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Original Article

Use of avoidance behaviours to reduce the economic impacts of the EU Landing Obligation: the case study of a mixed trawl fishery

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The EU Landing Obligation (LO) is designed to reduce bycatch (i.e. unwanted catch) through more selective fishing practices, such as avoidance behaviours which consist in allocating fishing effort to other species, fishing grounds or seasons. Incentives for fishers to change their behaviours depend on their economic performances as well as their ability to avoid bycatch. Changes in economic performances under the LO are evaluated based on cost and revenue equations. The nested grid method is then used to explore the spatial and temporal distribution of landings and discards, and to suggest alternative effort allocation to avoid bycatch. This article is focussed specifically on the French otter trawl fishery in the eastern English Channel and southern North Sea. Results suggest that under the LO the choke species problem will curtail fishing activities earlier in the year, leading to significant economic losses. In the absence of significant quota top-ups (at least 75%), a change in fishing practices consisting in reducing overall bycatch by 30% is insufficient to reduce losses. With a particular attention to choke species, more economically efficient avoidance strategies can be found thanks to the nested grid method.

Keywords: avoidance behaviours, choke species, economic incentives, Landing Obligation, nested grid, otter trawl fishery

Introduction

The 2013 Common Fisheries Policy introduced a Landing Obligation (LO) to eliminate discards in European fisheries (Regulation (EU) N°1380/2013). Since 2015, fishers had to gradually retain on board, register and land all catches of regulated species, which are then deducted from quotas. These quotas are supposed to be lifted (i.e. top-ups) to help fishers during the transitional period, but it is still unclear which top-up level is allowed (Council Regulation (EU) 2018/120). Fish below Minimum Conservation Reference Sizes (MCRS) are unmarketable and restricted for non-direct human consumption (Regulation (EU) N°1380/2013). All LO regulations are expected to incentivise fishers to fish more selectively. The risks of not using more selective fishing practices are to process and land increased low-value catch quantities (Catchpole *et al.*, 2017). These additional quantities may result in a reduction in net profits (Condie *et al.*, 2013; Simons *et al.*, 2015), and catch limits may be reached more quickly for choke species. These are species for which the quota is caught first in mixed-fisheries (Schrope, 2010). Once the quota is exhausted, all fishing activities likely to catch the regulated species must stop within a given fishing area (Baudron and Fernandes, 2015). In this context, fishers may encounter additional regulatory, technical and economic constraints.

To comply with these constraints, fishers' interests are to reduce bycatch (i.e. unwanted catch) through more selective fishing practices. The development of selective fishing gears is extensively studied (Alzorriz *et al.*, 2016; Batsleer *et al.*, 2016; Mortensen *et al.*, 2017; Prellezo *et al.*, 2017; Kopp *et al.*, 2018), but it requires time, important financial resources and is hardly achieved in mixed-fisheries (Suuronen and Sardà, 2007; Catchpole *et al.*, 2008; Romero *et al.*, 2010). Another possibly complementary approach consists in allocating fishing effort to other species, fishing grounds or seasons to avoid bycatch (e.g. Batsleer *et al.*, 2013; Branch and Hilborn, 2008; Simons *et al.*, 2015). Using avoidance behaviours is of less concern, there are no investment requirements and bycatch could be reduced within a short period of time.

Incentives for fishers to change their behaviours depend on expected economic performances as well as their ability to avoid bycatch. In this study, direct impacts of the LO implementation on economic results are first assessed. Depending on the expected economic incentives, avoidance behaviours are then identified using a mapping method based on nested grids (Pointin *et al.*, 2018). The spatial and temporal distribution of landings and discards is thus explored with a particular focus on choke species, for which a reduction in bycatch is most likely to increase net profits. From the resulting maps, fishing areas and periods to be avoided (i.e. high bycatch) or to be favoured (i.e. low bycatch) are eventually identified.

Moreover, because of the idiosyncratic nature of bycatch and mitigation strategies (Uhlmann *et al.*, 2014; Catchpole *et al.*, 2014; Sigurḥardóttir *et al.*, 2015), these strategies are required to be developed on a case-by-case basis at the scale of a group of vessels with similar behaviours and fishing practices. Accordingly, a fishing fleet that is likely to be affected by the LO is taken as an example, in order to evaluate the economic incentives for fishers to reduce bycatch and to explore avoidance behaviours. As such, trawlers operating from Boulogne-sur-Mer were the focus of this study.

Boulogne-sur-Mer is one of the most important French fishing ports, in which large amounts of unmarketable fish are expected to be landed under the LO (Catchpole *et al.*, 2017). Trawlers >18 m comprise the majority of the fleet contributing to 71 and 61% of the port's auction sales by volume and value (FranceAgriMer, 2018). The trawl fishery; hereafter, referred to as trawlers, targets demersal and small pelagic fish using bottom or mid-water otter trawls in the eastern English Channel (EEC) and southern North Sea (SNS). Cornou *et al.* (2017) estimated that up to 40% of catches are discarded mainly due to regulatory (i.e. below MCRS) and economic considerations (i.e. high grading, the practice of discarding legal fish of low market value or damaged or poor quality).

In the following sections, trawlers are first identified based on the registered port and fishing practices, then according to their associated métiers, catch profiles (i.e. landings and discards) and economic performances (net profits). Economic performances are then re-assessed under the LO, and economic incentives are finally investigated by comparing economic performances according to several situations (with or without quota top-ups, with or without the use of more selective fishing practices). According to these incentives, the spatial and temporal distribution of landings and discards is explored using the nested grid method, aiming to the identification of potential avoidance behaviours at fine-spatial scales.

Material and Methods

Data

All data used in this study were collected between 2011 and 2016 under the EU Data Collection Framework (DCF) (2008/949/EC), and stored in the *Système d'Informations Halieutiques* database (Leblond *et al.*, 2008). In accordance with Ulrich *et al.* (2012), a métier-based approach was used: a "métier" is defined as a group of fishing operations (FOs) targeting a given species or group of species, using a given gear, during a defined period of the year and within a defined area (Mesnil and Shepherd, 1990). A métier is characterized by similar catch rates, fishing types, net profits, incentives etc. (Ulrich *et al.*, 2012).

Based on official data (logbooks, sales, and fishing effort data) and activity calendars (Berthou *et al.*, 2008), fisheries statistics were obtained from the SACROIS algorithm (Demanèche *et al.*, 2010). The algorithm provided the most likely estimates of total landings (in tonnes), revenue (in euros) and fishing effort (in days-at-sea and fishing hours) by individual vessel, fishing sequence (i.e. a combination of day, gear, and ICES statistical rectangle), and species. The algorithm also assigned to each fishing sequence a combination of gear and target species or species group (i.e. métier unit at DCF level 5). Fisheries statistics were used to identify métiers (e.g. gears, target species, fishing zones, catch compositions) and to calculate the associated fishing effort, landings, and revenue.

