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A bio-economic analysis of experimental selective devices in the Norway lobster (*Nephrops norvegicus*) fishery in the Bay of Biscay

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Abstract – Several fleets with various fishing strategies operate as a mixed fishery in the Bay of Biscay. Among the main fleets, bottom trawlers target Norway lobster (*Nephrops norvegicus*) and, together with gillnetters, they also catch hake (*Merluccius merluccius*). Trawling leads to average-size catches that are below the minimum landing size (MLS); such catches are discarded since they cannot be sold. These discards result in negative impacts on stock renewal, as most of them do not survive. This also results in an economic loss for both bottom trawlers and gillnetters since these discards represent a future loss of rent. This study, based on the 2009 and 2010 selectivity experiments at sea, assesses the short- and long-term bio-economic impacts of four experimental selective devices aimed at reducing *N. norvegicus* and *M. merluccius* discards over a 20-year simulation period. Tests were conducted at sea on a research trawler. Using the impact assessment model for fisheries management (IAM model), selectivity scenarios for trawlers in the Bay of Biscay were compared to a theoretical selective scenario of adopting an optimal device that catches only *N. norvegicus* and *M. merluccius* above MLS (9 cm and 27 cm total length, respectively). Costs and benefits were analyzed with the objective of finding the best compromise between a reduction in discards of undersized fish and a loss of valuable catches among the experimental devices. Selectivity scenarios show positive impacts on stocks but different economic impacts between fleets. The combination of a square mesh cylinder with a grid and square mesh panels gives the closest results to the theoretical scenario tested in terms of stock recovery and economic benefits. This experimental device leads to low economic losses in the short term and eventually to higher *N. norvegicus* yields, which would be favourable for fleets that greatly contribute to *N. norvegicus* fishing efforts.

Keywords: Demersal trawl fishery / Bio-economic analysis / Selectivity / Simulation / Selective device / *Nephrops norvegicus* / *Merluccius merluccius* / Atlantic Ocean

1 Introduction

Within the reform of the Common Fisheries Policy (CFP, EC 2009), discussions on discard bans and the relative failure of selective conservation measures have led to increased attention being paid to experimental selective devices. In order to reduce incentives to circumvent selectivity improvements, these devices should be designed to decrease discards as well as to limit economic losses due to the escapement of commercial grades. Furthermore, one of the objectives stated for fishery management is to fish at maximum sustainable yield (MSY) to ensure the exploitation of living marine resources in sustainable economic, environmental and social conditions (United Nations 2002). Considering one stock, MSY depends on exploitation patterns, thus on gear size selectivity, and on fishing efforts (Goodyear 1996; Macher et al. 2010; Scott and Sampson 2011). Gear size selectivity improvements combined with regulation of fishing effort are, therefore, key factors in exploiting a stock at maximal and sustainable yields. Improving selectivity, in particular reducing discards of the smallest individuals, results in higher fishing yields per unit and in greater catch values (Broadhurst et al. 1996; Fonseca et al. 2005a; Fonseca et al. 2005b). Within a joint production context, however, the objective of reaching MSY for all the stocks, or at least for all of the valuable stocks, is impossible.

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Increasing selectivity, specifically increasing capabilities for targeting one species more than another, is a way to fish for different stocks while remaining closer to MSY.

The performances of selective devices may vary depending on given parameters, such as the fishing grounds (Macbeth et al. 2007), the time of year (e.g., Özbilgin and Wardle 2002), the twine thickness of the gear (Lowry and Robertson 1996) or the trawl speed (Weinberg et al. 2002). Additionally, a selective device that is not perfectly suited to the target species and to the minimum landing size regulations may allow commercial fish to escape. This results in short-term economic losses for vessels that have adopted a selective device. In the medium term, losses can be offset by potential benefits expected from the savings made as a result of a measure, which result in higher biomass and larger individuals. This transitional phase may last several years or even permanently penalize vessels if the device is too selective (i.e., if it lets too many commercial grades escape). To date, there is no perfectly suitable selective device, and selectivity devices are often not selective enough to significantly affect discard levels (Stockhausen et al. 2012). To develop a new suitable device, it is necessary to look for a compromise between short-term losses of commercial catches, benefits from stock recovery in the medium term and the reduction in discards.

The Nephrops-hake fishery in the Bay of Biscay is an example of a mixed fishery characterised by high levels of bycatch and discards, where selectivity improvement has been a challenge for several years. The fishery includes around 430 vessels and generated around 134 million euros gross revenue in 2009. *N. norvegicus* and *M. merluccius* in the Bay of Biscay are caught by fleets using different techniques that are used together and interact. Bottom trawlers targeting *N. norvegicus* operate on the sand-muddy area of "*Grande Vasière*" (ICES Divisions VIIIa, b) which covers the *M. merluccius* nursery grounds. They use poorly selective gears that lead to many undersized catches of target species and bycatches. In 2009, 58% of *N. norvegicus* catches in number of individuals (38% in weight) were discarded in the Bay of Biscay (ICES 2010) and the trawlers targeting *N. norvegicus* discarded 85% of *M. merluccius* catches in volume (46% in weight) (ICES 2011). Those discards were mainly composed of the smallest individuals, which were under the minimum landing size (9 cm for *N. norvegicus* and 27 cm for *M. merluccius*) and therefore could not be sold (ICES 2010). Discarding leads to negative impacts on stock renewal, as none of the *M. merluccius* discards survive and 70% of the *N. norvegicus* discards die (Guégen and Charuau 1975). This also affects catches of both species by other fleets, including gillnetters that catch older *M. merluccius*; this leads to an economic loss for the fishing sector, since the small individuals that are discarded could have been caught later when they reach the MLS. In fact, as both species prices depend – among other criteria – on fish size (Macher et al. 2008; Asche and Guillen 2012) opting for fish maturity increases economic benefit.

Over the past years, selectivity measures were gradually introduced as conditions for *N. norvegicus* fishing in the Bay of Biscay (ICES divisions VIII a, b, d, e). Since 2006, a 100 mm square mesh dorsal panel for the escapement of juvenile *M. merluccius* is required on each trawler catching more than 50 kg of *N. norvegicus* per day at sea in the area, or fishing in the "hake box"[1] (EC 2006). Since 2008, 90% of Nephrops-trawlers have adopted a mesh size of 80 mm, resulting from the requirement to adopt one of the three selective devices proposed by the national legislation for the escapement of undersized *N. norvegicus* (mesh size of 80 mm, square mesh ventral panel, or a rigid grid) (CNPMEM 2008[2]; JORF 2011[3]). Additionally, a recovery plan for the northern stock of *M. merluccius* was established in 2004 with the aim of increasing the spawning stock biomass to above 140 000 tonnes (EC 2004). More recently, the European Commission has moved towards a multi-specific management plan, by area, instead of monospecific management (EC 2009). The Bay of Biscay demersal fisheries (including Norway lobster, sole, and potentially hake) should thus be managed through this kind of plan. The bay of Biscay management plan must be defined and assessed in 2013, requiring an impact assessment of the management options, including the increase in selectivity and strategies to reach MSY for different stocks.

Experimental trials were carried out in 2009 and 2010 to make in-situ tests of different devices to improve trawl selectivity for *N. norvegicus* and *M. merluccius* fishing. Based on experimental data, the focus of the current paper is to analyse the short, medium and long term impacts of improving trawl selectivity of the Nephrops-fishery in the Bay of Biscay. Impacts are assessed for the trawlers themselves and for the gillnetters interacting with trawlers through hake fishing. Scenarios involving experimental selective devices scenarios are compared to scenarios involving a theoretical device that avoids catches of *N. norvegicus* and *M. merluccius* below the MLS. The biological impacts are then analysed through the evolution of the spawning stock biomass of both species. Finally, the socioeconomic impacts are examined through economic cost and benefit distribution among the fleets of the fishery.

This analysis is based on the impact assessment model for fisheries management (IAM model) developed by Macher et al. (2008). The bio-economic model is similar to the one described in Doyen et al. (2012) and applied to the Nephrops-hake fishery; but Doyen's model was developed for coviability analyses. Here, we use a holistic approach combining economic and biological aspects to test methods of reducing bycatches and discards. The empirical results of the experimental trials are used in the model to assess the bio-economic impacts of selective devices.

