Finally, the 80 mm codend mesh size was used in >30% of the sampled FOs from 2007 on; therefore, we used data from 2007 to 2010 to analyse its effects. The latter analyses were carried out thereafter, using the results of the former analyses to decide whether to control for the effect of the other selective devices in addition to year and season.

Additional subsetting was required to avoid confounding effects by other factors, for example, in the analysis of the effect of the grid on *Nephrops* catches and discards. The grid was used mostly in 2007, just during quarters 2 and 3; to avoid confusion with seasonal variations, the FOs using other devices in quarters 1 and 4 were excluded from the analysis, reducing sample size to 44 FOs (Table 3). We also tried to control for confusions between several selective devices and

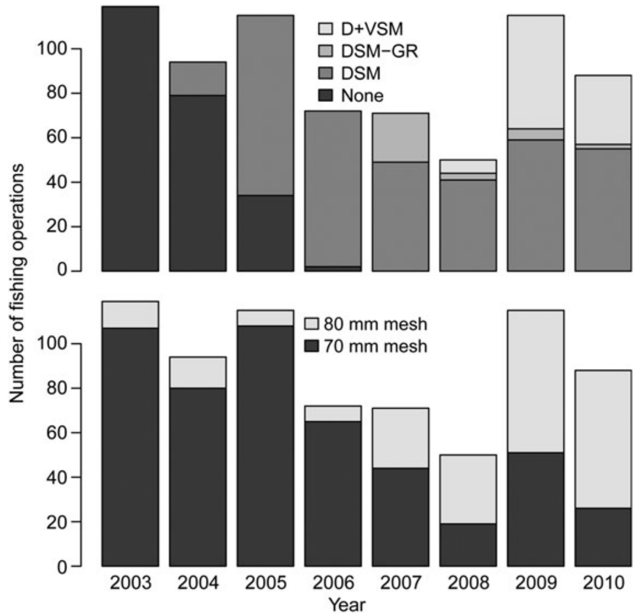

Figure 2. (a) Selective devices and (b) codend mesh size deployed during fishing operations sampled in the on-board observer programme, 2003–2010. None: no device; DSM, dorsal square-mesh panel; D + VSM, dorsal and ventral square-mesh panels; DSM-GR, dorsal square-mesh panel and grid.

excluded FOs using 80 mm codend mesh size to analyse the effect of the DSM, and FOs using the grid to analyse the effect of mesh size (Table 3). Another approach was to combine the selective devices which occurred primarily together, such as D + VSM with 70 mm mesh size vs. DSM with 80 mm (and no VSM) for the analysis of the effect of VSM on hake catches—and exclude all the other, rarer combinations (Table 2).

Estimating discards at the fleet level

The mandatory selective devices are expected to have affected the catches and discards of *Nephrops* and hake of the entire fleet if they were actually deployed and effective. Therefore, we expect the *Nephrops* trawler fleet hake discards to have decreased in 2005, and the *Nephrops* discards in 2008. Since the selective devices were meant to let small individuals escape, we expect the length-distribution of the catch to have shifted towards larger sizes in those years. To examine these hypotheses we estimated time-series (2003–2012) of the proportion discarded, weight discarded, and the 5th percentile of the length distribution of hake and *Nephrops* at the fleet level. Catch and discards were raised to the trip level by the proportion of FOs sampled per day, and to the fleet level by the number of days at sea. The total number of days at sea of the fleet is available from the logbook records. Confidence intervals were estimated by non-parametric bootstrap with 10 000 replicates. Details on the raising variables and estimation procedure can be found in Cornou *et al.* (2013).

However, catches and hence discards are also expected to depend on stock size, which should thus be controlled for. Unfortunately, the *Nephrops* stock in the Bay of Biscay is data-limited and there is no stock size estimate for this stock (ICES, 2014a). Since the *Nephrops* fishing grounds overlap with the hake nursery, higher hake discards, and a smaller hake catch (low length index) are expected when hake recruitment is high. To check for this, we plotted the hake recruitment index as estimated by ICES (ICES, 2014b) against hake discarded weight and catch length index.

