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Original Article

Contrasting impacts of the landing obligation at fleet scale: impact assessment of mitigation scenarios in the Eastern English Channel

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How the implementation of the European Commission's landing obligation (LO) would affect French vessels of the mixed demersal fishery in the Eastern English Channel was hardly foreseen because of the diversity of vessel characteristics and strategies in the area. Assessing whether the vessels would be able to mitigate the bio-economic impacts of LO and avoid choke situations through exemptions, by changing their fishing patterns or by avoiding areas, required fine scale spatio-temporal modelling of fish and fleet dynamics and of resulting technical interactions. We conducted a bio-economic impact assessment for seven scenarios of mitigation focussing on the differences across fleets and the impact of fleet spatial behavioural flexibility. We found that netters rapidly benefited from the LO as opposed to trawlers and that exemptions helped mitigate the economic loss with limited biomass loss. The avoidance strategies proved to be efficient in reducing unwanted catch of whiting and enabled unexpected protection of juvenile sole. Sensitivity analysis on the drivers of fishing behaviour indicated that the ability and efficiency of adapting fishing patterns depended on main gear and vessel size. Results evidenced the difficult trade-offs LO implies among stocks, fish stages, fleets, and even sub-regions, beyond the usual biological vs. economic contrasts.

Keywords: Eastern English Channel, impact assessment, ISIS-Fish, landing obligation, mitigation scenarios, spatial fishing behaviour, temporal avoidance areas.

Introduction

In 2013, the European Commission introduced the landing obligation (LO) as part of the Common Fishery Policy (CFP) reform in order to progress towards stock sustainability, prevent wasteful practices, and improve fisheries data quality (EU, 2013). This represented a major change in many European fisheries, which had previously been legally obligated to discard fish below a minimum landing size and above quota. Several studies investigated the odds of success of such a measure and often concluded that the impacts would depend on management regimes in place (Hoff *et al.*, 2019; Nielsen *et al.*, 2019) and the specificities of national implementations (quota management systems and control), fishers' reactions (Batsleer *et al.*, 2013; Simons *et al.*, 2015), and fishers' willingness to comply (Kraak and Hart, 2019). The case of the French fleets of the Eastern English Channel (EEC, ICES Division 7d) mixed fishery introduced another level of specificity at the fleet level. Indeed, with a high diversity of vessel sizes, species portfolios, métiers, and fishing grounds, the 448 French vessels targeting demersal fish in this area were unlikely to experience similar effects of the LO.

Fisheries in the EEC

The fisheries in the EEC were catching a large set of species, among which sole, plaice, cod, and whiting were regulated by total allowable catches (TAC) and minimum conservation reference size (MCRS) and therefore were affected by the LO. The French fleet targeting these demersal species have historical rights and quotas for these species but with contrasted situations. French fleets have a consequent share of TACs for plaice, sole, and whiting in the EEC. In contrast, cod quota is quite limited for the fleet catching it in the EEC.

In particular, métiers using bottom trawls presented mixed catches and targeted the four above-cited species as well as red mullet, and cephalopods over the course of the year. Bottom trawls in the area were operated by 75 exclusive or mixed trawlers and 195 trawlers-dredgers, which targeted scallops in winter and used bottom trawls or beam trawls the rest of the year (Lehuta *et al.*, 2015). Bottom trawls had an history of unwanted catch, and discard rates were up to 82% depending on métiers and species considered (Cornou *et al.*, 2021). Based on declared landings, the most frequent association of species affected by LO in bottom trawl was sole and plaice, but whiting and cod, and whiting and plaice were also caught together (Source DPMA, données déclaratives gérées par Ifremer—Système d'Informations Halieutiques). As far as unregulated species were concerned, plaice was also sometimes caught together with cephalopods and red mullet with cuttlefish. Discards mainly included undersized individuals, particularly for sole (95%) and to a lesser extent for plaice (up to 87%) and whiting (up to 77%) (Cornou *et al.*, 2021).

Nets (94 exclusive boats) and dredges appeared more selective than trawlers in their catch of the regulated species, both from the point of view of size and species. Netters seasonally relied on sole, with frequent simultaneous catch of plaice (Cornou *et al.*, 2021). Dredges used to target scallops were very selective and survival rates of undersized scallops were assumed very high.

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First reactions to LO implementation and potential mitigation in the EEC

In the EEC, the French demersal mixed fisheries felt particularly preoccupied by the introduction of the LO measure. Dialogue between stakeholders and scientists has long been established in the area, and a formal collaboration was set up starting in 2015 in the context of the EU project DiscardLess (EU H2020 633680).

Both existing scientific knowledge and fishers' expertise revealed that the application of the LO was indeed technically and strategically difficult for these fleets. First, in mixed-species fisheries managed by quota limits, the risk of choke species arises, creating a situation in which fishers have to stop fishing when they reach their quota for the species for which they have the lowest quota available. Second, regulatory system constraints (cod plan, technical measures, licenses, MCRS, and quotas) limit fleet adaptability and sometimes create incentives for discarding. For instance, some discards of cod were assumed to take place because of the cod plan implementation, which limited the proportion of cod allowed in daily landings. Finally, the EEC is a zone of intense human activities where competition for space exists (between fishers and between fishing and other activities such as maritime traffic, particularly intense shipping, or gravel extraction). Spatial restrictions apply to trawlers on the coastline, which further limits opportunities for avoiding areas of high discard rates (Girardin *et al.*, 2015).

Some studies (Ulrich *et al.*, 2011, 2017) and a specific ICES working group (WGMIXFISH, ICES, 2021a) already evidenced the potential for discards/under-utilization of quota in the North Sea and the EEC. However, the scale of definition of fleets in these studies did not reflect the heterogeneity of practices and therefore impacts in the area. In addition, the implementation of the LO was still incomplete (with a progressive introduction of the species and several exemptions for high survival rates) which prevented assessment of the impact of full implementation.

Previous experiments on selectivity improvements showed encouraging results for individual species (e.g. square mesh cylinders for whiting), but many measures were not adopted because of the important economic losses due to escapement of the smallest species (e.g. red mullet, selectFish project: https://www.comitedespeches-hautsdefrance.fr/wp-content/uploads/2016/01/Rapport_SELECFISH.pdf, Larnaud *et al.*, 2014).

Fishing activity in the region was seasonal in response to market demand and fish availability. However, fishers themselves admitted that short-term adaptation of their activity (target species and area choices) allowed them to avoid unwanted catch (Reid *et al.*, 2019). Skipper experience and real-time communication between boats also allow identification of undesirable aggregations at local scale (Reid, 2016; Mortensen *et al.*, 2018). Avoidance behaviour, and particularly seasonal avoidance of problematic areas, thus appeared as the best option to reduce unwanted catches.

Objectives of the study and plan

The aim of the study was to assess the possible impact of the LO on fleet activity and revenues and on stock biomasses in the EEC, to evaluate the potential of measures such as exemptions or avoidance behaviour in mitigating these impacts and to assess the degree to which fishers' adaptation modifies these results.

In order to allow an appropriate assessment of LO impacts in the region and testing of avoidance areas, a management strategy evaluation approach (Punt *et al.*, 2014) was proposed. The ISIS-Fish platform (Mahevas and Pelletier, 2004; Pelletier *et al.*, 2009) was selected as the operating model because it allows modelling (i) simultaneous catch of species and discards/choke due to both catch of undersized individuals and quota limitations; (ii) fishers' short-term behaviour; and (iii) spatio-temporal avoidance with effort reallocation. The existing parameterization of ISIS-Fish for the fishery (Lehuta *et al.*, 2015) was adapted to answer these specific questions related to impacts of the LO.

Stakeholder interaction took the form of regular (annual) meetings with representatives of the main producer organizations to present and discuss the data, assumptions, and the modelling tool; jointly define scenarios and outputs to consider; and reflect on results and limitations. Stakeholders also raised the need for discriminating impacts on the different fleets, because areas and seasons of practice, gear used and vessel size were likely to lead to different impact of the LO.