After a description of the fleet structure at the Nephrops-hake fishery, we present the experimental trials, the selective devices used in testing, the general structure of the IAM model and its parameterisation in order to account for selectivity in

[1] The "hake box" is an area stretching from North West to South East along the Bay of Biscay where fishing for *M. merluccius* is regulated according to *M. merluccius* recovery plan.

[2] CNPMEM, 2008, Délibération n° 34/2008, Conditions d'exercice de la pêche à la langoustine (*Nephrops norvegicus*) dans les eaux du golfe de Gascogne (divisions CIEM VIII a, b, d, et e). Comité national des pêches maritimes et des élevages marins.

[3] JORF 2011, Arrêté du 9 décembre 2011 encadrant la pêche de la langoustine (*Nephrops norvegicus*) dans la zone CIEM VIII a, b, d et e. Journal officiel de la République française 57.

Table 1. Fleet characteristics in 2009.

	Length class	Number of vessels	Mean landings (t per year) *N. norvegicus*	Mean landings (t per year) *M. merluccius*	Mean gross revenue per vessel (euros per year)	Dependence on other species (% total gross revenue)
Nephrops- trawlers	<12 m	19	12	6	179 227	27
	12–16 m	69	20	9	314 213	31
	16–20 m	23	26	15	473 242	38
Mixed trawlers	<12 m	74	0	7	140 118	87
	12–16 m	37	6	14	358 578	75
	16–20 m	40	7	11	417 960	78
	>20 m	25	1	7	552 607	97
Mixed gillnetters	<10 m	24	0	3	47 124	81
	10–12 m	16	0	3	181 672	94
	12–18 m	6	0	7	290 543	92
	18–24 m	9	0	23	275 432	74
Sole gillnetters	10–12 m	20	0	3	223 558	97
	12–18 m	34	0	6	395 949	95
	18-24 m	23	0	24	596 042	88

the given scenarios. The results of the simulations are then presented. We conclude by discussing the cost-benefit analyses of the selectivity scenarios and the limitations of selectivity measures.

2 Materials and methods

2.1 Fleet structure of the Nephrops-hake mixed fishery

French vessels operating the Nephrops-hake fishery in the Bay of Biscay were identified via 2009 data taken from the Fisheries Information System of Ifremer (Berthou et al. 2008). They were selected according to the following three criteria:

(1) a criterion based on vessel registration: all selected vessels were registered in 2009 in one of the maritime districts of the Bay of Biscay;
(2) an attendance rate criterion, based on the number of statistical rectangles located in the Bay of Biscay where the vessel operated compared to the total number of rectangles where the vessel fished (in the Bay of Biscay and outside): all selected vessels had an attendance rate above 10% in the Bay of Biscay area;
(3) a tonnage criterion: all selected vessels landed more than one tonne of living *N. norvegicus* or *M. merluccius*.

According to European segmentation (EC 2001), these vessels were classified into two segments: bottom trawlers and gillnetters. Statistical analyses and consultations with fishermen's representatives were carried out to identify the main fishing strategies among these segments. This work was done within a partnership between a bio-economic working group and stakeholders. The following fleets were thereby identified:

- Nephrops-trawlers for which more than 40% of the total gross revenue depends on *N. norvegicus*. These fleets target this species for the main part of the year and are therefore highly dependent on this species;
- Mixed trawlers that catch a mix of species, including *M. merluccius* and *N. norvegicus*;
- Sole gillnetters for which more than 30% of the total gross revenue depends on sole: they target sole but also take *M. merluccius* as bycatch;
- Mixed gillnetters that catch a mix of species, including sole and *M. merluccius*.

Fleets were then split according to vessel length to reduce the variability of gross revenue and cost structure per length category.

This selection identifies the vessels that are likely to be impacted by the adoption of a selective device for *N. norvegicus* or *M. merluccius* within the fishery. For each of the four above-mentioned fleets, fourteen sub-fleets were distinguished and taken into account in the analysis according to their vessel length. This study concerned 419 of the vessels in the Bay of Biscay Nephrops-hake fishery in 2009 (Table 1). In 2010, their landings of *M. merluccius* and *N. norvegicus* were 4000 tonnes and 2800 tonnes, respectively.

Figure 1 represents (i) the contribution of each sub-fleet to *N. norvegicus* and *M. merluccius* landings, calculated as landings per fleet and species divided by total landings of these stocks (ICES 2010); (ii) the dependence on these species calculated as the gross revenue by species and fleet divided by the total gross revenue by fleet. The fleets that contribute the majority of *N. norvegicus* landings are Nephrops-trawlers of 12 to 16 m (46% of the total contribution) and of 16 to 20 m (20% of the total contribution). These trawlers are also very dependent on *N. norvegicus*, since this species represents more than 50% of their total gross revenue. Nephrops-trawlers under 12 m contribute less than 10% of the total *N. norvegicus* landings but they are the most dependent on this species. The selected fleets do not contribute largely to *M. merluccius* fishing mortality (9% of the total *M. merluccius* fishing mortality), as the Bay of Biscay covers a small part of the northern *M. merluccius* stock area. In particular, smaller gillnetters contribute less than 0.2% of the total northern *M. merluccius* landings. However, these fleets depend on this species for a portion of their

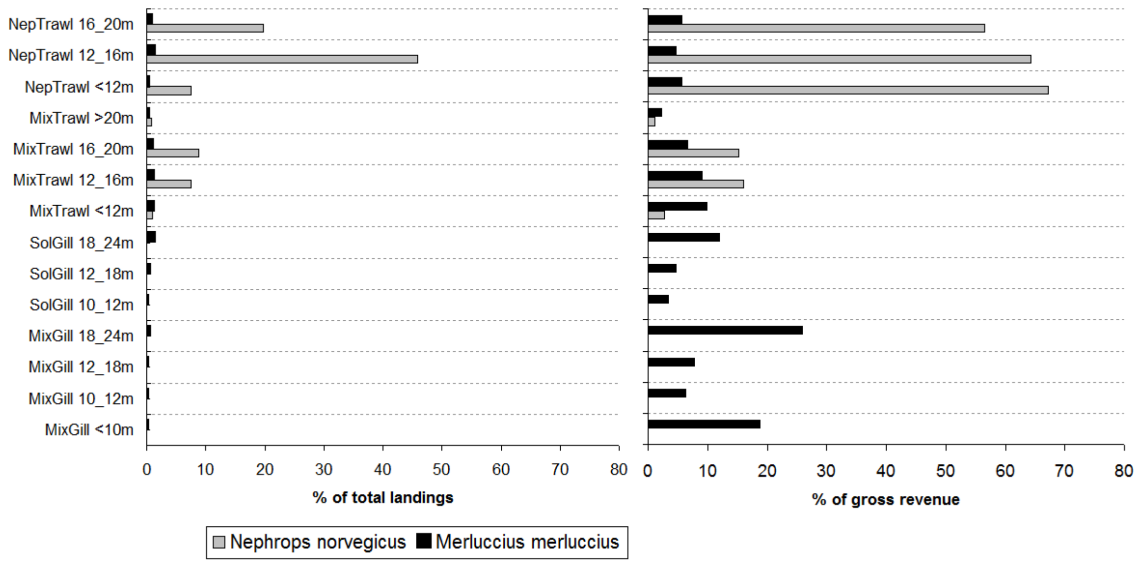

Fig. 1. Contribution to total landings of *Nephrops norvegicus* and *Merluccius merluccius* per sub-fleet, and dependence on both species per sub-fleet in 2009.

gross revenue. They were included in the analysis to assess the potential benefits of selectivity measures on gillnetters. Mixed trawlers under 12 m and over 20 m are more dependent on *M. merluccius* than on *N. norvegicus.*

2.2 Experimental data

A set of selective devices was developed and tested on board a research vessel in order to provide fishermen with different options to reduce their discard rate. A series of selective devices was tested in 2009 and, based on the optimal properties of the tested devices, a final device was tested in 2010. The four most relevant devices, in terms of discard reduction, are studied in this article: (i) a 70 mm stretched square mesh cylinder in the extension part of the trawl (Cyl70), (ii) a codend with two short selvedges forcing the codend meshes to open (2R), (iii) a codend with mesh fitted in T90 (T90), and (iv) the combination of a square mesh cylinder + a grid + two square mesh panels (CylGr) (Table 2). A theoretical device (Thresh) that allows for no catches of both species under the MLS was also analysed (Table 2a,b).