Results

Sampling was satisfactorily representative of the activity of the fishery in space and time (Table 1). This fishery was operated all year round, with a higher frequency from January to August. Most FOs took place in the morning, from 3 a.m. to 1 p.m. Trips were operated mostly in the 80–120 m depth range. On average ∼27 kg of *Nephrops*, 19 kg of hake, 2.5 kg of monkfish, and 4 kg of whiting were discarded per fishing operation while 42, 10, 7, and 3 kg were landed.

Catch, discard, and landing models

The models selected to explain *Nephrops* catch had a low-to-moderate explanatory power—from 7% of deviance explained for *Nephrops* catch in 2009–2010 to 67% for *Nephrops* catch in 2007 (Table 3). For hake, models explained around half of variability in catch weight (39–55%, Table 3), and one-third of variability in catch average length (29–38%, Table 3). Generally, the models selected for catch numbers and catch weight were the same and explained a comparable proportion of deviance, except *Nephrops* catch in 2005 (Table 3). All candidate variables were included in at least one of the catch models. Year effects were always significant in subsets including several years. Quarter effects were significant in all hake catch models and in most *Nephrops* models, except the

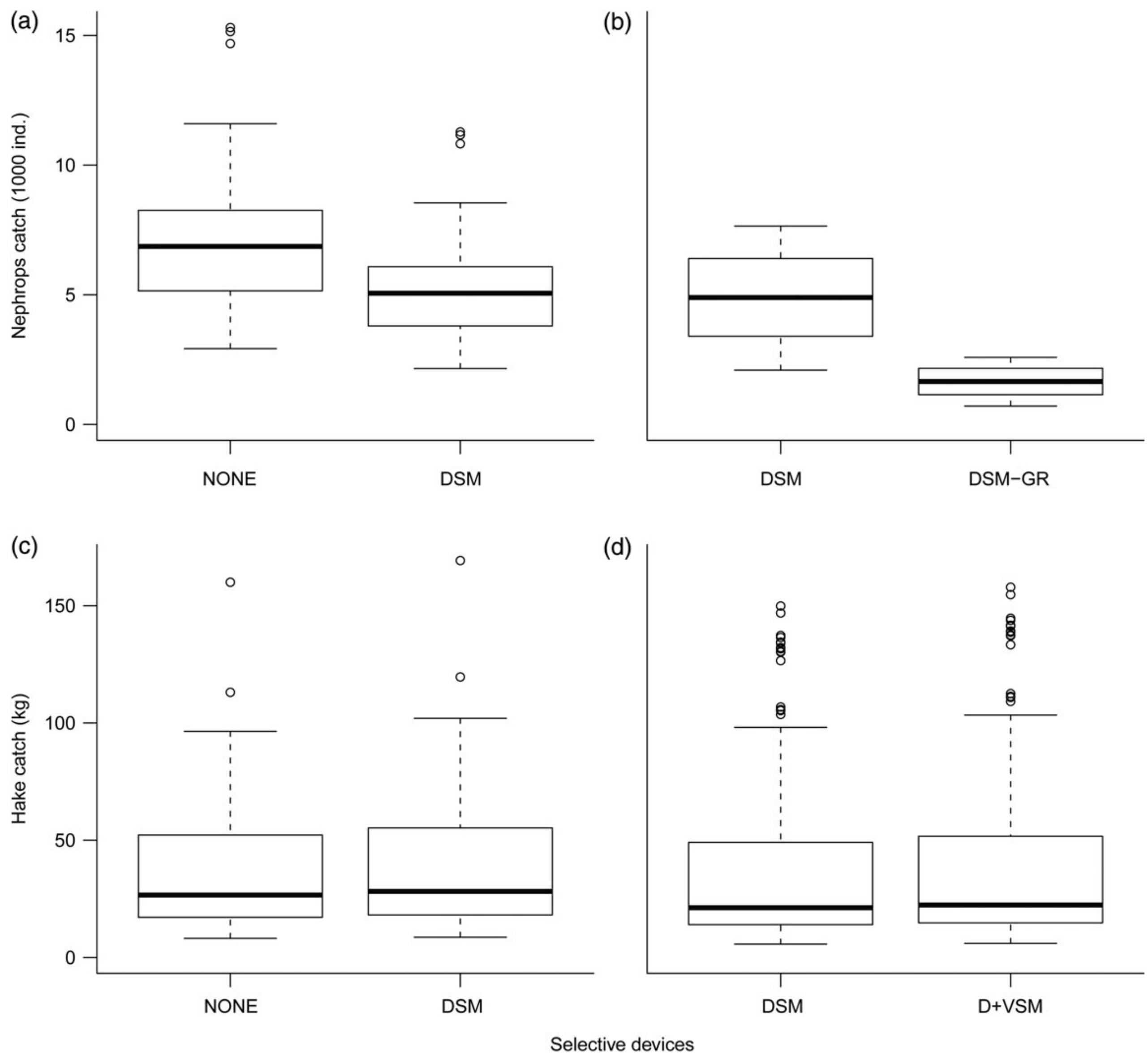

Figure 3. Predicted effect of selective devices on the catch of (a and b) *Nephrops* and (c and d) hake. The boxplots show the distribution of the catch (bold line: median, box: interquartile range, whiskers: 1.5 times interquartile range, circles: data outside this range) predicted by the models in Table 2, if all the fishing operations would have used the selective device on the *x*-axis. (a) Effect