The paper first briefly presents the simulation platform with emphasis on the features related to the modelling of discards and LO and fleet behaviour. The paper then details the seven scenarios evaluated and their results in terms of biomass and revenues, with a focus on the differences across fleets and the impact of fleet behavioural flexibility. The discussion compares the results obtained in the EEC with other EU areas faced with the same challenges in implementing the LO. Insights gained through the modelling exercise are discussed in light of the modelling assumptions and the recent evolution of the fishery. Finally, the paper concludes with a description of the uptake of the results by stakeholders.

Material and methods

ISIS-Fish

ISIS-Fish is a deterministic simulation model designed to explore the dynamics of mixed fisheries (Mahevas and Pelletier, 2004; Pelletier *et al.*, 2009). It is spatially explicit with a monthly time step. Fishing mortality results from the interaction between the spatial distribution of population abundance (dynamically predicted by the population sub-model) and the spatial distribution of fishing effort by fleet and métier (monthly updated by the exploitation and management sub-models). Fishing effort is standardized per gear, métier, and fleet to account for selectivity, targeting, and fishing power. The effect of management measures can therefore be explicitly modelled, either through modifications of the standardization parameters for technical measures (e.g. change in the selectivity curve) or through modifications of the level and spatio-temporal distribution of fishing time for seasonal closures or effort control for instance. Landings are counted against quotas at each monthly time step, and fishing activity may be stopped or adapted accordingly.

ISIS-Fish settings in the Eastern Channel

Model parameters are stored in a database that can be freely downloaded at http://isis-fish.org/downloads/DiscardLess_Channel_05102018.zip. The main features are described below and further details on the parameterization are available in Lehuta *et al.* (2015) and in Supplementary Material.

The EEC application focused on the main demersal TAC species of concern for the LO in Division 27.7d: sole (*Solea solea*), plaice (*Pleuronectes platessa*), cod (*Gadus morhua*), and whiting (*Merlangus merlangus*) and on the French netter, trawler, and trawler-dredger fleets targeting them. These fleets also targeted species that were not regulated by TACs or Minimum Landing Size but constituted a large part of their revenues, such as scallops (*Pecten maximus*), cephalopods, and red mullet (*Mullus surmuletus*). All were consequently explicitly modelled (Supplementary Table S1.1).

The biological models built on the structure and parameters of the stock assessment models when available and on scientific survey data (E. Foucher and J.P. Robin, pers. comm. for squid and cuttlefish) and literature otherwise. The model accounted for spatial distribution and migrations over the course of the year [details can be found in Lehuta *et al.* (2015), in the parameter database and in Supplementary Table S1.2].

Fleets were based on the segmentation created by the French Fishery Information System (Ifremer—Système d'Informations Halieutiques), which groups French vessels based on the main, or two main, gears used during the year. They were further segmented according to length class of the vessel and home region (North or Normandy), due to acknowledged differences in fishing grounds, seasonality and mesh size. It resulted in 17 fleets and 448 boats on average over 2008–2010 (Supplementary Table S2.1). The other boats operating in the EEC (including international fleets) were pooled into an inexplicit fleet "OTHER", whose fishing pressure is modelled using a fishing mortality rate adjusted to management constraints over the course of the simulations. The set of métiers practiced by fleets was defined by the combination of gear, mesh size and zone. Five main gears were considered (gillnet 100 mm, trammel net 90 and 100 mm, bottom trawl 80 mm, beam trawl 80 mm, and dredge). The set of species accessible to a given gear was constrained by observations, but no preferential targeting was assumed (Supplementary Table S2.2). Consequently, the catch composition reflected the assemblage available to the gear at the time and in the area of operation. Size selectivity was estimated for each gear and species based on onboard observed data (Cornou *et al.*, 2021). Fishing mortality of a given species and age class in a given cell is given by 1:

$$F_{\mathrm{age,sp,cell,t}} = \sum_{\mathrm{strategy}} \sum_{\mathrm{métier}} \frac{\mathrm{Effort}_{\mathrm{strategy,métier,t}}}{\mathrm{nbCells}_{\mathrm{métier}}} * \mathrm{Sel}_{\mathrm{métier,\ sp,age}} * q_{\mathrm{sp,age}} * \mathrm{TF}_{\mathrm{métier,\ sp}}, \quad (1)$$

with sp, the species; nbCells the number of cells in the metier zone; Sel the selectivity of the gear used by the metier for the age class of the species; q the accessibility of the age class of the species; and TF (target factor) the intensity of fishing of the metier on the species (Supplementary Table S2.2). Prices of fish were dynamically computed based on an empirical supply–demand model accounting for monthly landed values and catch categories (approximated by length classes) (DPMA, données déclaratives gérées par Ifremer—Système d'Informations Halieutiques. Supplementary Table S1.3). Prices therefore differ across scenarios and fleets depending on the age structure and volume of the catch.

In the EEC ISIS-Fish model, fish populations were heterogeneously distributed across several zones. Zones reflected the habitat structure identified by Girardin *et al.* (2018) for the Atlantis model adjusted to the 0.25 × 0.25 degree grid in ISIS-Fish (Supplementary Figure S1). Species distributions in each zone differ across age classes and may change over the course of the year to reflect seasonal migrations from and to spawning areas. Regarding métier zones, logbooks helped identify the main ICES rectangles of activity for each gear and fleet (Supplementary Figure S1). One métier per main rectangle is consequently created (e.g. OTB-27E9), while ICES rectangles with low effort for a given gear and fleet were pooled together in a unique métier (e.g. OTB-left). This resulted in 49 métiers. Effort was assumed homogeneously distributed over a métier zone but was heterogeneously distributed across zones.

A calibration was applied to estimate accessibility coefficients for each age group of each population. The calibration method is an evolutionary algorithm that aimed at minimizing discrepancies between observed and simulated annual catches at age of each population over the period 2008–2011 (Oliveros-Ramos and Shin, 2016). Validation used catch and abundance time series over the period 2012–2014, which were the latest data available at the start of the project.

Modelling fishers' behaviour

A fishing behaviour model was implemented in ISIS-Fish to simulate fishers' monthly responses to changes in ecological, economic and regulatory conditions. It assumes that the total monthly effort of a fleet (number of vessels and hours at sea) is constant (average 2008–2014). On the other hand, a gravity model dynamically predicts the allocation of this monthly effort across métiers [modified from Lehuta *et al.* (2015) and Marchal *et al.* (2013)]. According to inputs from fishers, the adaptive capacities of EEC fleets were limited due to boat characteristics (smaller boats are not able to expand their fishing area) and strategies (loss of skill to practise various métiers) and to regulatory constraints (quota availability and licenses limit their possibility to report their effort on other species) (Reid, 2016). Consequently, it was assumed that no new métiers or zones could be explored and that effort is only redistributed among the métiers practiced during the parameterization period. The gravity model allowed balancing habits (repetition of past behaviour) vs. opportunist behaviour (adaptation to new context) using a weighting factor α (2). For a given fleet, the proportion ($P_{métier\ i,\ t}$) of total effort of month t spent on a given *métier i* is determined to proportionally account for to fishers' habits (α) and with the rest $(1-\alpha)$ related to the current $(t-1)$ attractiveness of *métier i*. Fishers' habits are approximated by the percentage of effort on métier i the year before $(t - 12)$ (3). Attractiveness is approximated by a function proportional to the landed value minus fuel costs per unit of effort (PUE) and inversely proportional to landed quantity in the previous month (4). This last term was introduced to account for the fact that for the same profit PUE, fishers were expected to favour métiers with lower unwanted catches (i.e. unmarketable due to being under the legal size, over quota, non-commercial species, or low value), lower onboard sorting/handling effort, and higher value per kilo. It also compensated for the lack of explicit account of the ship's hold capacity in the model.

$$P_{métier\ i,t} = (1-\alpha) * \mathrm{Habits}_{métier\ i,t} + \alpha * \frac{\mathrm{Attractiveness}_{\ métier\ i,t}}{\sum_{i} \mathrm{Attractiveness}_{\ métier\ i,t}}, \quad (2)$$

$$\mathrm{Habits}_{métier\ i,t} = \frac{\mathrm{Effort}_{métier\ i,\ t-12}}{\sum_{i} \mathrm{Effort}_{métier\ i,t-12}}, \quad (3)$$

$$\mathrm{Attractiveness}_{\ métier\ i,t} = \left(\frac{\text{Landed value PUE} -- \text{Fuel costs PUE}}{\text{Landed quantity PUE}}\right)_{métier\ i,t-1}. \quad (4)$$

If $\alpha = 0$, fishers' behaviour is completely dictated by their habits and is reproduced identically from one year to the other. Inversely, if $\alpha = 1$, fishers are completely driven by the current conditions and allocate their effort on métiers proportionally to their attractiveness. In the following, α is referred to as "level of opportunism", while $(1 - \alpha)$ is referred to as "level of tradition". According to equivalent estimates of α by Marchal *et al.* (2013) and considering the fact that fishermen in the studied area do not show extreme changes in their behaviour, the impact of this opportunism level was explored by testing three alternative values for α : 0.1 (very traditional), considered the reference, 0.3 (intermediate), and 0.5 (very opportunist).