The French on-board observer programme (Obsmer) data were used to estimate discards and to explore the spatial and temporal distribution of landings and discards. The Obsmer data were collected by at-sea observers who were placed on fishing vessels for the duration of a fishing trip to sample catches during FOs (i.e. process from the time of launching a fishing gear until it is hauled back aboard). Within a trip, a random sample of FOs, ranging from one-third to half, were observed during which the retained and non-retained portions of the catch were observed separately by identifying, weighing and measuring all species. For the non-observed FOs, landings were only weighed and counted (Cornou *et al.*, 2017). Data finally included information on landings and discards in number, size and/or weight per species for each FO observed on-board individual vessels. Fishing trip characteristics were also included, such as trip duration or landing port.

Fishing cost information were derived from the BSPA (Statistical Office in the French Ministry of Fisheries) economic data, collected under the French DCF programme. Economic data were collected annually for a selection of vessels and stratified by maritime registration district and vessel characteristics (size, gear) (Van Iseghem *et al.*, 2011). When accounts were not available, which is mostly the case for small scale vessels, a questionnaire was used to collect economic data (Daurès *et al.*, 2008). Economic data made available included crew and landing costs, other variable costs and fixed costs. Crew costs are payments for the crew based on a sharing system, and also include social costs. Landing costs are the sum of taxes paid by fishers to land catches, accounting for about one-tenth of sales revenue for trawlers. Other variable costs include fuel costs plus costs for motor oil, ice, and food supplies. Last, fixed costs regroup costs for fishing equipment, gears, insurances, licences, repairs, and maintenance.

Case study

Trawlers were selected based on the following criteria: >18 m, registered at Boulogne-sur-Mer, using bottom and mid-water otter trawls, targeting a mix of cephalopod, demersal and pelagic fish (described in Table 1), fishing in the EEC and SNS (Figure 1) and operating at least 1 year from 2011 to 2016.

Table 1. List of the main species landed and discarded by trawlers from 2011 to 2016.

FAO code	English name	Scientific name	DCF level 5	MCRS (cm)	Price[a] (€/kg)	Contrib. (%)
BSS	Sea bass	*Dicentrarchus labrax*	DEF	–	6.95	7.5
COD	Cod	*Gadus morhua*	DEF	35	2.49	5.1
CTC[b,c]	Common cuttlefish	*Sepia officinalis*	CEP	–	2.05	8.5
DAB	Dab	*Limanda limanda*	DEF	–	0.51	1.1
HER	Herring	*Clupea harengus*	SPF	–	0.24	1.0
HOM	Horse mackerel	*Trachurus trachurus*	SPF	15	0.28	0.5
MAC[b]	Mackerel	*Scomber scombrus*	SPF	20[d]	0.72	12.1
PLE	Plaice	*Pleuronectes platessa*	DEF	27	0.92	1.4
SQZ[b,c]	Various squids	*Loliginidae*	CEP	–	4.03	26.2
WHG[a]	Whiting	*Merlangius merlangus*	DEF	27	1.36	16.3

Contrib., the percentage of revenue derived for each species all métiers combined; MCRS, Minimum Conservation Reference Size; DEF, demersal fish; CEP, cephalopod; SPF, small pelagic fish.

[a]Lowest price level from 2011 to 2016 (source: EUMOFA).

[b]Main target species.

[c]Non-quota species.

[d]30 cm in the SNS.

Individual fisheries statistics (landings in volume and value per species, and fishing effort), obsmer data and annual aggregated cost data were made available for this group of trawlers, all of which were assumed to have similar economic structures. Economic data contained average annual costs per category over the period 2011–2014. These costs were assumed to be adequate for the period 2015–2016, for which no data were available, as no major changes in input prices (e.g. fuel) occurred.

Identifying métiers, catch profiles, and economic performances

Based on individual fisheries statistics available for each trawler, average annual landings $L(i)$, in tonnes, and revenue $R(i)$, in euros, were computed for each métier i at the DCF level 5. Average annual discards $D(i)$, in tonnes, were estimated from the observed discarded proportions $\delta'(i)$, which were assumed close to the true values $\delta(i)$:

$$\delta(i) \sim \delta'(i) = d(i)/\ c(i) \tag{1}$$

$$D(i) = [\delta(i) \times L(i)]/[1\ \ \delta(i)] \tag{2}$$

where $d(i)$ and $c(i)$ are discard and catch estimated from the FOs observed on-board trawlers. Given that discards might be overestimated for species with a discarded proportion larger than 0.9, an alternative method of calculation was used as in Pointin *et al.* (2018).

To estimate net profits, the annual costs per vessel were allocated to each métier. Since trawlers were similar according to their technical characteristics, these costs were assumed not to be influenced by the year, the gear, the vessel size or age, as suggested by Daurès *et al.* (2013). Other variable costs $C_o(i)$ were thus assumed influenced mainly by the number of days-at-sea (Daurès *et al.*, 2013):

$$C_o(i) = C_o \times [N(i)/\sum_{i\in I} N(i)] \tag{3}$$

where C_o is operational cost; $N(i)$ is the number of days-at-sea; I is the set of métiers.

Fixed costs $C_f(i)$ were yearly distributed among metiers based on the time spent on each metier per year. For convenience, the number of days-at-sea was used as in Equation (3). Landing costs $C_l(i)$ were assumed proportional to revenue (Daurès *et al.*, 2013):

$$C_l(i) = C_l \times [R(i)/\sum_{i\in I} R(i)] \tag{4}$$

where C_l is landing cost.

Crew costs $C_c(i)$ were then estimated as:

$$\theta_c = C_c/(R - C_o - C_l) \tag{5}$$

$$C_c(i) = [R(i) - C_o(i) - C_l(i)] \times \theta_C \tag{6}$$

where θ_c is the percentage of revenue used to pay the crew, which is independent of métier as crew members and functions remain unchanged over the year.

Net profits $\pi\ (i)$ were finally calculated as follows:

$$\pi(i) = R(i) - C_o(i) - C_l(i) - C_c(i) - C_f(i) \tag{7}$$

Evaluating economic impacts of the LO implementation

Under the LO, the previously discarded species subject to quota should be landed and sold either for human (i.e. marketable bycatch) or non-human (i.e. unmarketable bycatch) consumption. Accordingly, catches to be landed, landing costs, crew costs, revenue and net profits were re-evaluated under the LO. Fixed costs were assumed unchanged, and other variable costs (except for costs for ice and fishing boxes) were also assumed unchanged as far as fishing effort remained stable (i.e. no choke species). The economic incentives for fishers to reduce bycatch were finally assessed by comparing net profits with or without the use of more selective fishing practices.