of the dorsal square-mesh panel (DSM) vs. no selective device on *Nephrops* catch, $n = 95$ FOs; (b) effect of the grid combined with DSM vs. DSM alone on *Nephrops* catch, $n = 44$ FOs; (c) effect of DSM vs. no selective device on hake catch, $n = 95$ FOs; (d) effect of the ventral square-mesh panel combined with DSM vs. DSM alone on *Nephrops* catch, $n = 163$ FOs.

Table 4. Summary of selective device efficacy on species-specific catch, discards, and landings: per cent change in the median of model-predicted catch components, if all fishing operations used in fitting the corresponding model in Table 3 would have used the given selective device, relative to the predicted amounts, if none would have used it.

Species	Catch component	DSM	GR	VSM	Mesh size
Nephrops	Catch	−26%	−66%	0	0
	Discards	−12%	−52%	0	−09%
	Landings	0	+25%	0	+09%
Hake	Catch	0	n.d.	0	0
	Catch mean length	0		0	0

n.d., not done.

models used to test for the VSM panel and grid effect; the latter was developed for a subset that included only two quarters (Table 3). This illustrates the strong seasonal and annual patterns in the catches of this fishery and justifies the subsetting approach taken to limit the confounding of these patterns with the selective-device effects. Apart from temporal patterns, spatial factors such as depth or latitude, and technical factors such as vessel power or the duration of the FO, explained a part of catch variability in many models (Table 3).

Nephrops discard and landing models, which included *Nephrops* catch as an explanatory variable, explained a higher proportion of variability—up to 89% (Table 3). Similar models were selected for discards and landings for all selective devices but the DSM panel,