Modelling TACs, MCRS, discards, and the LO

ISIS-Fish comprised a module for management procedures. TACs were dynamically computed to manage at F_{MSY} for all stocks under quota regulation (sole, plaice, cod, and whiting) from 2020 on, after a transition phase (2016–2020) (Supplementary Table S3.1). The transition phase consists of decreasing the target F regularly from the starting year to F_{MSY}. Interannual variations in the TAC were limited to 15% (STECF, 2015). ISIS-Fish was not coupled with the stock assessment models of the species; thus, population numbers were assumed perfectly known on 31st December of the previous year. Recruitment for the advice year was assumed equal to the last 3 years average, and we assumed no error on reported catch. Catch limits and biological closures for scallops were carefully modelled (Supplementary Material S3). France did not adopt individual quotas and we assumed a common quota pool.

Distinctions between scenarios implementing LO and Discard as Usual (DAU) scenarios concerned three aspects: quota computation, discards management, and TAC consumption. Regarding quotas, for all species concerned the procedure followed the one used by ICES during the transition period when landing advice was provided. When discards were available and included in the assessment, ICES computed catch advice and provided corresponding landing advice by removing the assumed rate of discards (Supplementary Table S3.1). When discards are not included in the assessment, landing advice is produced and catch advice is derived by adding the discard rate from available information. In simulations, catch quotas or landings quotas were similarly computed and used whether LO was enforced or not, which corresponded to assumed "quota uplifts" equal to the ICES estimates of discard rates [Council Regulation (EU) 2018/120].

TACs are set equal to the corresponding landings or catch advice, and the simulation procedure assumes that the TACs are fully implemented.

Regarding discarding behaviour, in ISIS-Fish, the separation of the catch between landings and discards was computed at the end of each time step according to decision rules. In the DAU scenario, discards occurred monthly according to the quarterly rates estimated for each species, age, and métier [Cornou *et al.*, 2021, (2008–2015 for sole, 2008–2014 for plaice, and 2012 for whiting and cod)]. Therefore these discard rates reflected MCRS and possible other causes of discards (e.g. highgrading) before the implementation of the LO. According to the information available at the time of the study, it was assumed that none of the discarded species survived except for scallops. In the LO scenario, the total catch was landed and discards were set to zero.

Quota consumption was updated monthly based on landed quantities. In DAU scenarios, when a quota was exhausted, métiers catching the species could still be practiced but the species was integrally discarded. In LO scenarios, if fish under the minimum conservation size were caught, they were landed and counted against the TAC but their price was set to zero to reflect the absence of commercialization opportunities. When a quota was exhausted, all métiers catching the species were forbidden (attractiveness set to zero). If all métiers of a fleet were forbidden, the fleet stayed at port; otherwise, effort of the forbidden métiers was redistributed over the remaining métiers according to the gravity model.

Scenarios

The scenarios are described in Table 1.

Exemption scenarios

De minimis exemptions were under negotiation at the time of the project; therefore, we designed two caricatural scenarios of exemptions. The first concerned métiers in which catch is composed of <5% of the species of interest (scenario "LO-exemption1"). The second targeted métiers in which catch represents <5% of the total catch of the species ("LO-exemption2"). Therefore, the first one used criteria at the métier scale, while the second used criteria at the stock scale. If the métier was exempted, it was allowed to continue fishing and discarding when the species TAC was exhausted.

Avoidance areas

Despite the scepticism of fishers regarding their capacity to avoid catching potential choke species, avoidance strategies were discussed during the stakeholder meetings. The main strategy proposed to avoid unwanted catches was the avoidance of areas and seasons with high probability of catching the species at risk. Promising areas were identified by mapping the risk of exceeding a certain percentage of the species in the catch based on geolocalized historical landings. The interactive maps were developed and made available to the fishers as part of the DiscardLess project (http://sirs.agrocampus-ouest.fr/discardless_wp4/index.php?action=fiche&code=2&type_code=IN&atl_version=0&idlang=UK, Reid and Fauconnet, 2018).

The maps were explored in search for a balance between limited coverage and seasons but high risk of encountering a high share of the species in the catch. The first scenario "Avoid-SolQ2" proposed to close areas hosting sole coastal nurseries in the Bay of Seine and off the Bay of Somme during the second quarter for trawlers (Figure 1). In these areas and periods, >80% of the trips consist of >10% sole. The two other scenarios "Avoid-WhgQ1" and "Avoid-WhgQ23" proposed closing an area located in the Strait of Pas de Calais (Figure 1) where whiting constitutes >30% of the catch in >50% of the trips in the first quarter and from April to September, respectively.

Simulation settings

Simulations were run for 15 years. They start in 2010 with a spin-up period of 5 years and are constrained with annual observed effort, quotas, discard rates, recruitment, and

Table 1. Scenarios simulated with the ISIS-Fish model of the EEC mixed fishery.

Scenario number	Scenario name	Scenario short name	Scenarios description	Adaptation scenarios
0	Discard as usual	DAU	Management at F_{MSY} using TACs and MLS, discards allowed	Each scenario replicated three times with level of opportunism in the behaviour model, respectively, set to 0.1, 0.3, and 0.5
1	Landing obligation without exemption	LO-noExemption	Management at F_{MSY} using TACs with uplift and LO	
2	Landing obligation with exemption 1	LO-Exemption1	LO + métiers exempted if the species is <5% of their catch	
3	Landing obligation with exemption 2	LO-Exemption2	LO + métiers exempted if their catch is <5% of total catch of the species	
4	Landing obligation with closure for sole	Avoid-SolQ2	LO-noExemption + spatial closure for sole from April to June	
5	Landing obligation with closure for whiting 1	Avoid-WhgQ1	LO-noExemption + spatial closure for whiting from January to March	
6	Landing obligation with closure for whiting 2	Avoid-WhgQ23	LO-noExemption + spatial closure for whiting from April to September	

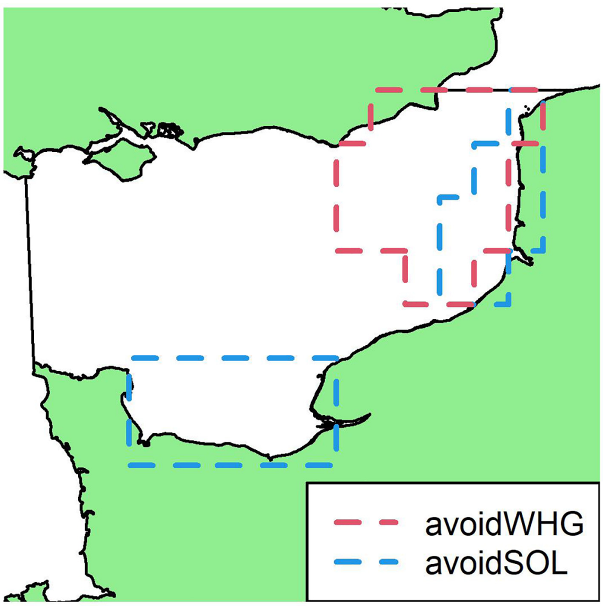

Figure 1. Management zones designed to avoid catch of whiting (red) and sole (blue). Zones were based on seasonal maps representing the risk of catching high proportions of the species to avoid in individual fishing sequences. The avoidance zone for whiting (respectively, sole) presented >50% (respectively, 80%) of fishing sequences with >30% of whiting (respectively, 10% of sole) in the landings.

migrations. In projections (from 2015 on), recruitment, migrations, discard rates, and total effort per fleet were constant (2008–2014 averages, corresponding to the calibration period, see Supplementary Material for details). The implementation of the management plans and LO (when appropriate) start in 2016. Each scenario is run for each of the three value of opportunism, leading to 21 simulations (Table 1).