Costs and revenue under the LO

Under the LO, the quantities of marketable $D_m(i,s)$ and unmarketable $D_u(i,s)$ bycatch were estimated per métier i and per species s using the Obsmer data:

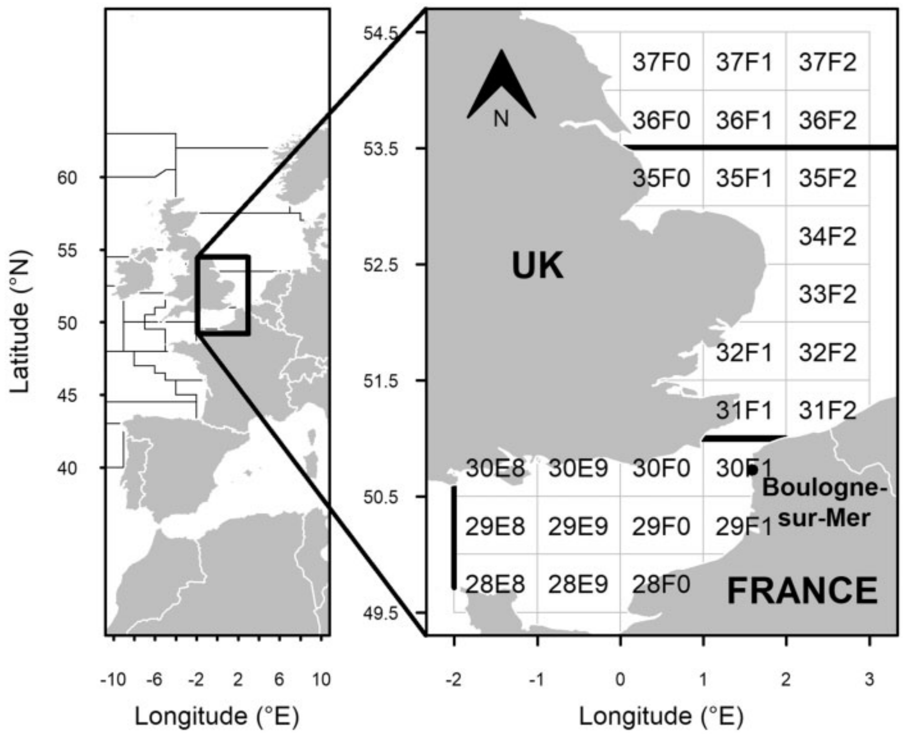

Figure 1. Map of the study area in the EEC and SNS. The ICES statistical rectangles are referenced by their codes.

$$D_{x\in[m,u]}(i,s) = D(i,s) \times \alpha_{x\in[m,u]}(i,s) \quad (8)$$

where $\alpha_{x\in[m,u]}(i,s)$ is the proportion of marketable (or unmarketable) bycatch; $D(i,s)$ is the quantity of species discarded.

Landings $L^*(i)$ and revenue $R^*(i)$ were re-evaluated as follows:

$$L^*(i) = L(i) + \sum\nolimits_{s\in S}[D_m(i,s) + D_u(i,s)] \quad (9)$$

$$R^*(i) = R(i) + \sum\nolimits_{s\in S}[p_m(s) \times D_m(i,s)] + p_u \times \sum\nolimits_{s\in S}[D_u(i,s)] \quad (10)$$

where $p_m(s)$ is the price for marketable bycatch sold at the lowest price level; p_u is the price for unmarketable bycatch set to 0.15 euros.kg^{-1} (Balazuc *et al.*, 2016); S is the group of regulated species caught by trawlers.

Landing costs $C_l^*(i)$ based mainly on *ad valorem* taxes were then given by:

$$C_l^*(i) = [C_l/\ R] \times R^*(i) \quad (11)$$

where C_l/R is the percentage of revenue used to pay landing taxes.

Crew costs $C_c^*(i)$ were re-evaluated according to the previous estimates of revenue $R^*(i)$ and landing costs $C_l^*(i)$, as in Equation (6). Changes in net profits were finally measured by comparing net profits $\pi(i)$ without and $\pi^*(i)$ with the LO:

$$\begin{aligned}\Delta\pi(i) &= \pi(i) - \pi^*(i)\\ &= \pi(i) - [R^*(i) - C_l^*(i) - C_c^*(i) - C_o(i) - C_f(i) + \beta]\end{aligned} \quad (12)$$

where β is the additional cost for ice, fishing boxes and transit taxes to land bycatch, which is set to 0.10 euros.kg^{-1} (Balazuc *et al.*, 2016).

Measurement of economic incentives

Fishers' best option to reduce bycatch is to use a combination of selective fishing practices (Rochet *et al.*, 2014). Any one change in fishing practices is thus expected to partially reduce bycatch. Considering also that bycatch can be very difficult to reduce in mixed-fisheries, a basic strategy consisting in reducing bycatch uniformly by 30% was assumed. Economic incentives for fishers to adopt this strategy were assessed by comparing the change in net profits resulting from the LO implementation with the change in net profits if fishers reduced bycatch by 30%.

Choke species

Net profits are expected to fall under the LO because (i) catch limits may be reached more quickly for choke species and (ii) target species catches may be substituted by lower-value ones, as a result of limited storage capacity. Since the storage capacity should rarely be limiting for trawlers (Balazuc *et al.*, 2016), the choke species problem was only considered in this article.

At Boulogne-sur-Mer, species quotas are managed by a producer organization, which means that all members (i.e. vessels) have access to a common amount of quota. Once a quota is exhausted, all vessels are no longer authorized to land that is to catch, the corresponding species. To simplify the analysis, these common quotas were allocated equally to each vessel, and were aggregated only for trawlers. The number of days N_q^* spent at sea by a trawler before species quotas $q(s)$ were reached was calculated based on the estimated annual landings $L^*(s)$:

$$L^*(s) = L(s) + D_m(s) + D_u(s) \quad (13)$$

$$N_q^* = [q(s)/ L*(s)] \times N \quad (14)$$

where N is the initial average number of days-at-sea per trawler (i.e. no LO).

The number of days spent at sea by a trawler until the first species quota is reached under the LO was given by $min\{N, N_1^*, N_2^*, \ldots, N_q^*\}$. Catches to be landed $L^*(i)$, revenue $R^*(i)$ and all costs in Equation (12) (except for fixed costs) were finally deducted in accordance with the smaller number of days spent at sea by a trawler.

Since species quotas were different between years and fishing zones (EEC vs. SNS), the occurrence of choke species and the economic incentives for fishers to reduce bycatch were evaluated separately in each fishing zone according to each year. Moreover, the economic incentives were analysed under two different quota top-up levels, for which changes were calculated from a baseline non-LO scenario: 0 and 75% of the estimated stock discards. Species quotas were thus assumed to be either not changed (worst-case scenario), or lifted by the highest possible level (best-case scenario) (Course *et al.*, 2011; Condie *et al.*, 2014).