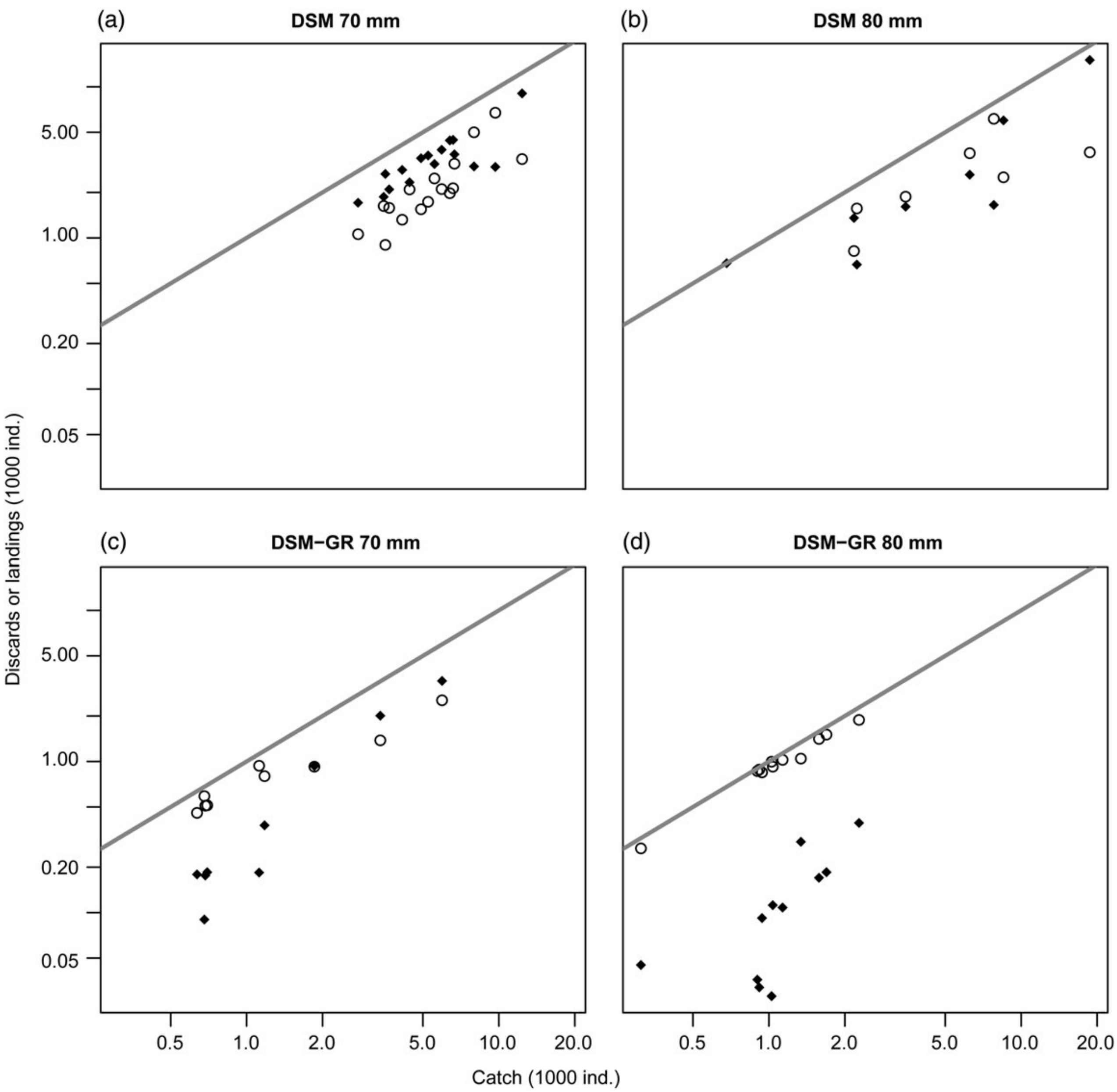

Figure 4. Effect of the grid and mesh size on the relationship between *Nephrops* catch and discards (black dots), and catch and landings (white circles). All figures are plotted on the same scale to allow comparison of magnitudes; note this scale is logarithmic. The grey lines depict the 1 : 1 relationship. DSM, dorsal square-mesh panel; DSM-GR, dorsal square panel and grid; 70 and 80 mm are the mesh sizes in the codend. Number of observed trips per panel: (a) 7, (b) 2, (c) 2, and (d) 1.

which significantly affected discards, but not landings. In addition to catch, these models included selective device, temporal variables (quarter and/or year), or both (Table 3). Hake catch average length models explained around one-third of variability (Table 3); explanatory factors included temporal variables, latitude for the grid model, and vessel power and fishing time for the DSM model.

Efficacy of selective devices

The DSM panel was found to significantly decrease *Nephrops* numbers caught—but not weight (Table 3, Figure 3a). The modelled reduction in the median number caught was 26% (Table 4). DSM also significantly decreased the amount discarded by 12% (Table 4), but did not affect *Nephrops* landings. Among all selective devices, the flexible grid was the most efficient in decreasing *Nephrops* catch and discards (Table 4). Catches were divided by a factor of 3 when the grid was combined with the DSM, compared with the DSM alone (Figure 3b, Table 4). The grid also affected the proportions discarded and landed—that is, both the intercepts and slopes of the discard-catch and landing-catch relationships (Table 3, Figure 4); the grid consequently reduced discards by half, while increasing landings by 25% (Table 4). These results should be taken with caution though since they rely on a small number of FOs (44) during only three observed trips (Figure 4).