Selected outputs

As requested by fishers, scenarios were evaluated both based on biological and economic outputs and at the fleet scale. Population biomasses, age structure, discards, as well as expected changes in revenues (landed values) for each fleet, and the date of fishery closure in the case of choke and quota utilization were assessed relative to the base case scenario: Discard as Usual (DAU). Results at short-term (first 3 years) and long-term (10 years after spin-up) time scales were explored, as fishers stressed the crucial importance of the transition phase.

Results

Impact of the LO at the fishery scale

A strict implementation of the LO (LO-noExemption) had either positive or no effect on population biomasses compared to DAU (Figure 2). The most spectacular effect is on sole biomass, which ends up 15% higher in the LO scenario. To a lesser extent, cod, red mullet, and cuttlefish populations also benefited from early closure of the fishery although the latter species are unregulated. Conversely plaice biomass did not benefit much (+2%) from the LO. Initial conditions and assumptions on recruitment strongly influenced the results: In the DAU simulation, the model predicted a decrease in biomass for plaice, red mullet, and veined squid but an increase for sole, cod, whiting, and scallops at least from year two onward. Results are therefore to be considered relative to the DAU situation. In addition, the increase in cuttlefish biomass is to be considered with caution given the short life of the species and the strong influence of recruitment and fishing mortality on its population dynamics. The average dynamics modelled should therefore not be considered quantitatively but rather as an indication that LO would release the pressure on cuttlefish

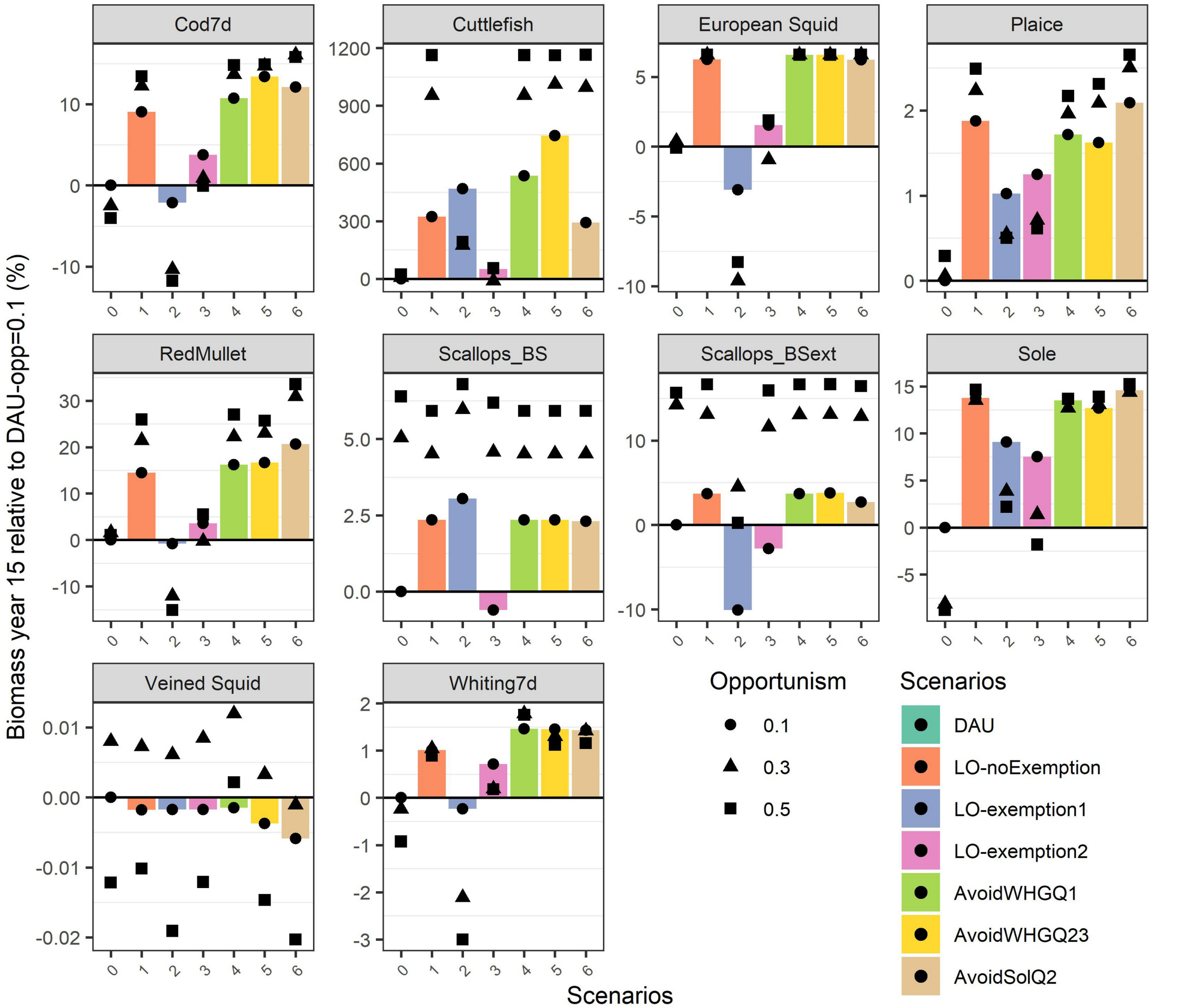

Figure 2. Biomass (%) of the ten stocks in year 15 under the seven scenarios (*x*-axis) and three assumptions of opportunism level in fleet behaviour (point shape) relative to the reference scenario "DAU" and very traditional fleet behaviour (low opportunism) (DAU; opp = 0.1). All stocks benefited from the strict implementation of the LO (LO-noExemption). When implementing exemptions 1 and 2, all stock biomass dropped below levels simulated in the LO scenario, and for some stocks, it even dropped below levels simulated in the DAU scenario. Spatial closures caused minor changes compared to the LO levels, except for cuttlefish. Species were differently sensitive to opportunism level, but for the majority of the stocks, higher opportunism led to higher biomass.

Under a strict implementation of the LO (LO-noExemption), choke situations occurred in the fishery leading to fishery closures (Supplementary Figure S4.1). Choke occurred in November because of plaice in the first year of implementation. The choke is probably a result of the high discard rates for this species that now, under the LO, count against the quota. From year four on, sole was the choke species. This choke situation was expected in view of the DAU simulation, where sole TAC was exhausted in September for most years. Closures first occurred in September but were progressively delayed to November by the end of the simulation. This improvement compared to the DAU scenario resulted from a progressive increase in TAC, due to increasing sole biomass, an effect of the protection offered by the LO. Choke resulted in quota underutilization for cod, plaice, sole (the first year), and whiting between 60 and 80%, 0 and 64%, 0 and 40%, and 10 to 50%, respectively, depending on years and opportunism levels (Figure 3). Chokes happened earlier when opportunism was high, as early as July for sole and August for plaice.

Under a strict implementation of the LO, annual gross revenues of the fishery dropped in the short term (up to −17% compared to DAU the fifth year), but they then slowly and non-monotonically improved and started to exceed DAU annual revenues the tenth (final) simulation year (Figure 4). This increase relied on increasing revenues for sole and whiting starting in year four after implementation and on generally increased prices (−6 to +77% depending on species). The cumulative loss over the 10-year period appeared overall limited (−5%). When opportunism was high, the annual loss rose to 34% the first year but summed to only −7% over the period.