Identifying specific avoidance behaviours

Based on the main choke species identified from the previous section, the spatial and temporal distribution of landings and discards were explored for the métiers most likely to be impacted by the LO. In doing so, the nested grid method was used to map landings and discards over the period 2011–2016 using the R software (Pointin *et al.*, 2018). This method adjusts the size of each grid cell as a function of the number of observations therein: small cell sizes are used in areas with many observations, and vice versa.

From the geographical coordinates of each FO observed from 2011 to 2016, the nested grids were constructed based on an iterative process of cell division: starting with a coarse regular grid, each cell was divided one or several times providing that the number of FOs therein was larger than a maximum threshold; each sub-cell with a number of FOs smaller than a minimum threshold was associated with low precision estimates. For each cell size, maximum and minimum FO thresholds were determined with a level of precision set to 0.35 (for more details, see Pointin *et al.*, 2018). To map landings and discards in each grid cell, total landings and discards were then estimated over the whole study area from 2011 to 2016. They were finally distributed proportionally in each cell depending on local (i.e. per cell) estimated proportions computed from the observed FOs (for more details, see Pointin *et al.*, 2018).

The resulting maps relied on several indicators to evaluate the sample representativeness. Trawlers were found satisfactorily covered by the Obsmer programme (Supplementary Figure S1A). Despite some significant differences, sampling effort was found temporally consistent with fishing effort between years (Supplementary Figure S1B) and between quarter (Supplementary Figure S1C). Sampling effort was also found spatially consistent with fishing effort (Supplementary Figure S2A) and landings (Supplementary Figure S2B), as measured by the global collocation index > 0.95 and local collocation index $= 0.92$ (Bez and Rivoirard, 2000). To minimize potential discrepancies within years, data were pooled over 2011–2016.

Table 2. Average technical characteristics for trawlers.

Technical characteristics	
Length (m)	23.4 (4)
Gross tonnage	10 486 (7)
Engine power (kW)	496.1 (16)
Fishers on board (No.)	5.27 (16)
Fishing trip duration (h)	71.9 (43)

Values in parentheses are coefficients of variation (%) between vessels.

To identify fishing areas or periods to be avoided (i.e. high bycatch) or to be favoured (i.e. low bycatch), the proportions of choke species discarded were mapped for the most impacted métiers according to the period of the year (i.e. quarter). The spatial distribution of FOs observed on-board trawlers from 2011 to 2016 was non–random (Supplementary Figure S6). Based on the nested grid method, grid cells were reduced to a size smaller than the spatial scale of clustering: FOs were distributed randomly in most of the cells (Supplementary Figure S7).

Results

Métiers, catch profiles, and economic performances

In total, 16 trawlers were selected with similar technical characteristics (Table 2). Crew size was relatively constant over the year. Fishing trips lasted on average 3–5 days according to the distance from the fishing areas: the longest trip duration occurred in the SNS (latitude $>52.5°$N). During the year, fishers on-board trawlers practised several métiers consisting of changes in target species, gear used and/or fishing areas. Three main métiers composed their fishing strategy: (i) bottom otter trawl for cephalopod (hereafter denoted as OTB_CEP), (ii) bottom otter trawl for demersal fish (OTB_DEF), and (iii) bottom/mid-water otter trawl for small pelagic fish (OTBM_SPF). The OTB_CEP métier accounted for 37% of days-at-sea in a year, which were spent mainly in the EEC (ICES statistical rectangles 29F0, 30F0, 29F1, 30F1) from August to March (Figure 2 and Supplementary Figure S3). The OTB_DEF métier (50% of days-at-sea) were practised mainly in the EEC (29F0, 30F0, 30F1), and to a more limited extent, in the SNS (31F1, 37F0) depending on the period of the year (Figure 2 and Supplementary Figure S4). Last, the OTBM_SPF (only 13% of days-at-sea) occurred predominantly in the EEC (29F0, 30F0, 30F1) from April to May, and may be pursued in the SNS (37F0) from May to June (Figure 2 and Supplementary Figure S5).

The OTB_DEF and OTB_CEP métiers generated most of landings in weight and value, discards in weight, and costs (Table 3). Fishers landed whiting (43% of total landings in weight) and mackerel (8%) from the OTB_DEF métier (Figure 3), squid (18%) and cuttlefish (12%) from the OTB_CEP métier but also whiting (19%). From both métiers, herring (7 and 22%, respectively), dab (17 and 20%) and whiting (42 and 14%) were mostly discarded. The OTBM_SPF métier was less productive (Table 3), with mackerel (60%) and whiting (76%) being respectively the most landed and discarded species (Figure 3).

Economic impacts of the LO implementation

Top-up vs. no change in quotas

Under the LO, fishers would reach several species quotas within a restricted number of days-at-sea depending on the fishing zone