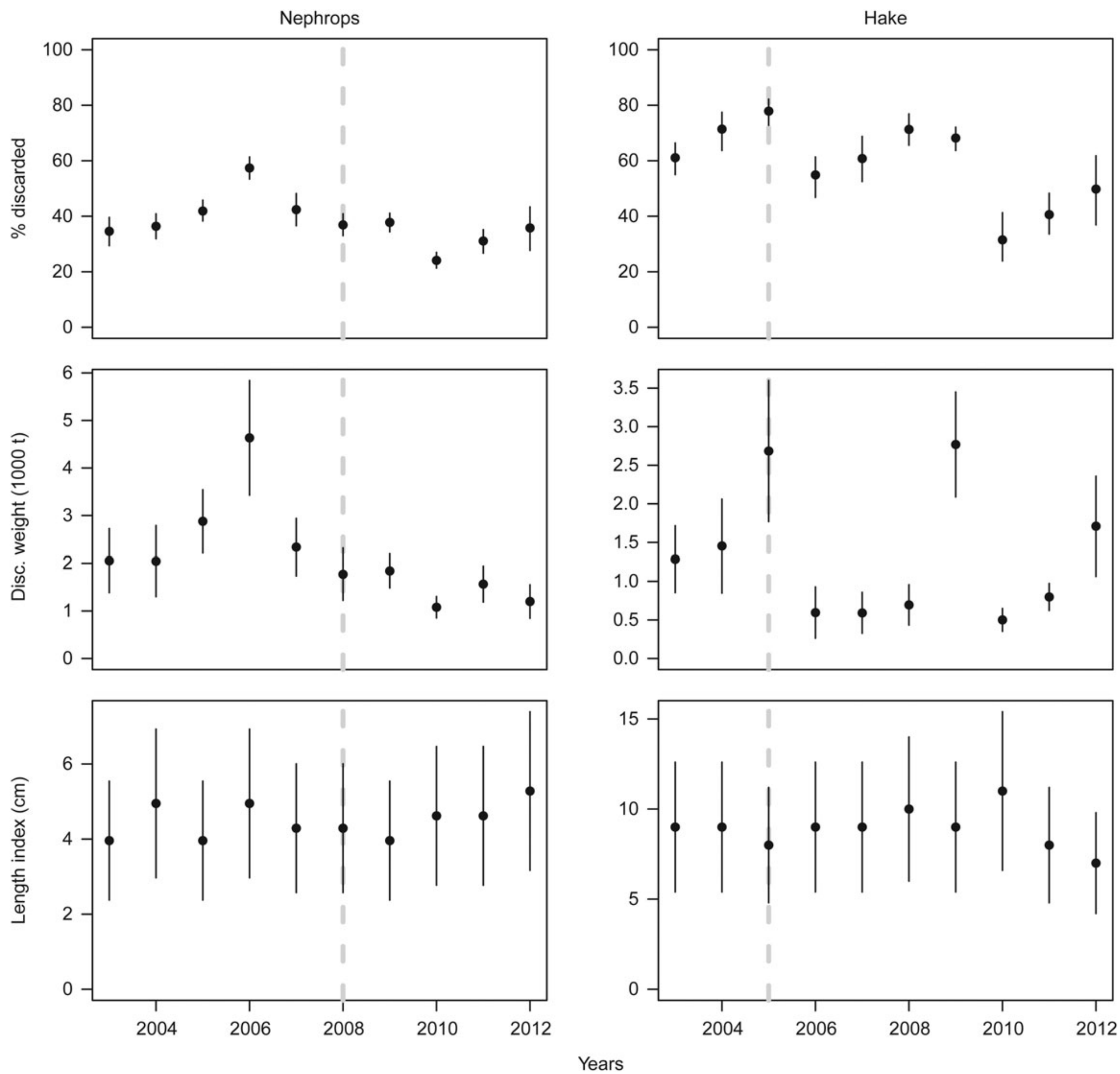

Figure 5. Time series of (top) per cent discarded, (middle) discarded weight, and (bottom) the 5th percentile of the length distribution of the catch of (left) *Nephrops* and (right) hake by the French *Nephrops* trawler fleet in the Bay of Biscay, as estimated based on the National on-board observer programme data. Vertical bars are 95% confidence intervals of the estimates, obtained by a resampling method. Grey lines indicate the change in regulation most relevant to each species: the DSM panel mandatory from 2005 to avoid hake, and at least one among three selective devices mandatory from 2008 to protect small *Nephrops*.