The experiment took place in the northern part of the Bay of Biscay on the "Gwen Drez" research vessel, a 24.5 m-trawler of 106 gross tonnage (Meillat et al. 2011). The selective devices were tested during the spring of 2009 or 2010[4]. The gears were rigged in a twin trawl configuration, the selective device set on one trawl and the standard trawl remaining unchanged. For each test at sea, the size of *M. merluccius* and *N. norvegicus* catches and the quantity of other caught species were recorded; this was done for both standard and selective trawls.

For the 2009 trials, the standard trawl was a simple 70 mm diamond mesh codend. In 2010, the compulsory square mesh panel for *M. merluccius* escapement was added to the standard trawl to obtain results comparable to the commercial fleet performance.

The size composition of *N. norvegicus* catches was converted into age according to the slicing method and a length-weight relationship depending on the sex (Conan 1978; ICES 2010):

$$\begin{aligned} \text{male}: \quad & \mathit{Weight} = 0.00039 \times (\mathit{Length} + 0.5)^{3.18} \\ \text{female}: \quad & \mathit{Weight} = 0.00081 \times (\mathit{Length} + 0.5)^{2.97} \end{aligned}$$

The age composition of *M. merluccius* catches was calculated according to an ad hoc conversion, based on the assumption of growth consistent with the tagging results (de Pontual et al. 2006; Drouineau et al. 2010; ICES 2010).

2.3 The bio-economic model

The bio-economic IAM model developed by Macher et al. (2008) was used to assess the impact of selective device adoption on both the stock and the fishing companies. The IAM model is an integrated model coupling the biological dynamics of fish stocks with the economic dynamics of a fishery to perform impact assessment for fisheries management. The model is age-structured, spatially aggregated and assesses the impacts of a management measure on fishing mortality, spawning biomass, total catches, catches by fleet, gross revenue and gross operating surplus at each time step. It is structured on a modular basis and can take into account dynamics of different species, fleets and fishing strategies. The model was developed in R/C++.

[4] Fish selectivity performance may change according to the season. Season may have a significant effect through the water temperature (He 1993; Özbilgin and Wardle 2002), the condition factor of individuals (Ferro et al. 2008), the length-girth circumference relationship (Özbilgin et al. 2006) and the population structure (Ferro et al. 2008; Özbilgin et al. 2011). However, our experiment was conducted when undersized *M. merluccius* were abundant and accessible by standard gears, in order not to under estimate the potential bio-economic benefit from switching to a selective gear.

Table 2a. Characteristics of the selective devices and sea trials.

Selective device used for each scenario	Code	Technical characteristics	Number of hauls	Period of trials
(A) 70 mm stretched square mesh cylinder	Cyl70	Cylinder of 70 mm stretched square mesh of 2 m × 1 m inserted in the extension of the trawl	15	from May 5 to 15, 2009
(B) Codend with 2 short selvedges	2R	Two selvedges of 75% of the stretched length of the codend to force the mesh to keep open	6	from June 13 to 25, 2009
(C) Codend with the mesh fitted in T90	T90	Mesh mounted at 90° to keep them open during the fishing operation	10	from June 13 to 25, 2009
(D) Combination of a square mesh cylinder with a grid and 2 square mesh panels	CylGr	A 2-m long square mesh cylinder with 100 mm stretched mesh in the upper third of the cylinder and 70 mm stretched mesh in the bottom two-third of the cylinder. This cylinder is set at the entrance of the extension part of the trawl – "EVAFLEX" grid with 13 mm spaced bars set just behind the cylinder on the top panel of the trawl – One 62 mm stretched square mesh panel for *N. norvegicus* escape of 1 m × 1.5 m size on the bottom panel of the extension part of the trawl	26	from April 23 to 12, 2010
Theoretical gear	Thresh	Fictive and theoretical gear assumed to release *N. norvegicus* and *M. merluccius* under MLS and to retain both species above MLS	–	–

Table 2b. Continued.

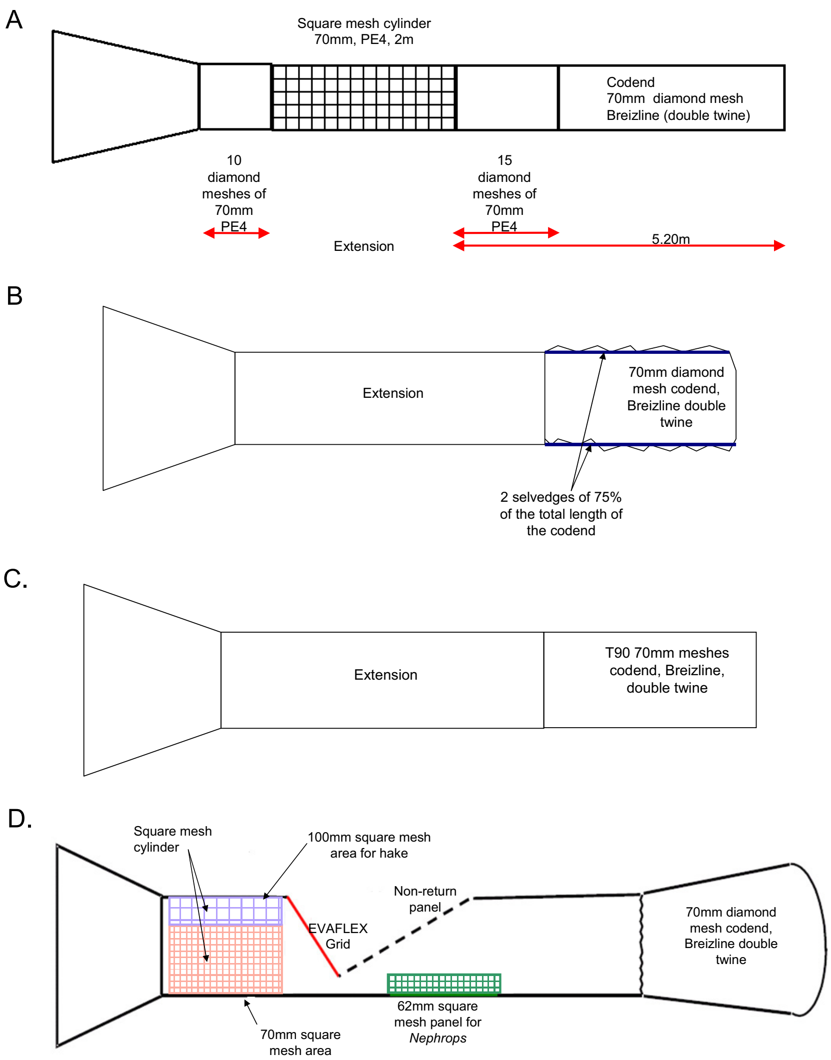

Table 3. Biological parameters of the *Nephrops norvegicus* stock.

Age group	Fishing mortality	Stock size (10^6)	Natural mortality	Maturity rate (%)	Discard (%)
1	0.02	659	0.3	0	100
2	0.39	529	0.3	0	97
3	0.58	206	0.25	75	49
4	0.56	138	0.25	100	14
5	0.44	66	0.25	100	6
6	0.44	31	0.25	100	6
7	0.40	13	0.25	100	2
8	0.43	5	0.25	100	6
>8	0.43	4	0.25	100	2

Sources: ICES 2011 and unpublished data.

Table 4. Biological parameters of the *Merluccius merluccius* stock.