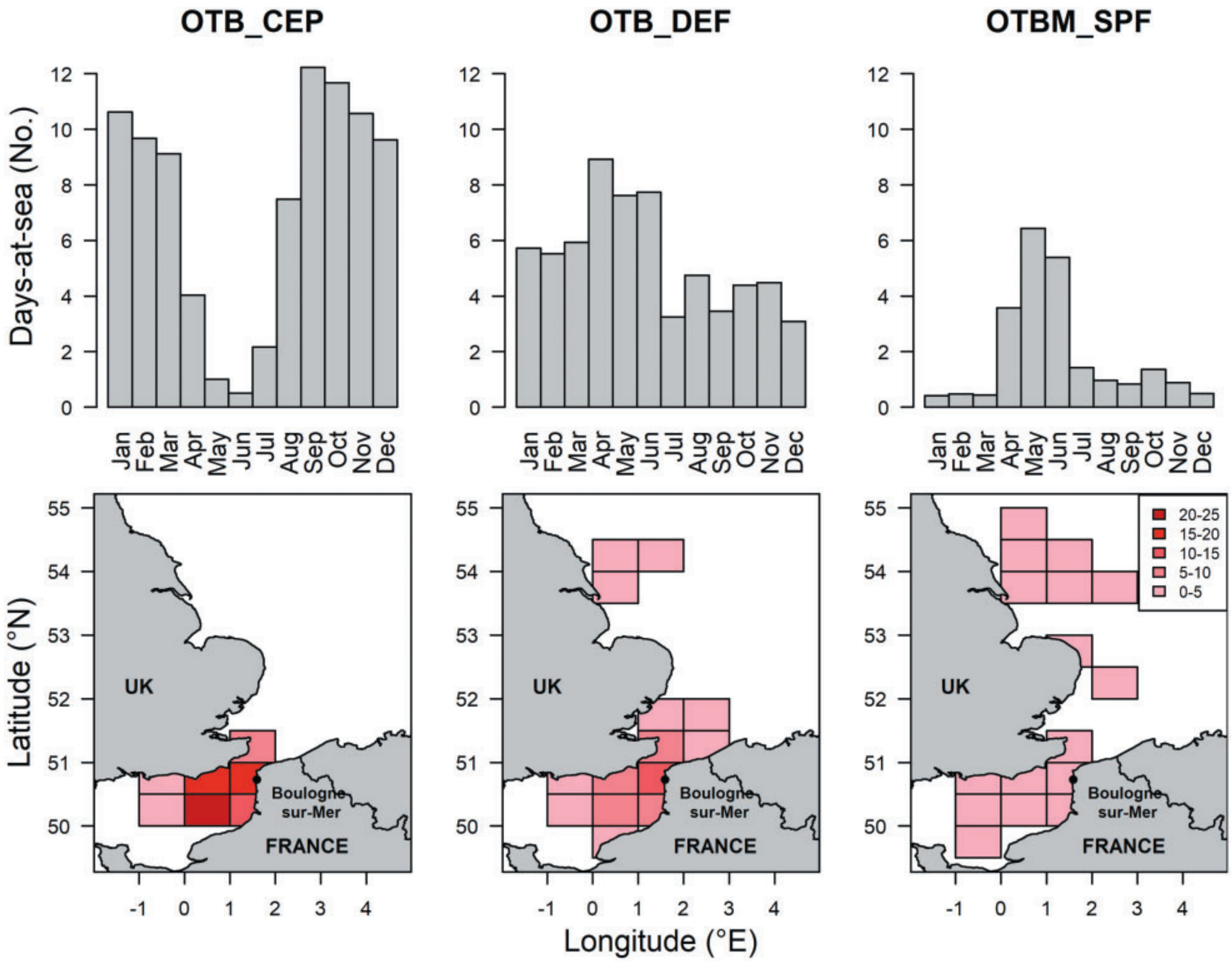

Figure 2. Average number of days-at-sea per month (top) and per ICES statistical rectangle (bottom) in a year for each trawler as reported in the fisheries statistics. Each column corresponds to a métier: OTB_CEP or OTB_DEF, and OTBM_SPF.

(Figure 4). In most scenarios, the main choke species would be horse mackerel as it would be associated with the most restricted numbers of days-at-sea, except under a 75% top-up scenario, in which the main choke species would be mackerel in the SNS. Based on existing (i.e. as usual) fishing behaviours, the numbers of days spent at sea by trawlers would decrease by ∼15–85 days depending on the fishing zone and quota top-up level. Under a 0% top-up scenario, the number of days-at-sea would drop from 135 to 50 days in the EEC, and from 39 to 14 days in the SNS. It would decrease to a much lesser degree under a 75% top-up scenario: from 135 to 105 days in the EEC, and from 39 to 24 days in the SNS.

The loss of profits would be proportional to the reduction of days-at-sea (Figure 5). Based on existing fishing behaviours, net profits would decrease greatly under a 0% top-up scenario. For all métiers combined, fishers would lose ∼46 000 euros in the EEC and 20 000 euros in the SNS, while they would lose ∼13 000 euros in the EEC and 7000 euros in the SNS under a 75% top-up scenario. The most affected métier would be the OTB_CEP métier (total losses of about 34 000 and 10 000 euros under the 0% and 75% top-up scenarios, respectively), followed by the OTB_DEF métier (22 000 and 7000 euros) and OTBM_SPF métier (10 000 and 3000 euros).

With uniform bycatch reduction of 30%

Considering fishers would be able to reduce their bycatch by 30%, the number of days-at-sea (Figure 4) and the related net profits (Figure 5) would be less restricted compared with the previous scenarios. Under a 0% top-up scenario, fishers would be allowed to spend more days-at-sea (9 days in the EEC and 4 days in the SNS), resulting in an increase in net profits (5000 euros in the EEC and 2000 euros in the SNS). A 75% top-up scenario would produce more significant increases: 21 days for 11 000 euros in the EEC, and 6 days for <1000 euros in the SNS. Under a 75% top-up scenario, fishers would be slightly affected by choke species because quotas would be exceeded late in the year. They would thus benefit from the landings of marketable and unmarketable bycatch of regulated species, explaining changes in net profits would be positive in the EEC.

Specific avoidance behaviours

In most scenarios, the most profitable behaviours for fishers would be to avoid horse mackerel bycatch while practising the OTB_CEP and OTB_DEF métiers in the EEC. Under a 0% top-up scenario, horse mackerel quota would be reached after only 50 days-at-sea (compared with the initial 135 days-at-sea), so the

Table 3. Summary of métier characteristics, and the average annual landings, discards, revenue,[a] and costs per vessel from 2011 to 2016.

	Métiers		
Variables	**OTB_CEP**	**OTB_DEF**	**OTBM_SPF**
Gear	Bottom otter trawl	Bottom otter trawl	Bottom/mid-water otter trawl
Target species group	Cephalopod	Demersal fish	Small pelagic fish
Zones	EEC	EEC – SNS	EEC - SNS
Annual landings per vessel (*t*)	150	140	90
Annual discards per vessel (*t*)	60	70	20
Annual revenue[a] per vessel (10^3 euros)	360	250	100
Annual cost per vessel (10^3 euros)	370	260	100
Most valuable species	squid, cuttlefish, whiting	whiting, squid, mackerel	mackerel, whiting

[a]No information was available on fishing subsidies, so a significant portion of revenue was ignored.

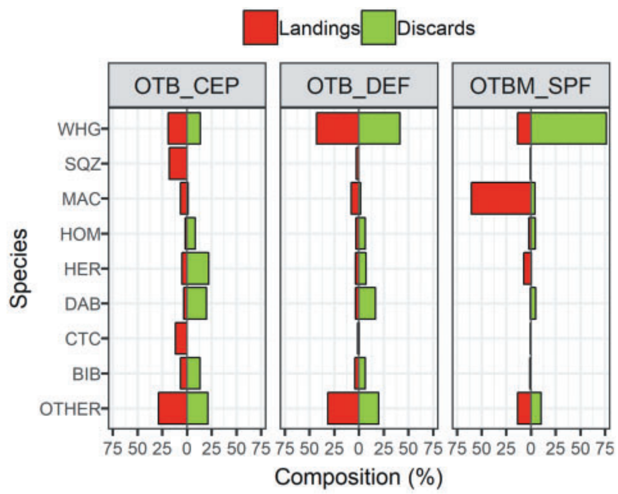

Figure 3. Average species composition (%) of landings and discards in weight for OTB_CEP or OTB_DEF, and for OTBM_SPF. Only the most landed and discarded species are displayed (see Table 1 for species codes).

trawl fishery would close during the first half of the year. Fishers would thus be incentivised to avoid horse mackerel bycatch beforehand. As a consequence, three isolated areas with high discarded proportions (>0.8) should be avoided in the EEC from January to March, and along the south coast of England from April to June (Figure 6). These avoidance behaviours would apply primarily to the OTB_DEF métier. Under a 75% top-up scenario, fishers would be incentivized to avoid bycatch during the second half of the year as the fishery would close later (after 120 days-at-sea). Fishers should therefore avoid operating in the southern EEC from July to September (especially when practising the OTB_CEP métier), and in the mid-part of the EEC and in the region off Boulogne-sur-Mer from September to December (Figure 6).