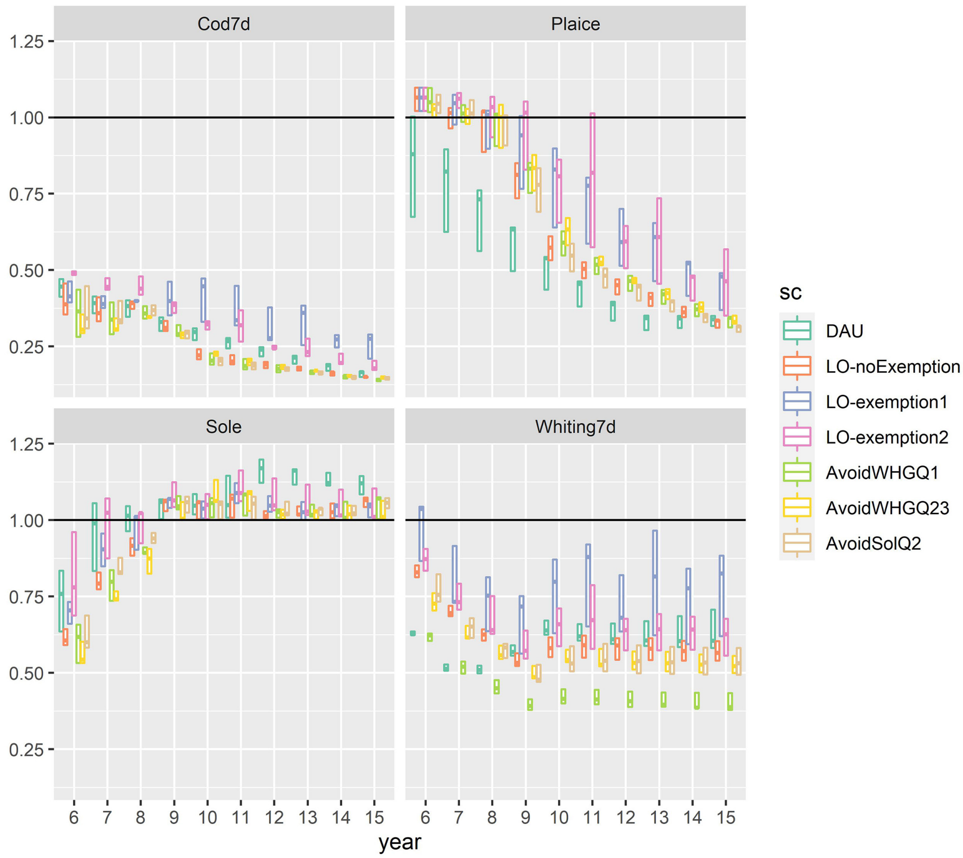

Figure 3. TAC utilization for French fleets across years and species. The figure displays the proportion of the TAC utilized by the fleets each year. The boxes represent the dispersal of values obtained with three hypotheses about fleet behaviour (the box spreads from the minimum to the maximum value and the bar is the median).

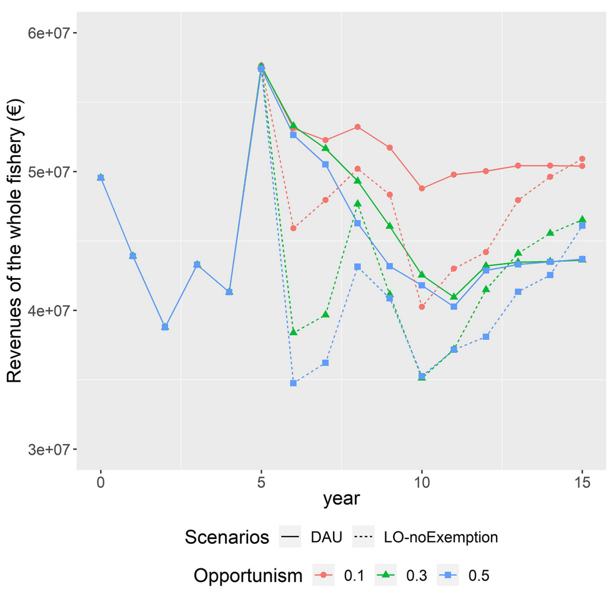

Figure 4. Evolution of the annual revenues generated by the fishery in the Discard as Usual scenario (DAU) and when the Landing Obligation (LO-noExemption) is implemented in the sixth year (year = 5). Revenues of the fishery were lower with the LO. From the year of implementation on, revenues dropped more and faster under the LO scenario but were higher after 10 years. The level of opportunism in fleet behaviour (colours) influenced the amplitude of loss but not the evolution pattern. Higher level of opportunism in fleet behaviour generally led to lower revenues, with exceptions some years under the LO scenario.

Impact of the LO at the fleet scale

At fleet levels, contrasting impacts of LO on revenues were detected, mainly displaying an opposition between trawlers and netters (Figure 5, left). In the LO scenario compared to the DAU scenario, four fleets displayed important losses in gross revenues over the simulation period (between 10 and 16%), and seven fleets displayed limited loss (<7%). For the remaining six fleets, cumulative revenues over the simulation were higher (from +2 to +11%) with the LO. The pattern was primarily explained by the nature of the fleet: netters were globally simulated as "winners", with revenues rapidly higher in the LO scenario than in the DAU; and trawlers as "losers", their annual revenues always being lower in the LO simulation. This is due to the large dependence of netters on sole, and the improved situation of the stock under LO, while for trawlers, the gain on sole did not compensate for the loss on all the other target species. It also pertains to the seasonality of their respective activity: netters concentrated around two-thirds of their revenues in the first semester, while revenues were more evenly spread in the year for trawlers. Second, netters from Normandie experienced higher benefits from the LO than netters from the North. On the contrary, trawler fleets from the North suffered lower losses than trawlers from Normandie. Vessel size did not explain differences in impacts between fleets. The situation of dredgers was contrasted (1 "winners", 5 "losers"), with no obvious explanation for the differences.