Age group	Fishing mortality	Stock size (number 10^6)	Natural mortality	Maturity rate (%)	FU10 discard (%)	FU9 discard (%)	FU13 discard (%)
0	0.18	236	0.4	0	100	100	0
1	0.35	132	0.4	11	24	37	0
2	0.50	62	0.4	73	0	0	0
3	0.85	25	0.4	93	0	0	0
4	0.96	7	0.4	99	0	0	0
5	0.94	1	0.4	100	0	0	0
6	0.76	0	0.4	100	0	0	0
7	0.89	0	0.4	100	0	0	0
>7	0.89	0	0.4	100	0	0	0

Sources: ICES 2011 and unpublished data.

In this study, the model took into account the 14 sub-fleets fishing in the Nephrops-hake fishery and the dynamics of *N. norvegicus* and *M. merluccius* stocks. The simulation period was 2009−2030, which allowed the transitional phase to be analysed following the adoption of a new selective device, corresponding to changes in the age structures of the stocks of both species. The impact of selectivity scenarios were analysed through the biological and economic outputs of the model. The evolution of the stock status of both species over the simulation period was analysed via spawning stock biomass. The evolution of discards and landings of both species is presented at the Bay of Biscay fishery level. We analyzed the evolution of economic impact by fleet through the average gross operating surplus, which in turn indicates the profitability of fishing activity. For cost-benefit analyses, we used the net present value of the producer surplus or income. The calculations are described in Macher et al. (2008). A discount rate of 4%, as suggested by Arrow et al. (1996) and Portney and Weyant (1999), was adopted in France by the French Public Authorities in charge of economic planning (Lebègue 2005).

2.3.1 Model parameters

The stock data used in the simulations were outputs of an ad hoc stock assessment for *N. norvegicus* and *M. merluccius* based on a standard virtual population analysis method and on ICES (ICES 2011). The biological parameters per age group for both species (fishing mortality, initial stock size, natural mortality, maturity, discard rates) are given in Tables 3 and 4.

Table 5. Fishery units or *métiers* by fleet.

Fishery Unit	Description of the métier or strategy	Modelled fleets
FU9	Nephrops-trawling in shallow to medium water	Nephrops-trawlers
FU10	Trawling in shallow to medium water	Mixed trawlers
FU13	Gillnets in shallow to medium water	Sole gillnetters and mixed gillnetters

Hake discard rates per age group were modelled distinguishing *métier* by fleet, as defined in the ICES Working Group on Fisheries Units (ICES 1991). Three different *métiers*, corresponding to different exploitation patterns and discarding behaviours can be distinguished for *M. merluccius* (Tables 4 and 5). Gillnetting does not induce any discard, while *N. norvegicus* trawling and mixed trawling induce discards of *M. merluccius* of younger ages.

Initial data per sub-fleet, used in the simulations were those collected in 2009 by Ifremer (Berthou et al. 2008; Daurès et al. 2008). The structure in terms of cost per sub-fleet is given in Table 6.

2.3.2 Model assumptions

During the simulation period, the recruitment was assumed to be constant and was calculated as the geometric mean value

Table 6. Costs structure per sub-fleet (% mean gross revenue).

		Landing costs (%)	Fuel costs (%)	Other variable costs (%)	Maintenance and repair costs (%)	Other fixed costs (%)	Crew costs (%)	Gear and rigging costs (%)
Nephrops-trawlers	<12 m	5.3	13.5	1.1	6.4	7.6	43	4.4
	12–16 m	5.5	16.1	2.1	8.6	11.2	44.3	4.5
	16–20 m	6.4	21.2	3.1	7.2	11.1	39.6	5.6
Mixed trawlers	<12 m	7	14.5	1.3	6.6	9.2	46.3	4.5
	12–16 m	5.4	17.5	2.6	7.5	10.9	42.8	4.4
	16-20 m	6.3	20.6	3.5	6.6	11	39.3	5.5
	>20 m	6.1	25.8	3.7	8.7	10.8	36.8	6.7
Mixed gillnetters	<10 m	3.6	3.5	1.6	6.8	11.5	56.1	7.3
	10–12 m	3.9	5.1	2.4	5	9.2	56.2	14.7
	12–18 m	5.9	6.1	3.2	6.9	8.4	48.3	10.2
	18–24 m	6.6	7.5	3	7.4	7.5	46.2	11.2
Sole gillnetters	10–12 m	4.9	6	1.4	5.3	10.4	52.9	9.9
	12–18 m	5.4	5.9	2.9	7	9.1	48.4	8.5
	18–24 m	6.6	7.5	3	7.4	7.5	46.2	11.2

Sources: Berthou et al. (2008); Daurès et al. (2008).

of the estimated recruitment from 1987 to 2008 for *N. norvegicus*, and from 1992 to 2006 for *M. merluccius*.

The number of vessels and the number of days at sea per sub-fleet were assumed to be unchanged over the simulation period. While this assumption is valid in the short term, it is expected that the number of vessels or days at sea will increase if profits in the fishery increase, as discussed in Macher et al. (2008). This would mitigate the benefits expected from selectivity measures. Our analyses were performed with all things being equal, to highlight the differences between the selective scenarios, the status quo and the theoretical scenario. The analyses of the fleet's dynamics are in progress. This should enable us to estimate variations in the number of vessels according to fishery profits.

Since there are no consolidated data available on catches per *métier*[5] or fleet in the fishery, the bio-economic model assumed that each species per sub-fleet is caught by only one *métier*. The catch data for species other than *N. norvegicus* and *M. merluccius* collected during the experimental trials were too few to be used in the bio-economic simulations. Therefore, the value of landings relative to the other species was assumed to be constant.

The survival rate for discards was assumed to be 30% for *N. norvegicus* (Guéguen and Charuau 1975) and 0% for *M. merluccius* (Hill and Wassenberg 2000).

Prices of both species by length were assumed to be constant over the simulation period. In 2009, hake production in the Nephrops-hake fishery in the Bay of Biscay represented less than 10% of the total landings of this stock and about 16% of the hake net consumption in France (Berthou et al. 2008; France Agrimer 2010). The net consumption of *M. merluccius* in France represents around 25 000 t (11 000 t from national production, 17 000 t from imports and 2500 t from exports), while *M. merluccius* landings in the Nephrops-hake fishery is around 4000 t. The assumption of a constant price by grade as an initial approximation is, therefore, acceptable. Hake prices are more structured by length or age categories than by variation in quantity.

The Nephrops-trawlers in the Bay of Biscay landed 2770 t of *N. norvegicus* in 2009, i.e., 62% of the French production of fresh *N. norvegicus* – which is sold alive from day-trip vessel landings and well recognised by consumers within the fresh fish category. The price is differentiated by length, but variations in quantity may also impact price. However, no significant elasticity could be estimated for this species. For our analyses, we assumed constant prices per grade as an initial approximation and will discuss the limitations of the results obtained under this assumption.

2.3.3 Selectivity scenario simulations

Selectivity scenarios (Table 2) were used to simulate the adoption of selective devices by modeled trawler sub-fleets that catch more than one tonne of *N. norvegicus* or *M. merluccius* per year. We analysed the impacts of selectivity improvements on the trawlers themselves and on the gillnetters interacting with them through *M. merluccius*.

The adoption of each selective device was simulated from the year 2010. Scenarios were compared both to the status quo and to a theoretical scenario, including a fictive device where all *N. norvegicus* and *M. merluccius* under the MLS escape.

The adoption of a selective device was simulated in the bio-economic model by integrating a selectivity factor per species and age group into the equations of catches and discards. For each selective device v, each species s (either *N. norvegicus* or *M. merluccius*) and each age group i, the selectivity factor $S_{v,s,i}$ is given by:

$$S_{v,s,i} = \frac{C_{select,v,s,i}}{C_{standard,s,i|v}}. \quad (1)$$

[5] *Métier* refers to target strategies of one or several species using one gear and during a given period or season and in a given area.

Where $C_{select,v,s,i}$, is the sum of catches in number by species and age group for the hauls, with the selective trawl and $C_{standard|vs,i}$, are the sum of catches in number by species and age group for the hauls with the standard trawl (used together with the selective trawl as twin trawls).