Discussion

At Boulogne-sur-Mer, the LO implementation is likely to impact fishers on-board trawlers. The restricted numbers of days-at-sea due to the occurrence of a choke species will curtail fishing activities earlier in the year, leading to significant profit losses particularly for the most practised métiers. These consequences will vary depending on species quotas and top-up levels. As a result, fishers will be incentivized differently to use bycatch-avoidance behaviours: e.g. they will be strongly incentivized under a 0% top-up scenario by low horse mackerel quotas. The most profitable behaviours will thus consist in avoiding horse mackerel bycatch by reallocating fishing effort in space and time. Accordingly, they will be incentivized to operate away from specific fishing areas in the EEC during the first half of the year.

LO direct economic impacts

Quota restrictions are one of the main reasons for fishers' economic losses. Before LO implementation, fishers discarded over-quota catches and legal fish of low market value or damaged or poor quality (i.e. high-grading). From now on, all catches of regulated species have to be landed and counted against quotas. The system is now based on catch quotas, instead of the standard landing quotas. Condie *et al.* (2014) suggested that the greater the discrepancies between catch quotas and the actual catches, the greater fall of revenue. It is the reason that, in a worst-case scenario in which catch quotas are set at the same level as the previous landing ones, major discrepancies are expected for highly discarded species (e.g. herring, horse mackerel and whiting). To help fishers during the transitional period, catch quotas are however supposed to be lifted up to a fixed percentage of the previously estimated levels of discard. In a best-case scenario, fishers are granted with extra quotas accounted for 75% of the estimated stock discards. Consequently, they are able to spend more days-at-sea, land more fish, and produce more revenue before the first species quota is reached.

In most scenarios, horse mackerel is the main choke species for the studied trawlers, while in the literature, cod, plaice, and whiting are usually cited as the main ones for similar fisheries (Russel *et al.*, 2015; Catchpole *et al.*, 2017; Mortensen *et al.*, 2018). The reasons for this are: (i) horse mackerel quotas were divided by more than two from 2011 to 2016, resulting in low available quotas for trawlers; (ii) available quotas for the other species remained steady or increased because fish stocks were in good conditions (e.g. ICES, 2017a, 2017b). It is also important to notice that different countries fishing in this area are subject to different quotas (which means different choke species) and so the decisions that other fleets will have to make will differ from French vessels.

Little economic incentives for uniform bycatch reduction

The LO combined with a catch quota system is likely to create economic incentives for fishers to use more selective fishing

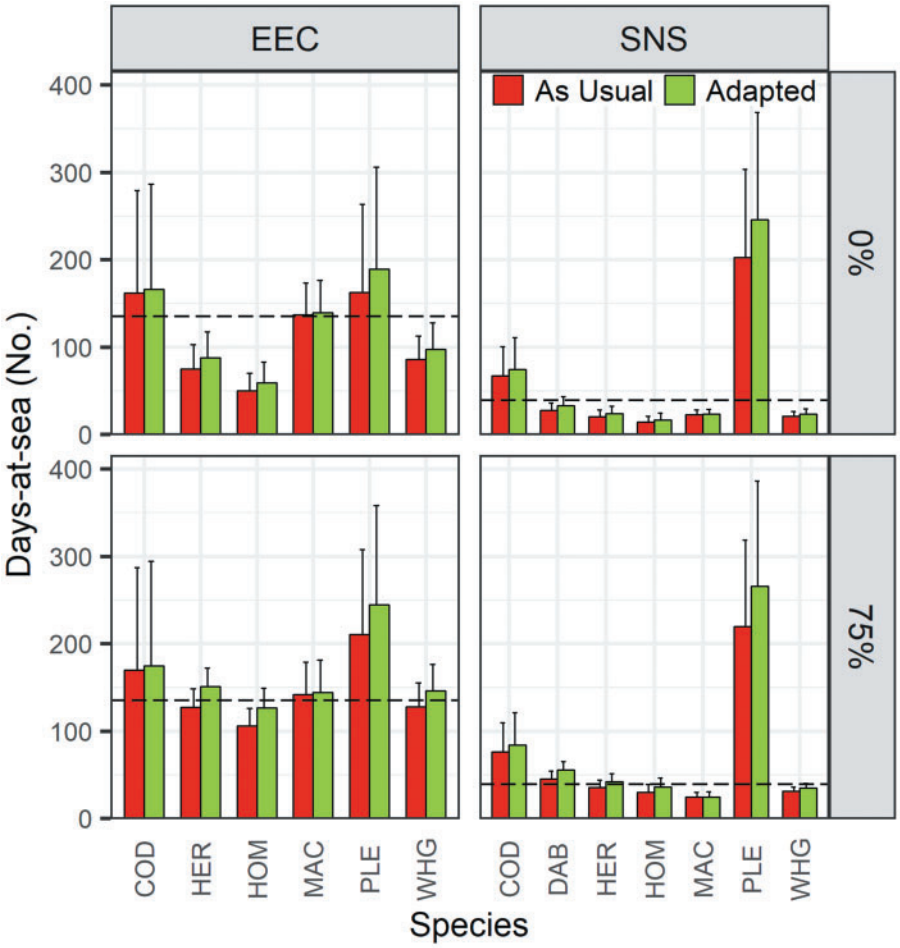

Figure 4. Maximum number of days-at-sea before each species quota is reached based on a LO scenario combined with either 0% or 75% quota top-ups in the eastern English Channel (EEC) and southern North Sea (SNS). Fishing behaviours are assumed as usual (As Usual), or adapted to reduce bycatch by 30% (Adapted). The dashed line represents the number of days-at-sea calculated from a baseline non-LO scenario (135 days in the EEC and 39 days in the SNS). Bars indicate the inter-annual variability from 2011 to 2016. See Table 1 for species codes.

practices. If bycatch could be reduced by 100%, species quota would be less limiting for fishers compared with business-as-usual (i.e. quotas would not be fulfiled early in the year). Their economic performances could be increased, leading to a potential increase in fishing effort and revenue (Condie *et al.*, 2013). The trawl fleet is however a mixed-fishery for which a multitude of bycatch is caught and is hardly avoidable (Balazuc *et al.*, 2016). Fishers are thus assumed to be able to reduce bycatch only by 30%, resulting in minor improvements in their economic performances. The savings represent only a marginal part of net profits, and depend mainly on choke species.