The 80 mm mesh size in the codend was not found to affect the catch of hake nor *Nephrops*. However, mesh size significantly decreased the proportion of *Nephrops* discarded (Table 3, Figure 4), so that the amounts discarded/landed with 80 mm mesh size were on average 9% lower/higher than with 70 mm (Table 4).

No selective device was found to significantly affect any of the hake variables analysed: the models selected for hake catch weight, numbers, or average length did not include the DSM panel in 2005, nor any of the *Nephrops* selective devices introduced later (Figure 3c and d, Table 3). The square-mesh panels, DSM or VSM, tended to increase hake catch, but the difference was small compared with the variability in hake catch driven by the other factors (Figure 3c and d). The mesh sizes combined with presence/absence of VSM did not reveal any significant difference either (Table 3).

Changes in discards when new regulations enter into force

The amounts and proportions of *Nephrops* and hake discarded by the whole fleet and the catch length index have fluctuated without marked trend over 2004–2012, except *Nephrops* discarded weight, which seems to be decreasing since 2006. The first year the dorsal mesh square panel was mandatory, 2005, coincided with a peak in hake weight discarded and in the proportion discarded, as well as a smaller 5th percentile of the catch length distribution (Figure 5). However, this did not coincide with a peak in hake recruitment, which rather happened in 2008 and 2012 (ICES, 2014b). There was no relationship between hake recruitment and hake discarded weight or length index (Figure 6). Although proportion discarded was slightly lower in 2006–2007, 2005 cannot be said to mark a step in the widely fluctuating time series of weight and proportion of hake or *Nephrops* discarded (Figure 5). Similarly, 2008 does not seem to mark a step in *Nephrops* discards or 5th percentile of the catch length distribution, despite the mandatory use of at least one selective device that started that year (Figure 5). The decrease in *Nephrops* discarded weight may be an outcome of the decreasing fishing mortality imposed on that stock since 2006, which resulted in decreased catches (ICES, 2012), rather than a change in selectivity.

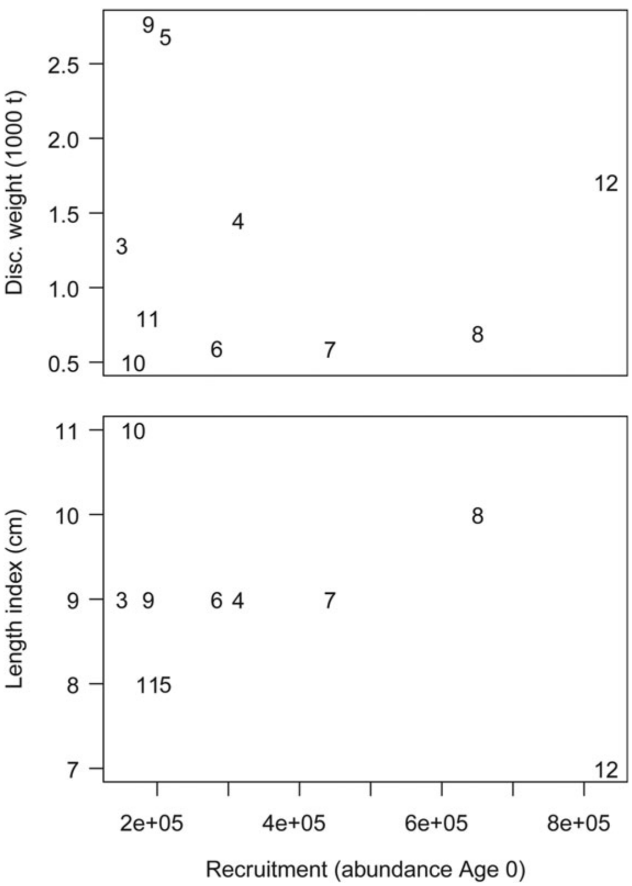

Figure 6. Relationship between hake recruitment (from ICES, 2014b) and (top) hake discarded weight and (bottom) the 5th percentile of the length distribution of hake caught by the French *Nephrops* trawler fleet in the Bay of Biscay, as estimated based on the National on-board observer programme data. Each point is labelled with the corresponding year of the XXIst century (e.g. three stands for 2003, etc.).