Experimental data were collected from a small number of hauls and the distribution of catches in the standard and selective trawls showed a high variability between hauls (Meillat et al. 2011); this was true even in the test of the combined selective device for which there was a higher number of hauls. The selectivity factor used in the model was calculated from the total number of catches over all the hauls to overcome the low number of hauls tested.

For each modelled sub-fleet f, the catches in number per species s (either *N. norvegicus* or *M. merluccius*) and per age group $i, C_{s,i,f}$, are given in the bio-economic model by:

$$C_{standard,s,i,f} = F_{s,i,f} \times N_{s,i} \times \frac{(1-e^{-Z_{s,i,f}})}{Z_{s,i;f}}. \qquad (2)$$

Where F is the fishing mortality, N the total number of individuals and Z the total mortality.

For each of the sub-fleets adopting the selective device, such as Nephrops-trawler sub-fleets and mixed trawlers of 12 to 20 m, the new catches in number relative to the adoption of a selective device by bottom trawlers in the Bay of Biscay are given by:

$$C_{v,s,i,f} = S_{v,s,i} \times C_{standard,s,i,f}.$$

Discards in weight, D, in the bio-economic model are given by:

$$D_{standard,s,i,f} = w_{s,i} \times C_{standard,s,i,f} \times d_{s,i,f}. \qquad (3)$$

With w the mean weight, and d the percentage discarded in number.

For each of the sub-fleets adopting the selective device, such as Nephrops-trawler sub-fleets and mixed trawlers of 12 to 20 m, the new discards in terms of weight is given by:

$$D_{v,s,i,f} = w_{s,i} \times C_{v,s,i,f} \times d_{s,i,f}. = S_{v,s,i,f} \times D_{standard,s,i,f}$$

For the theoretical scenario, the fishing mortality per age group i and species s of the sub-fleets f that adopted the selective device v ($Fth_{s,v,,f}$) is adjusted in order to simulate the escape of all individuals under the MLS:

$$Fth_{s,i,f} = (1 - r_{s,i}) \times F_{s,i,f}. \qquad (4)$$

Where $r_{s,i}$ is the fraction of the species s in age class i below MLS[6].

Therefore, the fishing mortality of individuals that are above the MLS is assumed not to be impacted by the device.

The gross revenue per fleet (or gross value of landings GVL) is obtained by adding the revenues from the modelled species (s) and the revenue from other species, which are not modelled (*oths*):

$$GVL_f = \sum_s (P_{s,f} \times L_{s,f}) + GVLoths_f. \qquad (5)$$

Where P is the price per species and fleet, L is the weight of landings per species and fleet, and GVL is the gross value of landings.

Gross value added per fleet is given by:

$$GVA_f = GVL_f - fuelc_f - ovc_f - rep_f - Fixc_f. \qquad (6)$$

Where *fuelc* are the fuel costs, *ovc* are the other variable costs, *rep* are the repair and maintenance costs and *Fixc* are fixed costs.

The gross operating surplus per fleet (or producer surplus as a proxy) is calculated as the difference between the GVA minus the crew costs *ccw*:

$$GOS_f = GVL_f - fuelc_f - ovc_f - rep_f - Fixc_f - ccw_f. \qquad (7)$$

Where *ccw* is calculated following the sharing system that exists in French fisheries. The crew cost wages are a part of the return to be shared, i.e., of the gross revenue minus the variable costs of the trip.

3 Results

The catch data of *N. norvegicus* and *M. merluccius* are given per age group and per selective device (Appendix 1). All tested selective devices reduced the catches of small *M. merluccius* and *N. norvegicus*, though not in the same proportion. The T90 device primarily reduced catches of all ages in both species compared to a standard trawl. This device reduced discards below MLS but also let a high proportion of commercial catches escape. The Cyl70 device had the smallest impact on *N. norvegicus* catches of young ages compared to a standard trawl. For *M. merluccius* catches, each selective device releases a high proportion of age 1 catches.

The simulation of bio-economic impacts in the short and long term allowed us to analyse the effects of these reductions.

3.1 Biological impacts

The model simulations indicate that the adoption of a selective device by Nephrops-trawlers in the Bay of Biscay increases the *N. norvegicus* spawning biomass and, in a more moderate way, the *M. merluccius* spawning biomass as well (Fig. 2). The age structures of both species stocks were modified in response to the adoption of the selective device by trawlers and remained stable during the simulation period, taking into account the assumptions of constant recruitment and fishing efforts over the simulation period.

The simulations show high reductions in *N. norvegicus* discards in the first year following the adoption of the selective device by trawlers in each scenario compared to the status quo (Fig. 3). The quantity of discards slightly increases due to changes in age structures of both species.

Selective devices lead to a decrease in both species landings during the first year of adoption (Fig. 4). The more the selective device lets marketable catches of the escape of both species, the greater the loss of their landings during the first

[6] For *N. norvegicus*, we assume that age 3 corresponds to the MLS according to slicing method. The fraction $r_{s,i}$ is equal to 1 for individuals of age 1 and 2, and equal to 0 otherwise.

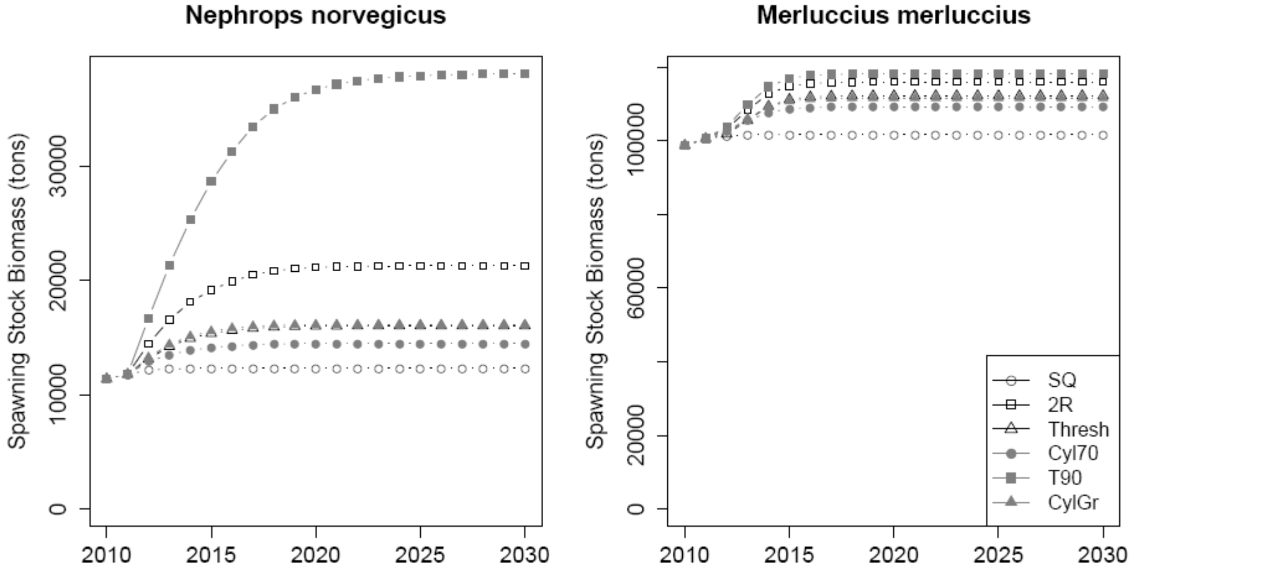

Fig. 2. Evolution over the 2010-2030 simulation period of *Nephrops norvegicus* and *Merluccius merluccius* spawning biomass (t) according to the given scenarios.