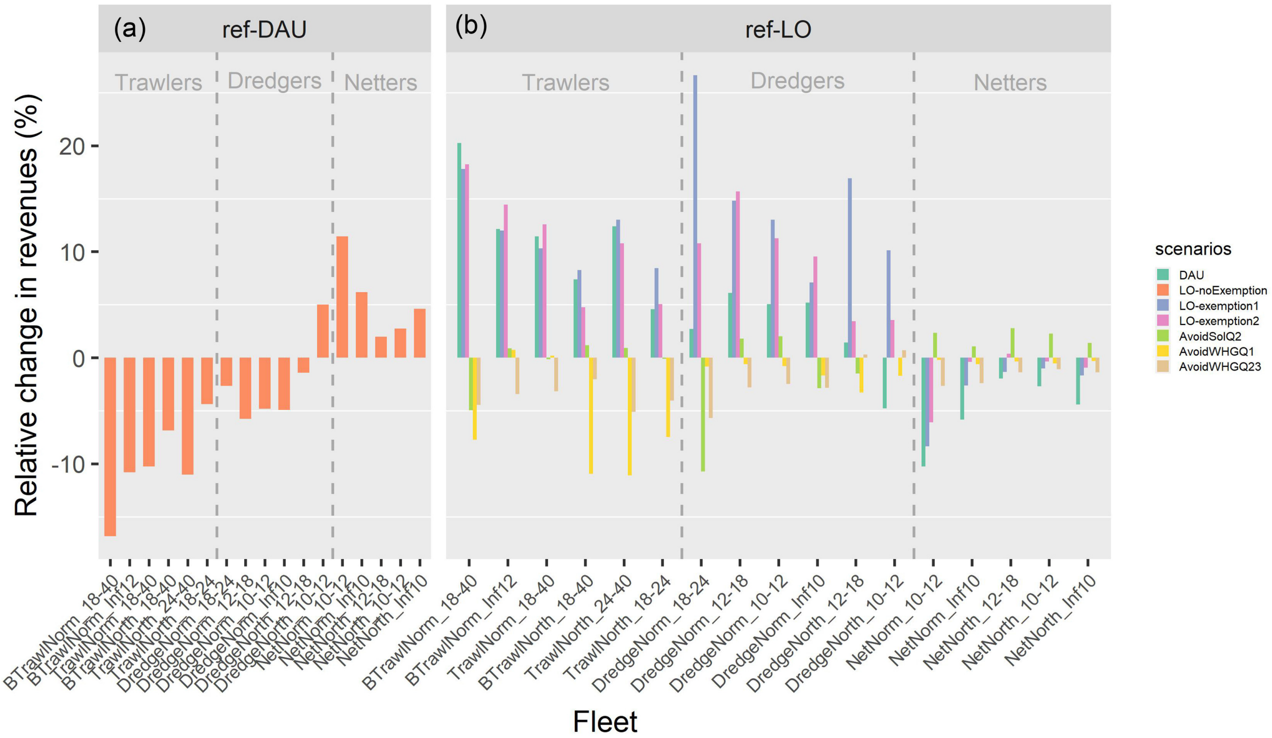

Figure 5. Change in revenues cumulated over the simulation period for the different fleets (*x*-axis) highlighting the opposition between the impact scenarios had on trawlers and netters. Cumulated revenues are lower (respectively, higher) for trawlers (respectively, netters) under the landing obligation scenario (LO-noExemption) compared to the Discard as Usual scenario (DAU) (left panel). Mitigation measures had contrasted impacts on trawlers and netters revenues when compared to revenues in the strict implementation scenario (LO-noExemption) (right panel). Exemptions were efficient to mitigate LO impact for trawlers but were detrimental to netters (right panel). The opposition between trawlers and netters was not systematic when avoidance areas were implemented.

Effect of fleet behaviour

The impact of the fleet behaviour assumptions on biomass (Figure 2) and catch was low compared to the impact of the LO, except for cephalopods and scallops. The general effect of increased opportunism was reversed between LO and DAU: Under the DAU scenario, higher opportunism meant lower biomass and higher catch, while under the LO scenario, higher opportunism meant higher biomass, and lower catch. For some species (sole, plaice, squids, and scallops) however, this pattern evolves in time.

The more opportunistic the fleets, the higher the LO impact. For 12 over 17 fleets, the relative impact of LO on revenues (either positive or negative) increases non-linearly with the level of opportunism (Figure 5). Therefore, netters benefitted from being opportunistic, while trawlers lost more when trying to adapt. Indeed, the increased efficiency of trawlers led to quicker quota exhaustion and higher losses. The nonlinearity of the impact mostly consisted of a decrease in the slope between opportunism of 0.3 and 0.5, which illustrated limitations in adaptation opportunities. For the five remaining fleets, two netter fleets and three dredger fleets, the effect of opportunism level is non-monotonic, demonstrating a necessary trade-off between tradition and opportunism.

The bigger the boats, the larger the relative changes in revenue when the assumed level of opportunism is increased. Whatever the direction of change induced by increased opportunism, the amplitude of change in revenues, for a given scenario, was lower for smaller boats than for bigger boats and for netters than for trawlers. The size pattern was found at the global fleet scale but also within fleet segments using the same gear type, which demonstrates that it did not result only from the fact that netters are generally smaller than trawlers and dredgers. We interpret this as a demonstration of the larger opportunities for adaptation offered to bigger boats and trawlers, likely resulting from a higher diversity in target species, fishing grounds, and therefore métiers. On the contrary, the amplitude of the opportunism effect was independent of vessel home region. Finally amplitudes were systematically lower in LO simulations than in DAU, which illustrated the loss of adaptation opportunities due to LO.

Impact of exemptions

The two exemption scenarios produced higher global revenues than the strict LO scenarios (from +4 to +25%) and were thus efficient at mitigating the risks for trawlers and dredgers (Figure 5, right). For dredgers, revenues over the period were higher with the exemptions than in the DAU simulation (up to +25%). For trawlers, revenues with exemptions were approximately the same as in the DAU simulation. For netters, revenues were lower than in the LO by <10%. Whether exemption 1 or 2 was more beneficial depended on the fleet considered. For netters, differences were generally small between the two exemption scenarios (2%). For trawlers, the exemptions had distinct regional effects, with fleets in the North making more revenues with exemption 1 than exemption 2, and the reverse in Normandie. Finally for dredgers, four out of the six fleets did better under exemption 1, but no pattern in size or region explained it.

The mitigation of LO effects by the exemptions caused a reduction in population biomasses compared to LO, in particular for cod, red mullet, and European squid, for which biomass fell below DAU levels (Figure 2). Discards were reduced by a minimum of 60% compared to the DAU simulations, but they were significantly higher in the exemption 2 scenario. Depending on management objectives defined for stocks, exemption 2 may represent a compromise. It led to biomass levels close to the ones observed in DAU, 60% reduction in sole discards while minimizing impacts of LO on fleet revenues.

Impact of avoidance measures

The closure designed to avoid whiting in the first quarter (AvoidWHGQ1) reduced catch of whiting by 23% the first year (14% over the period) compared to the LO simulation (Figure 6a) and led to cumulative losses of revenue on the other species of <3% (mainly squids −11%). The closure in quarters 2 and 3 is less efficient and decreases whiting catches by 13% only in the first year (−6% over the period), with losses in revenue for other species of 11% spread over their main targets. In both cases, the reduction in whiting catch was robust to the assumptions on fishers' behaviour, but for some fleets the revenues of other species changed up to 60% between traditional and opportunistic behaviours. The closure in the first quarter did not affect netters' revenues. Closure in the second and third quarters led to a decrease in netters' revenues of 9%, mainly due to losses in plaice and whiting revenues.

The closure designed for sole (AvoidSolQ2) is inefficient at reducing sole catches that instead increased, but it helped decrease the catch of juvenile sole (Figure 6b). Catches of sole of age 2 were reduced by 5% and catches of older soles increased by 2%, leading to slightly higher sole revenues for both trawlers and netters under this scenario (+7%) over the simulation period (Figure 5b). This result is robust to assumptions on fishers' behaviour. The impact on sole biomass was negligible, which made it an interesting measure to improve selectivity, but it had little effect on choke date (delayed by one month in one year over ten).

Following the presentation of preliminary runs, fishers' representatives pointed out the complexity of the results and associated graphs. They asked for more interactive manners of presenting results that would allow a progressive increase in graph complexity. Results were therefore made available through a shiny interface, where the type of outputs, years of interest, scale (cumulative or disaggregated), fleets, populations, and reference scenario are user-selected; thus, the graphs may be built and modified by the fishers' representatives themselves (http://sirs.agrocampus-ouest.fr/discardless_app/app10/).

Discussion

This work was one of numerous studies aiming at evaluating the bio-economic impact of the LO. Nonetheless, to our knowledge, none of them evidenced the contrasts in impact the LO may have on different fleet segments operating in the same region; they instead often focused on one unique fleet (Bourdaud, 2018; Pointin *et al.*, 2019). The work also increased realism and precision in the evaluation of effects by using a monthly time step to assess the timing of when choke situations would occur, while most studies use an annual scale (but see Calderwood and Reid (2019) for assessment of day of choke in the context of monthly quotas). It also assessed the efficiency of spatial closures to avoid unwanted catches, using a spatially explicit model that includes fishers' reactions, instead of being based on statistical analysis of past activity (Simons *et al.*, 2015; Garcia *et al.*, 2017; Alzorriz *et al.*, 2018; Bourdaud, 2018; Pointin *et al.*, 2019). Finally, the results illustrated how unequal the possibilities of adaptation are across fleet segments, depending on the diversity of their target species, fishing grounds, and vessel size.