Discussion

The efficacy of the selective devices deployed in the *Nephrops* trawler fishery in the Bay of Biscay is heterogeneous. The DSM panel intended to let small hake escape seems to be inefficient for that purpose—but it decreases *Nephrops* catches and discards, without affecting the landings. The VSM panel does not affect the catch or discards of either species. Increased mesh size decreases *Nephrops* discards by a small amount while increasing landings by a similar amount. The device that most effectively reduces *Nephrops* discards seems to be the flexible grid but this result is supported by a small number of observations. Overall the selectivity measures enforced in this fishery have had limited efficacy, and the proportions discarded at the fleet level did not change after the measures entered into force. These results can be related to the uptake of the devices by the fishers. This study is also confronted with the technical difficulty of providing evidence of selective gear efficacy based on observational data. Below we discuss these two points in turn.

There seems to be some consistency between the efficacy of the selective devices, and the degree of uptake by the fishers—at least, those fishers whose trips were sampled. The DSM panel, meant to let juvenile hake escape, was mandatory since 2005. Since it did not affect catch or discards but was the only choice available, it was taken up by all fishers from 2006 (Figure 2). Among the three devices meant to decrease *Nephrops* discards, the flexible grid significantly reduced *Nephrops* discards and catches. The grid was used on about one-third of the sampled trips in 2007, then only sporadically. This device was found by fisher organizations to be costly and to wear out fast (Guigue, 2008). One might hypothesize that the small gain in landings was not sufficient to compensate for the extra costs generated by the frequent replacement of a costly device. This would be an economical reason for the grid not being widely adopted. Although the VSM panel did not affect the catch of any species, fishers kept using it after the first uptake in 2009—although not in increasing proportions. This device is cheap and simple to use (Guigue, 2008), and does not affect landings. Among the three *Nephrops* devices, the 80 mm codend reduces *Nephrops* discards without any catch loss, and with a small increase in landings (Table 4). Fishers regularly have to change their codend when it is worn-out and can therefore easily increase the mesh size at no extra cost. Therefore, unsurprisingly this mesh size is increasingly used since 2007 (the fraction of observed FOs using a 80 mm codend, which fluctuated ∼10% in 2003–2006, increased to one-third in 2007 and 73% in 2010). The larger mesh size seems likely to become the predominant selective device deployed in this fishery as a consequence of the 2008 regulation.

These findings are consistent with previous reports. The few studies examining the efficacy of devices implemented by professional fishers at the fishery scale have reported limited success. Regulations to mitigate the high bycatch of juveniles in the Argentine hake trawl fishery (i.e. a minimum mesh size and seasonal closure of a nursery area) were ineffective in reducing the catch and discard of juvenile hake, owing to poor compliance (Romero *et al.*, 2010). Square-mesh panels and larger codend mesh size introduced in 2002 in the English and Welsh fishing fleet operating in the North Sea to reducing discarding reduced the proportion of fish discarded from >80% to ~75%, by, for example, decreasing the catch of small whiting (Enever *et al.*, 2009). Sieve nets introduced in the North Sea brown shrimp fishery as a mandatory technical measure to reduce juvenile fish species bycatch reduced some of the unwanted fish catch, but were less effective at reducing 0-group plaice, the largest component of the bycatch (Catchpole *et al.*, 2008). In both cases, the regulation had an effect in the desired direction, but did not address completely the bycatch issue. Suuronen and Sardà (2007) review several other case studies where technical measures implemented in European trawl fisheries have had no or limited efficacy. Generally, selective-device-related measures have had limited efficacy when (i) the expected effect had been overestimated to start with; (ii) fishers felt little incentive to implement the technical measure; on the contrary, they feared a loss of landings as a side effect of the discard reduction; and/or (iii) enforcement was inconsistent, and acceptance was limited (Catchpole *et al.*, 2005, 2006a; Suuronen and Sardà, 2007). For the *Nephrops* trawl fishery, fishers have deployed those selective devices they felt the most incentivized to—those that did reduce catches the least for the least cost.