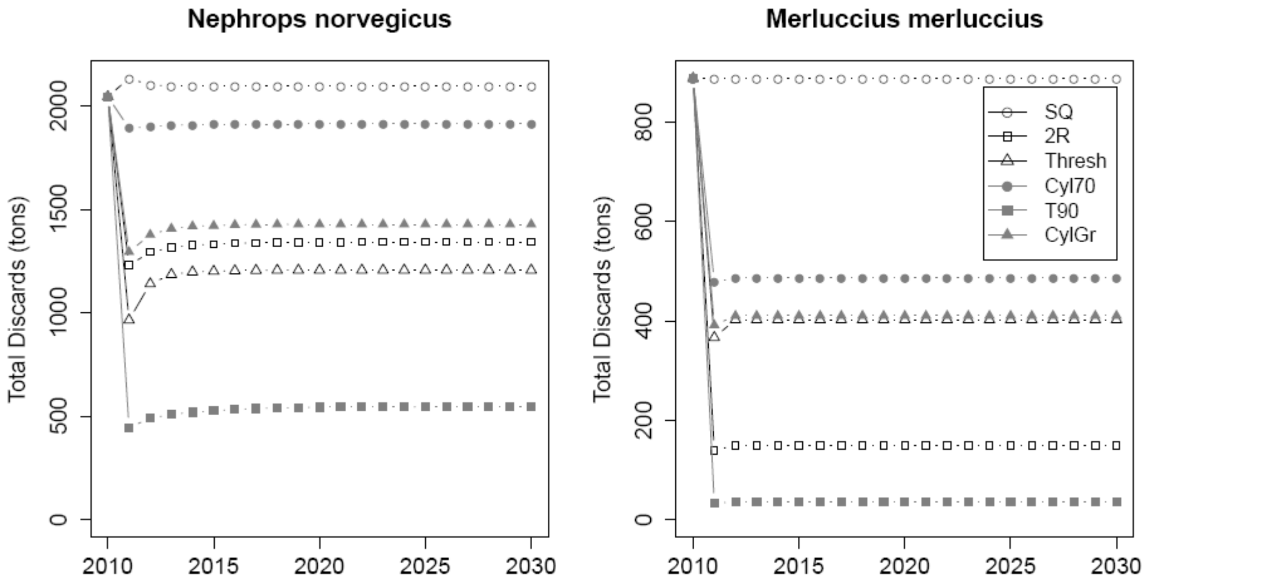

Fig. 3. Evolution over the 2010-2030 simulation period of total *Nephrops norvegicus* and *Merluccius merluccius* discards (t) by the modelled fleets according to the given scenarios.

year of use. From the second year onwards, both species landings gradually increase in each scenario, as the fishery eventually catches the individuals that were spared while they were smaller than the MLS and did not suffer from natural mortality. The fishery contributes little to the fishing mortality of the northern stock of *M. merluccius*. Therefore, the impact of the selective devices on the *M. merluccius* stock dynamics is low and the advantage resulting from the escapement of undersized individuals is also low.

At equilibrium, the theoretical scenario was the only one that leads to an increase in *M. merluccius* landings compared to the status quo. In the case of the other scenarios, the advantage resulting from the escapement of undersized hake does not offset the loss caused by the escapement of marketable catches of hake. Among all the tested scenarios, this theoretical scenario leads to the highest long-term yields of *N. norvegicus*. The CylGr scenario leads to the second highest yield, which suggests that the device provides a good compromise between a release of undersized individuals and a loss of marketable ones. Only the T90 scenario performs poorly compared to the status quo, suggesting that the device is too selective and does not enable the vessels to benefit from the recovery of the stocks. The Cyl70 scenario results in the lowest decrease in *N. norvegicus* discards compared to the status quo, which suggests that this selective device has little impact on the *N. norvegicus* exploitation pattern by trawlers. The 2R

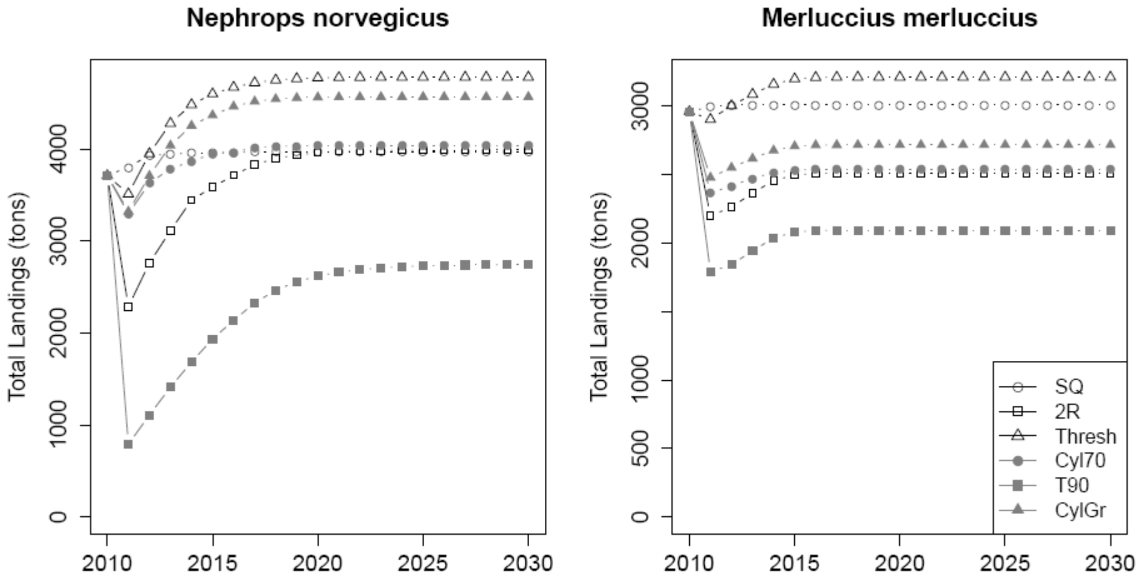

Fig. 4. Evolution over the 2010-2030 simulation period of total *Nephrops norvegicus* and *Merluccius merluccius* landings (t) by the modelled fleets according to the given scenarios.

scenario leads to a small increase in *N. norvegicus* landings at the end of the simulation but to a high loss of marketable catches in the short term, which may compromise trawler activities during the transitional phase.

3.2 Distribution of economic impacts between fleets

The distribution over time of the economic impacts among the selected sub-fleets from the Nephrops-hake fishery shows differences between the economic losses resulting from the adoption of a selective device on trawlers and the collective benefits of the measure for trawlers and gillnetters (Fig. 5).

During the first year of adoption, the escapement of marketable fish leads to a loss in gross operating surplus for trawlers. The more the sub-fleet is dependent on *N. norvegicus* landings, the greater the impact is on its gross operating surplus during the first year of the transitional phase; scenarios T90 and 2R present the strongest economic impacts.

At equilibrium, the gain in gross operating surplus in each scenario where experimental selective devices are adopted compared to the status quo shows that the loss of *M. merluccius* landings is offset by the benefits due to an increase in *N. norvegicus* landings. In these scenarios, the increase in gross operating surplus is greater for Nephrops-trawlers that are 12−16 m and 16−20 m, compared with the other sub-fleets. These fleets contribute a large amount to the *N. norvegicus* fishing mortality and the losses of marketable fish are largely offset by a greater overall yield for the same fishing effort. The T90 scenario generates excessive losses of marketable fish, which leads to a transitional period of lower gross operating surplus compared with the status quo (for sub-fleets that adopted this selective device). The gross operating surplus then increases and becomes constant at equilibrium. Thus, at equilibrium, this scenario leads to the lowest positive surplus for Nephrops-trawlers.

3.3 Cost-benefit analyses of the selectivity scenarios

The difference between the net present value of producer surplus over the 2010–2030 simulation period provided by selective scenarios and by the status quo was calculated for each selective scenario, assuming a 4% discount rate (Fig. 6). The adoption of the theoretical device leads to greater benefits for the entire fishery compared to status quo. In fact, it allows only *N. norvegicus* and *M. merluccius* above the MLS to be caught, and the individuals that are under the MLS, and thus not saleable, are saved for future profits. Among the experimental devices tested, the CylGr device provides the best compromise between a reduction in undersized discards and a loss of marketable catches. The adoption of a 70 mm square mesh cylinder leads to lower profits compared with the status quo. The scenarios T90 and 2R lead to a loss of profitability for the selected fleets compared with the status quo, since the benefits from the recovery of both species stocks do not cover the loss of marketable fish.