Similar to other studies, our results predicted short-term negative effects of the LO on fleet performance, eventually compensated by improved stock status in longer term (Prellezo *et al.*, 2016; Garcia *et al.*, 2017). With regard to choke risks, Pointin *et al.* (2019) anticipated horse mackerel to present a choke situation first, while Batsleer *et al.* (2013) predicted a choke problem on cod for the same fishery. Our results suggested that the quota for cod would not be limiting under the current stock status whether LO was implemented or not. This situation can partially be explained by the poor status of this stock in the EEC and southern part of the North Sea (ICES, 2021b) over the last ten years. French fleet have quota but can hardly fish it because of the low biomass in this area. Horse mackerel was not considered in the current study because it is relatively specific to the trawler fleet from Boulogne-sur-Mer (which was the focus of Pointin's study) and more negligible at the regional scale. In addition, the fleets modelled in the present study catch horse mackerel seasonally, as a bycatch, in small volumes, and totally discard it (Cornou *et al.*, 2021) because they do not own quota for it. If the LO was strictly applied, they would need to totally stop fishing during the season when horse mackerel is present in the EEC. This is a typical situation where spatial/temporal avoidance might not be the solution and in practice de minimis exemptions are enforced for horse mackerel in the area until May 2022 [Regulation (EU) 2020/2015, 2022]. Given the very small catches involved compared to the total horse mackerel quota, we believe that TAC redistribution could be a more appropriate solution, ensuring appropriate data collection and avoiding changes in fishing behaviour.

Conversely, we predicted that the LO might help the sole stock to rebuild to the point where it becomes a choke species, because catch opportunities would not grow as fast as biomass (under the considered reference points). This adverse consequence of stock recovery with the LO was also anticipated for hake in the North Sea (Baudron and Fernandes, 2015). In our case, this possibility appeared relatively unrealistic to fishers, limiting their acceptance of the results. Indeed, they currently experience catchability problems with the sole stock, and their quota was not reached in the past years. Similar to our model, the assessment model was optimistic about the stock status, which raised questions regarding current understanding of the pressures applied on the stock and its spatial structure (Archambault *et al.*, 2018).

Sole being a choke species under LO is also unexpected because discard rates are low compared with discard rates of plaice and whiting, which were anticipated to be the choke species in similar fisheries (Fitzpatrick *et al.*, 2019; Pointin *et al.*, 2019). In simulations, plaice was limiting in the first year, but it had low consequences because the choke occurred late in the year. This result demonstrated the efficiency of "uplifts"

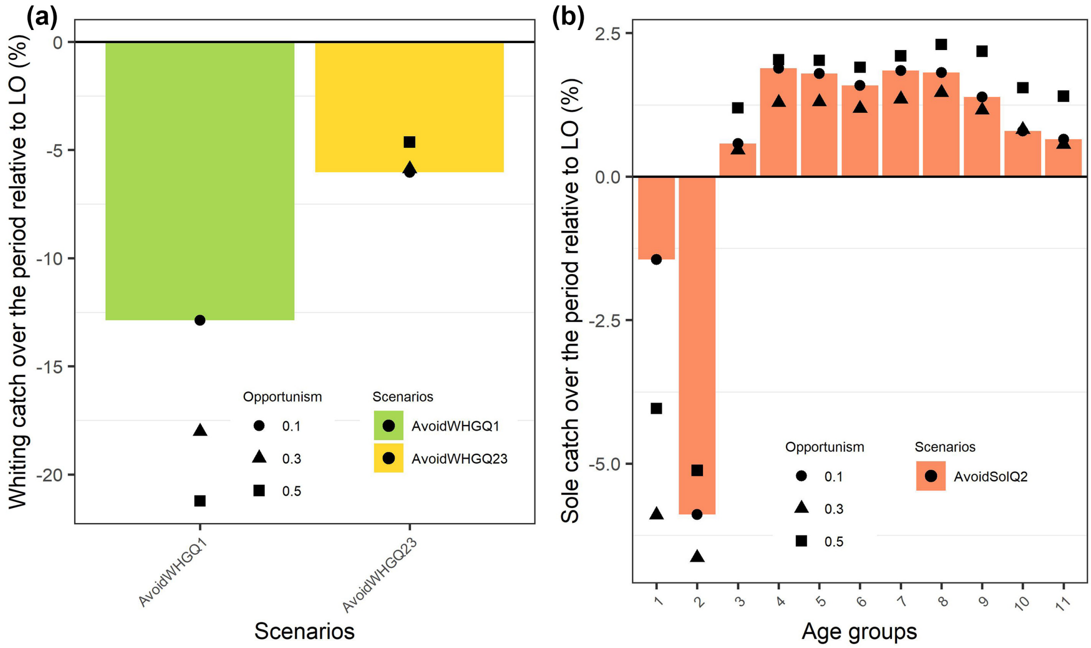

Figure 6. Impact of the avoidance areas on the catch of the target species. (a) Decrease in whiting catch under the two scenarios of avoidance compared to the LO scenario (LO). (b) Decrease in catch of younger sole under the avoidance scenario compared to the LO scenario. Results are sensitive to the assumptions on the level of opportunism in fleet behaviour.

in mitigating the impact of LO, particularly in an ideal case like ours, where simulated discard rates are in line with ICES estimates (derived from the same data).

As modelled, the exemptions were good short-term mitigation measures to limit the fleets' economic losses at the cost of higher discards and lower stock biomasses compared to the LO scenario. Trade-offs therefore need to be considered in the selection of exemption schemes: first between fleets, with differences across regions, and second between two of the objectives of the LO: improved stock status and reduced discards. Indeed, while exemption 1 limited discards more than exemption 2, it led to stock biomasses possibly lower than the status quo (DAU). In practice, the European Commission delivered *de minimis* exemptions for fleets if they proved either that it was difficult to achieve greater selectivity or that the landings of undesirable species would cause disproportionately high costs. Most of these de minimis exemptions stopped in 2020 and the allowed discard rates in the remaining exemptions (whiting and sole) are low (respectively, 5 and 3% of the annual catch of the species). In 2021, the main exemption still in place and delivered is for high survival rate for plaice [Regulation (EU) 2020/2015, 2022] and for sole below MCRS in limited conditions (boats under 10 m in coastal areas outside nurseries).

Spatio-seasonal closures have been proposed in several studies to help avoid unwanted catches, but we showed that they may have unexpected effects when fleet and stock responses are accounted for. In most studies, the expected impact of closures was derived from past performances assuming constant fishers' behaviour and stock catchability (Batsleer *et al.*, 2013; Pointin *et al.*, 2019). The closures tested here were selected according to similar analyses that estimated a decrease in catch. However, when evaluated in the simulation, the case of sole demonstrated instead an unforeseen, yet interesting, shift in selectivity to the oldest ages. This advocated in favour of accounting for dynamic, spatially explicit and behavioural features when pretesting the impact of closures.

Impacts of the LO were very different depending on the fleet considered. In this regard, the Eastern English Channel concentrates the sources of inequities encountered independently in other regions. For instance, de Vos *et al.* (2016) pointed out the contrast between trawlers and netters. Mortensen *et al.* (2018) evidenced the unequal opportunities of adaptation between small and large boats pertaining to home range and storage capacities. Prellezo *et al.* (2016) and Garcia *et al.* (2017) also highlighted how "uplifts" when homogeneously redistributed for fleets, acted as a reward to the most selective fleets in the Basque case study. While we did not test the effect of "uplifts" explicitly in our simulations, the known discrepancies between trawlers' and netters' discard rates and the evident benefit of LO to netters suggested the same phenomenon may occur.

In this context, fishers' reaction was important to take into account. Similar to previous modeling studies (Simons *et al.*, 2015; Garcia *et al.*, 2017; Alzorriz *et al.*, 2018; Bourdaud, 2018; Pointin *et al.*, 2019), we relied on a theoretical model instead of an empirical model (Holland and Sutinen, 2000). However, unlike these previous models, we allowed tradition and habits to come into play in fishers' decisions, on top of profit maximization. It was considered necessary because tradition acts as a proxy for the marked seasonality of species in the area and of other factors influencing choices but rarely modelled (i.e. share of space between activities in the channel, market demand, and Producer Organization rules). According to the elasticity analysis, the balance between tradition and opportunism influenced the amplitude of impact of the LO but did not change the general evaluation of losers and winners.