In recent years, quotas have been reduced drastically for certain species, making them high-risk choke species (e.g. horse mackerel, herring, and mackerel). In cases where these species are rarely discarded, there will be little incentive for fishers to use more selective fishing practices (e.g. fishers are not incentivized to avoid mackerel bycatch in the SNS, assuming a 75% top-up scenario is implemented). In contrast, if these species are highly discarded (e.g. herring, horse mackerel, and whiting), fishers will be strongly incentivized to use more selective fishing practices.

The economic impacts of the LO may be underestimated as the additional effort and costs incurred for handling, sorting and storing bycatch have not been considered in the analysis. In reality, fishers on-board trawlers are expected to work more hours during a fishing trip, leading to an increase in labour costs (Balazuc *et al.*, 2016). They are thus likely to be more strongly incentivized to reduce the time required to handle, sort and store bycatch by fishing more selectively, as suggested by Johnsen and Eliasen (2011). Negative economic impacts may also be worse due to increased landing costs because of new equipment and infrastructures required at fishing port to deal with bycatch landings.

Limitations of this approach

This study explores the degree of incentives for fishers to reduce bycatch under the LO. Besides, it identifies métiers, fishing areas and/or seasons for which fishers are mostly incentivized to avoid bycatch. These aspects are however very sensitive to a number of assumptions. First, the assumption that species quotas were distributed equally between all members of a producer organization (i.e. each member held its own quotas), although they should be available for all members, in which case the system is competitive (generating a race for fish; Batsleer *et al.*, 2013). In such systems,

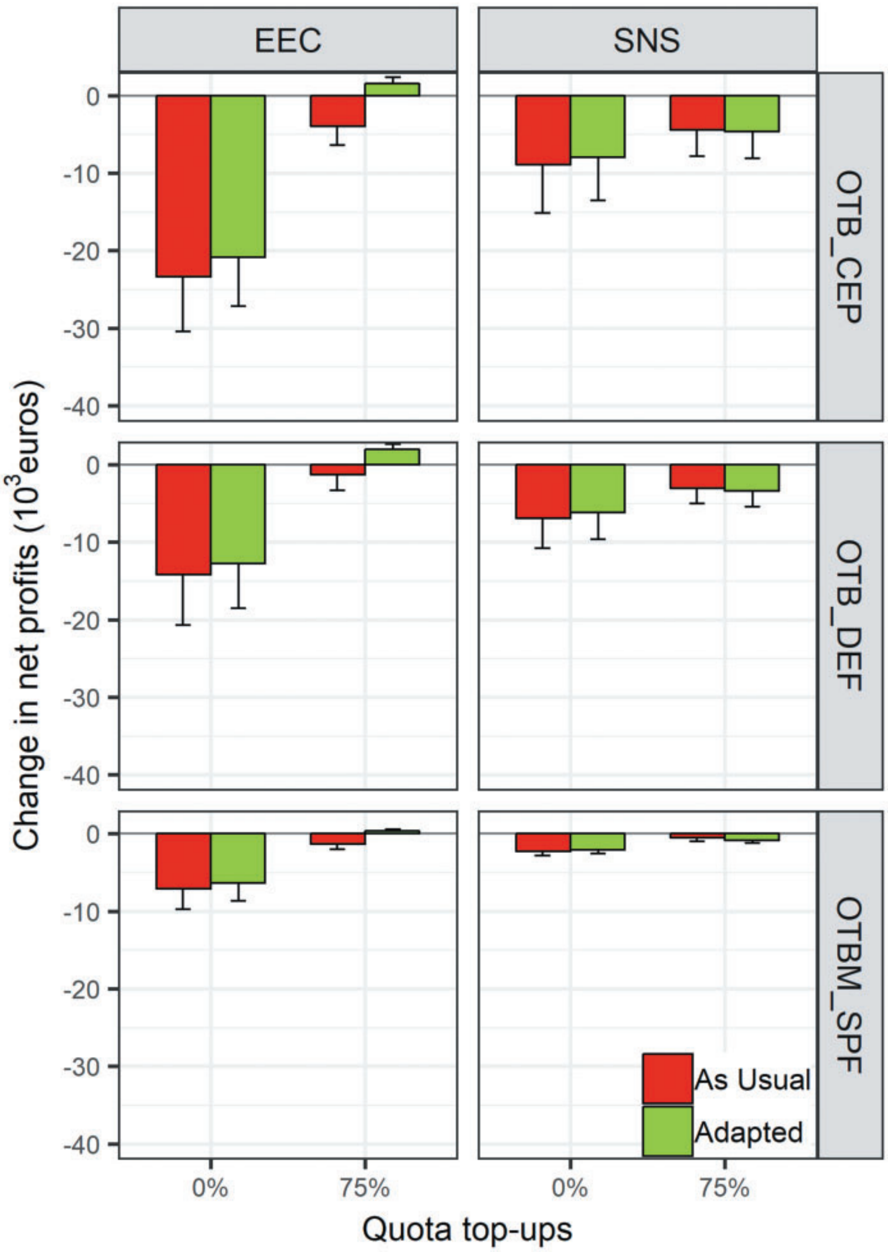

Figure 5. Change in net profits (10^3 euros) from a baseline non-LO scenario compared to a LO scenario combined with either 0% or 75% quota top-ups. Fishing behaviours are assumed as usual (As Usual), or adapted to reduce bycatch by 30% (Adapted). Bars indicate the inter-annual variability from 2011 to 2016. Results are shown for bottom otter trawlers targeting cephalopod (OTB_CEP) or demersal fish (OTB_DEF), and for the bottom/mid-water otter trawlers targeting small pelagic fish (OTBM_SPF) in the eastern English Channel (EEC) and southern North Sea (SNS).

fishers attempt to maximize landings before species quotas are reached. As a result, it is more difficult to incentive fishers to use more selective fishing practices as individual vessels have their own free will (e.g. if one fisher decides not to fish more selectively, it will eventually go against all others). Second, fish prices are assumed to be fixed, while these are known to vary depending on the time, and the quality and size of individual fish (e.g. Meuriot and Gilly, 1987). Third, the LO exemptions are disregarded, such as for fish damaged by predator, with high survival rate, or included in *de minimis* exemptions (Regulation (EU) N°1380/2013). The estimated quantities of marketable and unmarketable bycatch are thus slightly over-estimated.