According to our simulations, the adoption of any of the selective devices would mainly impact trawler profitability and would have less impact on the gillnetter profitability (Fig. 7). For each scenario, fleets encountered periods of short-term losses and periods of medium- and long-term benefits. These periods are long for trawlers, but other fleets are less impacted. The gillnetters benefit from the higher selectivity of trawlers via the increase in the *M. merluccius* stock. Adopting the 2R or the T90 device is not economically profitable for the selected fleets, since these devices let too many marketable fish escape. The CylGr device allows bio-economic impacts to be distributed among the fleets with impacts close to the theoretical device (except for small and large mixed trawlers). The device leads to high yields per unit effort for *N. norvegicus* fishing over the simulation period. It therefore benefits the fleets that contribute the most to the *N. norvegicus* fishing effort. This scenario leads to negative economic impacts for mixed

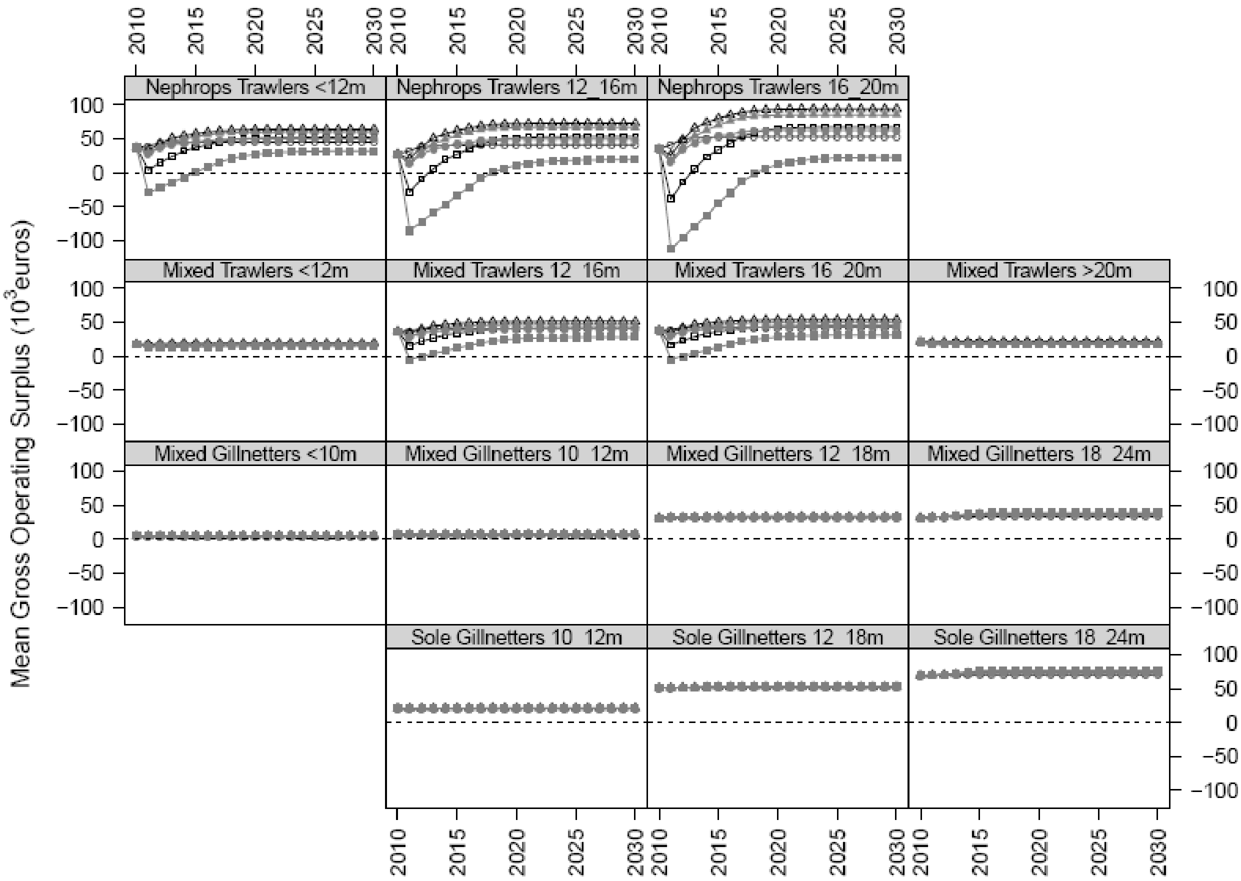

Fig. 5. Evolution over the 2010-2030 simulation period of the mean gross operating surplus, per sub-fleet and per scenario.

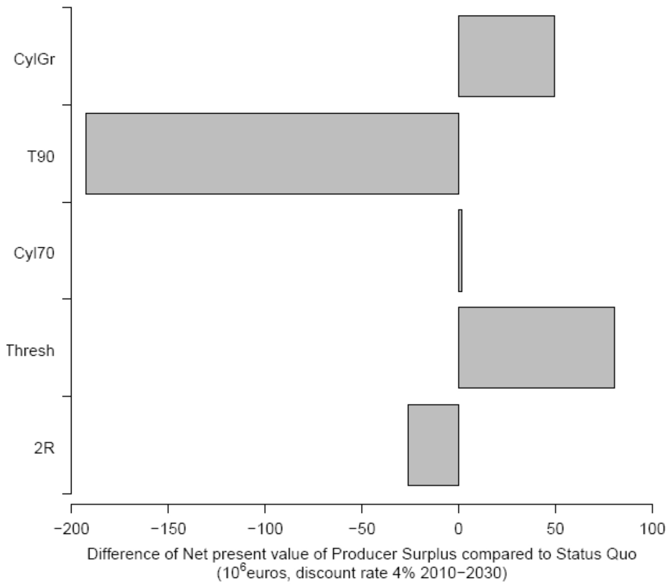

Fig. 6. Difference of net present value of total fishery surplus between selective scenarios and the status quo.

trawlers under 12 m and over 20 m, compared to the status quo, since these sub-fleets are more dependent on *M. merluccius* rather than *N. norvegicus* catches (Fig. 7).

Sensitivity analyses regarding various discount rates show that the order of the cost-benefit analyses by selective device does not change according to the range of discount rates (2%−8%) (Appendix 2).

4 Discussion

Assessing the impacts of experimental and theoretical selective devices allows us to initiate a discussion on the biological and economic effects of improving the selectivity of trawlers. The analysis carried out in this study estimates the costs and benefits of selectivity measures from the fishermen's point of view. Trade-offs were estimated between the short-term costs and the medium- and long-term benefits, as well as the distribution of the bio-economic impacts within the fishery. This study has direct applications in policy and management and can be used in the sustainable management of fisheries. By decreasing discards and improving the exploitation pattern of target capabilities, the improvement in fishing selectivity can thus help achieve public policy objectives of fishing at MSY or reducing discards. There is an apparent trade-off between improving selectivity and reducing fishing effort to maximize production (Macher et al. 2010), and selectivity is an important issue in this context.