Counterintuitively, we found that decisions driven by short-term profit were less beneficial to fishers when LO is enforced. The explanation lies in that profit-driven behaviour implies a higher short-term fishing pressure and consequently lower stocks and revenues in the long term. The results may depend on the chosen formulation for the behaviour model that reflected our understanding of fisher motivations (more benefit per hour for less volume). The gravity model could have been fitted to data as done by Marchal *et al.* (2013) to confirm the relevance of variables used and assess the actual relative weight of tradition and opportunism at the fleet scale. Instead, we adopted an elasticity analysis approach, which had the advantage of highlighting the sensitivity of the results to the assumption as evidenced by Garcia *et al.* (2017). It also provided an indication for fishers on how to more efficiently adapt, and in our case a warning on the short-term expectations of economic optimization.

As illustrated, the fine spatio-temporal scale adopted to model the dynamics of the fishery, and the diversity of fleet segments modelled, allowed the date of fishery closure to be assessed, spatial measures to be explicitly modelled and fishers' behaviour to be adapted over the course of the year to the conditions of the stocks. Nonetheless, this spatio-temporal scale and fleet segment scale did not allow exploring the totality of the complex questions raised by the LO, which constitute challenges for future impact assessments.

First, although, ISIS-Fish is one of the few fisheries models operating at a monthly time scale instead of yearly, it does not fully reflect the range of temporal scales at which fishers may adapt. On the one hand, fishers probably rely on more short term and even real-time information when making decisions about métier and fishing grounds. Previous works showed how fishers were able to change fishing grounds in the course of a trip (Eliasen and Bichel, 2016; Reid, 2016; Mortensen *et al.*, 2018), and Frangoudes (2019) reported on real-time communication between fishers about areas to avoid. On the other hand, we ignored possible annual planning of the yearly activity in order to optimize quota utilization such as assumed in other models (Batsleer *et al.*, 2013; Bourdaud, 2018). When asked about the temporal scale at which decision were made, EEC fishers admitted that it was a mix of long-term planning and short-term adaptation.

Second, data limitations constrained our ability to model the catch process at the appropriate scale, that is, the scale of the fishing operation. As pointed out by Garcia *et al.* (2017), the scale of the fishing operation would be the appropriate level for defining métiers in a mixed fishery, instead of the fishing sequence (combination of day × gear × statistical rectangle) because sequences may combine hauls for different métiers, therefore hiding a higher selectivity at the fishing operation scale. The large mix of species reported in logbooks at the scale of the fishing sequence forced us to limit métier definition to the gear and area choice without any further target species consideration. This assumption possibly resulted in a pessimistic view of fishers' ability to avoid species and report their effort in the case of a choke situation. On the contrary, the mix of species reported in logbooks is generally assumed underestimated due to the absence of declaration of discards in logbooks, which is hardly compensated for by the limited coverage of onboard observations (1% of fishing trips).

Third, fishers showed interest in the quantification of the extra time dedicated to sorting fish under LO, which could possibly reduce the time spent fishing. Again data availability and the monthly time scale of the model prevented us from providing such estimations. Incorporating this consideration would require models operating at fishing operation levels such as DISPLACE (Bastardie *et al.*, 2013). Even there, the determinism of sorting is probably multifactorial and hard to model.

Danish seine also developed in the EEC French fleets in the last 5 years and appeared as a possible alternative, as it targets unregulated species such as red mullet and cephalopods. Several Danish seiners or boats able to fish with demersal seine and demersal trawl gear entered the fishery in the last couple of years. This could not be included in the model because it occurred after the parametrization period of the model and the absence of previous records of the activity prevented the estimation of the métier parameters.

Fourth, the spatial extent of the model domain, restricted to Division 27.7d, misrepresented the flexibility and constraints for the largest vessels, which are able to operate outside 27.7d. These vessels also fish on the same cod and whiting stocks but with different quotas in Division 27.4c, which simultaneously represents extra flexibility, in case of a choke situation in the EEC and an extra threat of choke in 27.4c.

Finally, the French quota is divided among POs and independent fishers. The latter are a minority and boats mainly divide between two POs. While it could imply that fishers from one PO choke prior to the others, in practice, trades are allowed and occur frequently between POs, which minimizes this risk. Our assumption of a common pool of quota is therefore acceptable. The collective French system thus offers extra flexibility compared to ITQ system. In other countries such as Denmark, quota pools were created following the LO implementation to allow for exchanges between vessels and provide this flexibility (Mortensen *et al.*, 2018). However the French system is not a sufficient incentive for individual fishers to work on selectivity (Kraak and Hart, 2019).

Retrospectively, between exemptions and problems on sole's catchability, the risk of choke in the EEC fishery primarily applied to species not accounted for in our study such as rays, sea bass, horse mackerel, and mackerel. These data-poor or widely distributed species are rarely modelled (Garcia *et al.*, 2017; Pointin *et al.*, 2019) and quotas were not yet enforced on sea bass at the time the model was set up. While catch of the modelled fleets represents a small share of harvest of these pelagic stocks, the historic catch of French fleets on them, and consequently quotas, is also low (possibly due to high discard rates) and mostly allocated to pelagic fleets. Moreover stock fluctuations in pelagic stocks are important and poorly predicted, increasing the risk of mismatch between catch and catch opportunities. These *a posteriori* learnings lead us to recommend that in the context of the LO, the selection of species to include in the models not only relies on usual criteria such as fleet dependency and commercial interest, but also on catch opportunities, particularly if they are low and associated discard rates are high.

In the end, it should be mentioned that stakeholders' uptake of these results, and more generally their interest towards behavioural or technical solutions to reduce unwanted catches, was low by the time the project ended. Although the demand for scientific support in mitigating LO impacts was high at the beginning of the project because of choke risk (Fitzpatrick and Nielsen, 2019), the development of opportunities for exemptions and the slow enforcement of controls (discards rates did not decrease in the last years, ICES, 2021c) led fishers to switch interest toward scientific evidence to support exemptions (relative to high survival rate of plaice for instance). Besides, fishers felt they already were able to avoid areas of unwanted catch based on their knowledge of species seasonality and assemblages and real-time exchange of information. In addition, we noticed that they were more keen on receiving spatial information in the form of maps, which they could use to self-adapt their areas of practice or justify exemptions, rather than in the form of evaluated closures seen as possible new regulatory constraints.

One strength of our results is that they evidence the complex trade-offs that need to be considered when evaluating the LO, beyond the usual contrast between biological vs. economic objectives. Here we showed that such a measure implies balancing effects among stocks (with squids, scallops and whiting biomass possibly impaired by LO), fish stages (avoidance measure for sole lowered juvenile catch but increased adult catch), fleet strategies (netters vs. trawlers), and even harbours (North vs. Normandy) and that outcomes could critically depend on the fleets' reactions.

The risk of choke situations and the difficulties in implementing and evaluating the LO should be examined in regard of the constraint of the relative stability. In fact, as shown by ICES (2021b), many of the national TACs are not fully used, and some of the choke situations result more from the inadequacy between catch opportunities and fleet capacity than from biological safeguards. We believe that redistribution of quotas among countries and fleets and multi-species considerations in quota settings are more likely to succeed in reducing discards than the implementation of the LO.

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Supplementary Data

Supplementary material is available at the ICESJMS online. The supplementary material documents model biological (Supplementary Material S1) and fleet (Supplementary Material S2) parameters as well as the specifications of the management measures (Supplementary Material S3).

Data availability statement

The parameters of the model used in this article are available in a database freely downloadable on ISIS-Fish website at http://isis-fish.org/downloads/DiscardLess_Channel_05102018.zip and reported in the article and in its online supplementary material.

The fisheries data underlying the parameterisation were provided by Ifremer SIH - Système d'Informations Halieutiques with permission of the French ministry.

The survey data underlying the parameterisation are available in ICES database DATRAS.

Conflict of interest statement

The authors, Sigrid Lehuta and Youen Vermard, certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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Author contributions

SL developed the model, ran the simulations, and wrote the article. YV contributed to the design of the model and scenarios and participated in the interpretation and rendering of results.

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