Specific avoidance behaviours supported by on-board observer data and mapping tools

Rochet *et al.* (2014) recommended that fishers adopt a combination of mitigation strategies if they want to comply with all LO regulations, including avoidance behaviours. By contrast with a uniform reduction of bycatch, specific avoidance behaviours, which can be explored and identified using nested grids, could benefit more fishers. Provided that all quality indicators are met, the resulting maps are thus considered meaningful for fishers to visualize how best to reallocate effort when faced with the problems associated with choke species. Such mapping tools could be used by other fisheries successfully. It is important to mention that this could also be

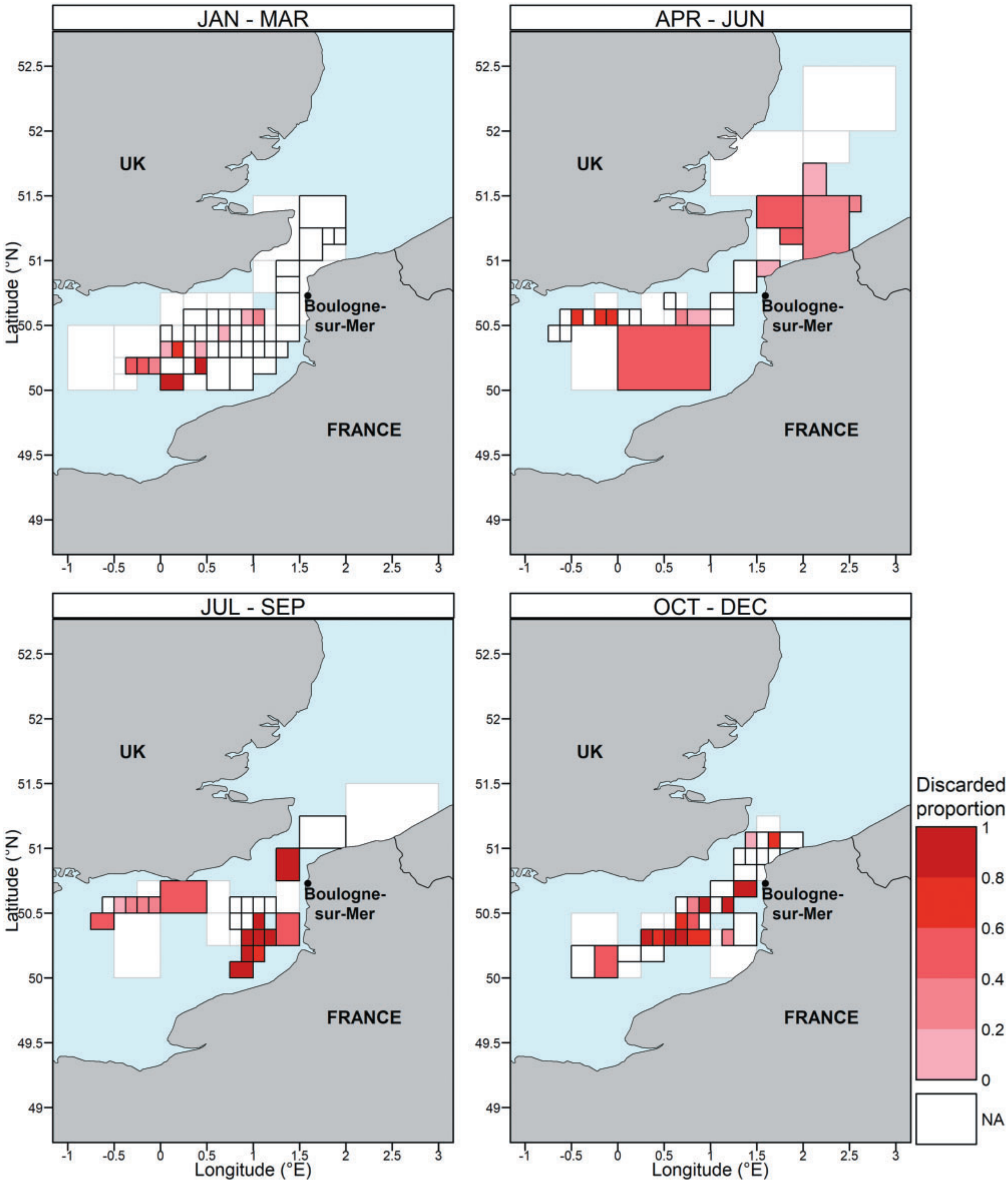

Figure 6. Discarded proportion of horse mackerel for OTB_CEP or OTB_DEF from January to March, April to June, July to September and October to December. The proportions are displayed only in cells containing 90% of catch-per-unit-effort. Black (grey) lines define cells with (in)sufficient amounts of FOs to make estimates with a precision level of 0.35.

achieved with mapping methods developed in other studies with regard to discard hotspots (e.g. Vilela and Bellido, 2015).

According to Cornou *et al.* (2017), horse mackerel is mainly discarded due to regulation (i.e. below MCRS) and economic considerations (i.e. low or no market value). More specifically, undersized fish are mainly found along the south coast of England, while low-value fish are found in the mid-part of the EEC (Pawson, 1995; Carpentier *et al.*, 2009). It can however be assumed that while fishers attempt to avoid bycatch they will also strive to maintain commercial catches to maximize revenue from fishing trips (Rochet *et al.*, 2014). A further analysis should therefore explore the spatial and temporal distribution of landings and discards for the main target species. In the end, fishing areas to be favoured (i.e. low bycatch and medium/high commercial catches) could also be explored.

The spatial distribution of species is dynamic and depends on the environment, perhaps more particularly in the context of climate change. Avoidance behaviours are thus expected to change in the near future. Further studies should therefore focus on predicting the spatial and temporal distribution of species taking into account those changes. Moreover, avoidance behaviours imply fishing effort to be reallocated to other species, fishing zones and/or periods, which may lead to unknown ecological consequences (e.g. on fish stocks or benthos). Accordingly, further studies should also investigate these consequences.

Perspectives

Based on equations and nested grid procedures, this study can be easily applied to other fishing fleets provided that the necessary data on landings, discard levels, cost and revenue are available. Additional information on labour costs could also be incorporated.

In cases where data on landings and discards are shared in near-real time between vessels, the nested grid method could be used to identify more efficiently avoidance behaviours, as suggested by Eliasen and Bichel (2016). One possible application would thus consist in creating an automatic calculation and visualization tool for fishers (e.g. Vilela and Bellido, 2015). The objectives of such a tool would be to ease data processing (e.g. reduce calculation time), to perform detailed analyses of fishing métiers (e.g. at port and/or fleet's scale), and to produce a large number of maps. These maps would then be shared with fishers. Currently, this is feasible only if a 100% observer coverage is applied, or if the LO is fully implemented and accepted by fishers.

Supplementary data

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

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