The interpretation of these results is limited by technical reservations. First, on-board observer data potentially incur a deployment bias (non-random distribution of observers among sampling units) and/or an observer effect resulting from changes in fishing practice or location in the presence of observers (Benoît and Allard, 2009). The French on-board observer programme is prone to the deployment effect, since accepting observers onboard is not mandatory, but takes place on a voluntary basis. This voluntary basis may reduce the observer effect—since the fishers involved are willing to participate in the programme, they may be more committed to comply with the recommendation to behave as if the observer was not there. On the other hand, the voluntary basis is also likely to affect exactly the effect investigated in this study: the uptake and deployment of the selective devices. One could assume that the fishers most committed to improve their gear selectivity would also be the ones more dedicated to the observer programme. However, none of these effects have been investigated or quantified in this fishery. Thus, the results about how selective devices were deployed in the sampled trips would need to be corroborated by complementary data on the actual device uptake by the whole fleet (e.g. a questionnaire survey, or an analysis of the selective-device market).

Another weakness of the study is that the data were not specifically collected to analysing selective-device efficacy. Rather, the on-board observer programme is designed to estimate discards and catches of the main species caught by the principal fleets (European Union, 2008). To balance the analysis designs across the main factors likely to affect the amounts caught and/or discarded and avoid potentially confounding the effect of interest, we used a subsetting approach. Subsetting allows a rigorous testing of the selective-device effect, however, the cost is a decrease in sample size. Among the 687 observed FOs available, only 44–259 could be used for the analysis of a given device efficacy. Given the high variability of catch and discards, small sample size results in selecting models with few explanatory variables, with selective devices not retained as significant factors. This may explain inconclusive results found for hake. Indeed, since hake is a bycatch species in that fishery, hake catch and discards are still more variable than those of the target species *Nephrops*, and larger sample sizes might be required to estimate effects. The limited number of FOs retained for analysis also limited the complexity of the models we could develop. The parameters of non-linear models or mixed-models were non-significant, or estimates bore a high uncertainty, and therefore we did not present these models.

Overall, the technical regulations in the Bay of Biscay *Nephrops* trawler fishery seem to have been only partly effective in reducing discard amounts and proportions. In 2012, this fleet discarded ~5159 tons of fish (95% confidence interval: 3627–6898), almost half of its catch (Cornou *et al.*, 2013); 36% of the *Nephrops* catch was discarded, that is, over 1000 tons. This limited success can be ascribed to several factors. Although all selective devices implemented had been extensively tested beforehand, both on-board scientific and commercial vessels, the expected net benefits may have been overestimated. It often happens that difficulties unseen during the technical experiments show up when a new gear or selective device is implemented by commercial fishers, for example wear after a device has been used for a while (Madsen and Valentinsson, 2010). Fishers were actively involved in the development and testing of the materials, a factor contributing to success (Catchpole and Gray, 2010). They were also left with the decision of which selective device they were to use, rather than imposed a one-fits-all regulation, which might also have increased compliance. However, it seems that overall the incentives to reduce discards in this fishery were not strong enough to induce fishers to adopt the most effective gears and/or to use their gears in the most effective manner. This may change under the new Common Fisheries Policy, which includes a landing obligation for many regulated species (European Union, 2013).

Since the technical measures did not completely solve the bycatch and discard issue, what could be done to reduce discards in the Bay of Biscay *Nephrops* trawler fishery? Obviously fishers can be further encouraged to use some of the selective devices. Especially, the combination of several devices may be promising, and their efficacy needs further investigation. A number of other devices (rotated mesh, radial escape section, etc.), or alternative gears such as pots or traps are being developed and tested (http://www.aglia.org/). Second, limiting the duration of FOs would be a way to avoid trawl clogging and would also probably help reducing discards—this confirms earlier findings based on analyses of fishing strategies (Catchpole *et al.*, 2006b; Trenkel *et al.*, 2008). Third, a different allocation of effort into locations and/or seasons with limited discards is worth investigating, although conflicts between minimizing discards of several species while maximizing catches of the target species might complicate identification of optimal strategies. All these strategies will need to be combined if the fishers are to comply with the new Common Fisheries Policy by January 2016.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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