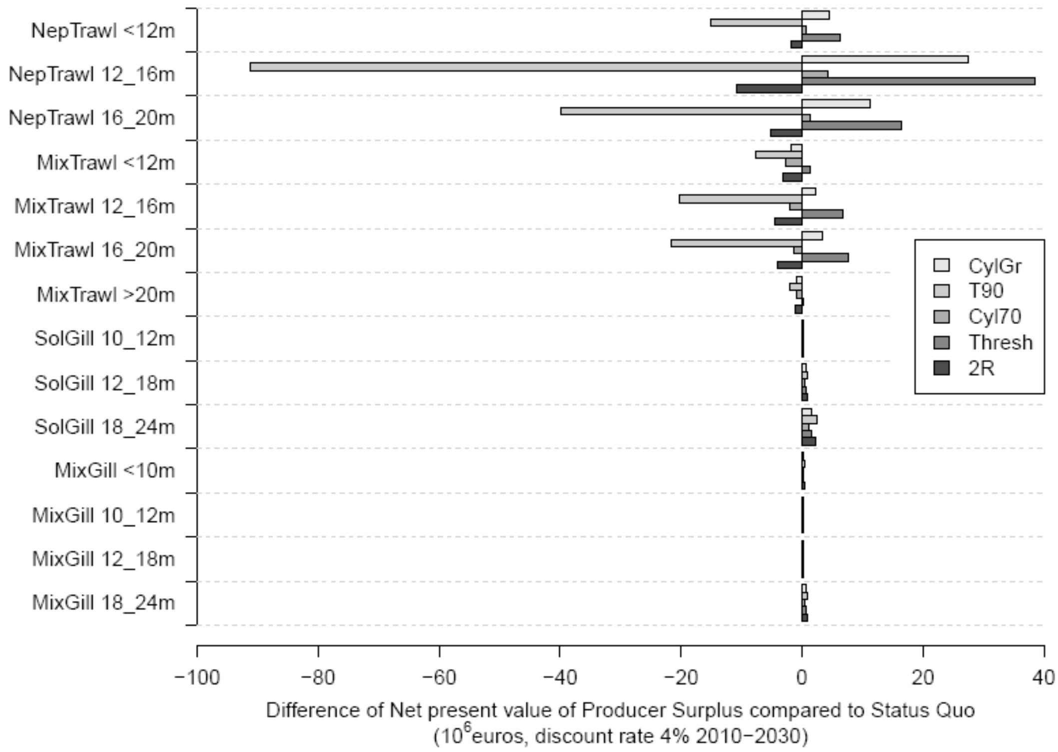

Fig. 7. Difference of net present value of producer surplus, per sub-fleet, between selective scenarios and the status quo.

The analysis shows that, with the combination of a square mesh cylinder with a grid and square mesh panels, it is possible to decrease under-sized discards and limit economic losses in the short term, to generate global profits for the fishery and to achieve stock recovery. The scenario gave results close to those observed with the optimal theoretical selective device but with a lower reduction in discards. The CylGrid device limits the escapement of commercial grades and therefore provides low incentives to circumvent the use of selectivity. The divergence between private costs of this kind of conservation measures and the collective benefits, and between the short-term losses vs. the "uncertain" expected long-term gains, are in fact the main reasons why individual fishermen bypass the selective measures. Another reason is the cost of adopting the selective device, which is mainly the cost of the escapement of commercial grades. The direct costs of the selective devices vary between 75 euros for the Cyl70, 600 euros for the 2R and the T90 and 900 euros for the CylGr. These costs are less than 1 000 euros (i.e., 0.3% of the mean gross revenue of a Nephrops-trawler of 12−16 m). Costs of implementation are negligible compared to the costs of selectivity due to the escapement of commercial grades in the short term. This underlines what is at stake when designing high performance devices that provide a fair compromise between reducing discards and limiting short-term losses.

Another reason for designing high performance and non-deformable selective devices is the difficulty in monitoring and controlling selectivity measures. The number of adjustments that can limit the changes in stock age structures or selectivity regarding bycatch species may cancel the effect of adopting selective devices. Strong incentives to increase selectivity are the best way to prevent non-compliance with selectivity measures. Rights-based management can provide some incentives to increase selectivity and can also prevent the increase of fishing efforts when benefits are evident (Macher et al. 2008). This measure could be combined with other kinds of incentives to increase selectivity. If not regulated, right-based management, such as individual quotas, can thus also be responsible for high grading practices (Copes 1986; Vestergaard 1996). A discard ban, which has been discussed at the European level, could also be a strong incentive to increase selectivity.

A number of limitations in the methodology described in this paper need to be highlighted, as they may impact the results obtained even if they do not change the conclusions concerning the need for selectivity improvements. One limitation is the sampling protocol of the experimental tests on selective devices: except for the test of the combined device CylGr in 2010, the standard trawl was not equipped with the square mesh panel for the escape of juvenile *M. merluccius* during the 2009 experiments, as it was implemented in 2010. The escapement rate of *M. merluccius* observed with the selective devices tested in 2009 compared to the standard trawl used in 2009 may, therefore, be overestimated in comparison with the escapement rate that we calculated by comparing the standard trawl with the square mesh panel used from 2010. As a consequence, the bio-economic impacts of the scenarios compared to the status quo are likely to be overestimated, except for the CylGr scenario.

Other limitations arise from the model assumptions and their influence on results:

(i) the dynamics of *M. merluccius* and *N. norvegicus* were included in the model while the dynamics of other species were assumed to be unaffected by selectivity improvement in the fishery. This assumption is reasonable for most species where the Nephrops-hake fishery makes a small contribution to fishing mortality, except for the contribution of the modelled trawler fleets on sole landings, which is about 21% (ICES 2010; Berthou et al. 2008). However, sole, Norway lobster and hake are not caught by the same *métier*. It is, therefore, to be expected that the impacts of these devices on sole stocks remain limited if fishermen are able to change gear during a single trip.

(ii) *N. norvegicus* and *M. merluccius* prices per commercial grade are assumed to be constant in the simulation, whereas price-quantity relationships can impact the results by mitigating the short-term losses and the long-term benefits, as illustrated in Macher et al. (2008) where price per grade is endogenous to the model[7].

(iii) The dynamics of vessels entrying and leaving the fishery are not taken into account in the model. They are assumed to remain constant over the simulation period. The paper shows, however, that the CylGr device benefits those fleets that contribute most to *N. norvegicus* fishing efforts. By increasing the long-term economic benefits for *N. norvegicus*, it is possible to create an incentive to increase fishing efforts and to enter into the fishery (Maynou et al. 2006; Eggert and Ulmestrand 2000; Hoff and Frost 2008). This change in fishermen's behaviour may eventually outweigh the positive effects of adopting the selective device if the fishing effort regarding *N. norvegicus* is not regulated. To be effective, the selectivity measures must be complemented by control and access regulation measures to avoid rent dissipation induced by effort increases.

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[7] The results in Macher et al. (2008) showed that the negative impacts on landings in the short term were offset by an increase in price, via the effect of price-quantity elasticity. In the long term, price could be lower because of greater quantity of fish, but could also increase due to average length increases.

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Appendix 1. Experimental trial data.

Table S1. *Merluccius merluccius* catches (in number) per age group and per selective device tested.

	Codend with 2 short selvedges		70 mm stretched suare mesh cylinder		Codend with the mesh fitted in T90		Square mesh cylinder + grid + 2 square mesh panels	
Age	Selective trawl	Standard trawl	Selective trawl	Standard trawl	Selective trawl	Standard trawl	Selective trawl	Standard trawl
0	26	372	2	3	10	337	87	327
1	445	1 689	1 493	3 120	177	3 671	961	1 471
2	95	122	230	265	190	306	177	224
3	6	4	7	7	15	19	15	23
4	1	2	1	2	2	3	9	10
5	1	0	0	0	0	0	1	3
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
+ gp	0	0	0	0	0	0	0	0
Total	573	2 188	1 733	3 398	394	4 336	1 250	2 057

Sources: Experimental trials "*SELECT trials*", 2009−2010.

Table S2. *Nephrops norvegicus* catches (in number) per age group and per selective device tested.

	Codend with 2 short selvedges		70 mm stretched suare mesh cylinder		Codend with the mesh fitted in T90		Square mesh cylinder + grid + 2 square mesh panels	
Age	Selective trawl	Standard trawl	Selective trawl	Standard trawl	Selective trawl	Standard trawl	Selective trawl	Standard trawl
1	125	163	11	17	45	164	20	643
2	819	1 455	842	908	386	1 602	2 730	5 326
3	1 170	1 963	1 386	1 640	413	2 484	5 987	8 589
4	500	871	635	705	286	1 410	3 276	3 795
5	203	327	246	289	149	666	1 589	1 496
6	62	80	80	111	49	210	534	506
7	14	34	35	37	39	136	207	196
8	11	18	15	18	12	45	117	91
>8	11	14	18	14	21	63	123	101
Total	2 915	4 927	3 267	3 738	1 399	6 780	14 583	20 742

Sources: Experimental trials "*SELECT trials*", 2009−2010.

Appendix 2. Sensitivity analyses of the net present value of total fishery surplus per scenario, compared with the status quo over the 2010−2030 simulation period for various discount rates.