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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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Abstract :

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

27 **Introduction**

28 The 2013 Common Fisheries Policy introduced a Landing Obligation (LO) to eliminate
29 discards in European fisheries (Regulation (EU) N°1380/2013). Since 2015, fishers had to
30 gradually retain on board, register and land all catches of regulated species, which are then
31 deducted from quotas. These quotas are supposed to be lifted (i.e., top-ups) to help fishers during
32 the transitional period, but it is still unclear which top-up level is allowed (Council Regulation
33 (EU) 2018/120). Fish below Minimum Conservation Reference Sizes (MCRS) are unmarketable
34 and restricted for non-direct human consumption (Regulation (EU) N°1380/2013). All LO
35 regulations are expected to incentivise fishers to fish more selectively. The risks of not using more
36 selective fishing practices are to process and land increased low-value catch quantities (Catchpole

37 *et al.*, 2017). These additional quantities may result in a reduction in net profits (Condie *et al.*,
38 2013; Simons *et al.*, 2015), and catch limits may be reached more quickly for choke species.
39 These are species for which the quota is caught first in mixed-fisheries (Schrope, 2010). Once the
40 quota is exhausted, all fishing activities likely to catch the regulated species must stop within a
41 given fishing area (Baudron and Fernandes, 2015). In this context, fishers may encounter
42 additional regulatory, technical and economic constraints.

43 To comply with these constraints, fishers' interests are to reduce bycatch (i.e., unwanted
44 catch) through more selective fishing practices. The development of selective fishing gears is
45 extensively studied (Alzorritz *et al.*, 2016; Batsleer *et al.*, 2016; Mortensen *et al.*, 2017; Prellezo
46 *et al.*, 2017; Kopp *et al.*, 2018), but it requires time, important financial resources and is hardly
47 achieved in mixed-fisheries (Suuronen and Sardà, 2007; Catchpole *et al.*, 2008; Romero *et al.*,
48 2010). Another possibly complementary approach consists in allocating fishing effort to other
49 species, fishing grounds or seasons to avoid bycatch (e.g., Batsleer *et al.*, 2013; Branch and
50 Hilborn, 2008; Simons *et al.*, 2015). Using avoidance behaviours is of less concern, there are no
51 investment requirements and bycatch could be reduced within a short period of time.

52 Incentives for fishers to change their behaviours depend on expected economic performances
53 as well as their ability to avoid bycatch. In this study, direct impacts of the LO implementation
54 on economic results are first assessed. Depending on the expected economic incentives, avoidance
55 behaviours are then identified using a mapping method based on nested grids (Pointin *et al.*,
56 2018). The spatial and temporal distribution of landings and discards is thus explored with a
57 particular focus on choke species, for which a reduction in bycatch is most likely to increase net
58 profits. From the resulting maps, fishing areas and periods to be avoided (i.e., high bycatch) or to
59 be favoured (i.e., low bycatch) are eventually identified.

60 Moreover, because of the idiosyncratic nature of bycatch and mitigation strategies (Uhlmann
61 *et al.*, 2013; Catchpole *et al.*, 2014a; Sigurðardóttir *et al.*, 2015), these strategies are required to
62 be developed on a case-by-case basis at the scale of a group of vessels with similar behaviours
63 and fishing practices. Accordingly, a fishing fleet that is likely to be affected by the LO is taken
64 as an example, in order to evaluate the economic incentives for fishers to reduce bycatch and to

65 explore avoidance behaviours. As such, trawlers operating from Boulogne-sur-Mer were the
66 focus of this study.

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

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

84 **Material and Methods**

85 **Data**

86 All data used in this study were collected between 2011 and 2016 under the EU Data
87 Collection Framework (DCF) (2008/949/EC), and stored in the *Système d'Informations*
88 *Halieutiques* (SIH) database (Leblond *et al.*, 2008). In accordance with Ulrich *et al.* (2012), a
89 métier-based approach was used: a "métier" is defined as a group of fishing operations targeting
90 a given species or group of species, using a given gear, during a defined period of the year and

91 within a defined area (Mesnil and Shepherd, 1990). A métier is characterised by similar catch
92 rates, fishing types, net profits, incentives, etc. (Ulrich *et al.*, 2012).

93 Based on official data (logbooks, sales and fishing effort data) and activity calendars (Berthou
94 *et al.*, 2008), fisheries statistics were obtained from the SACROIS algorithm (Demanèche *et al.*,
95 2010). The algorithm provided the most likely estimates of total landings (in tonnes), revenue (in
96 euros) and fishing effort (in days-at-sea and fishing hours) by individual vessel, fishing sequence
97 (i.e., a combination of day, gear and ICES statistical rectangle), and species. The algorithm also
98 assigned to each fishing sequence a combination of gear and target species or species group (i.e.,
99 métier unit at DCF level 5). Fisheries statistics were used to identify métiers (e.g., gears, target
100 species, fishing zones, catch compositions) and to calculate the associated fishing effort, landings
101 and revenue.

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

113 Fishing cost information were derived from the BSPA¹ economic data, collected under the
114 French DCF program. Economic data were collected annually for a selection of vessels and
115 stratified by maritime registration district and vessel characteristics (size, gear) (Van Iseghem *et*
116 *al.*, 2011). When accounts were not available, which is mostly the case for small scale vessels, a

¹ Statistical Office in the French Ministry of Fisheries

117 questionnaire was used to collect economic data (Daurès *et al.*, 2008). Economic data made
118 available included crew and landing costs, other variable costs and fixed costs. Crew costs are
119 payments for the crew based on a sharing system, and also include social costs. Landing costs are
120 the sum of taxes paid by fishers to land catches, accounting for about one-tenth of sales revenue
121 for trawlers. Other variable costs include fuel costs plus costs for motor oil, ice and food supplies.
122 Lastly, fixed costs regroup costs for fishing equipment, gears, insurances, licences, repairs and
123 maintenance.

124 **Case study**

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

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

135 **Identifying métiers, catch profiles and economic performances**

136 Based on individual fisheries statistics available for each trawler, average annual landings
137 $L(i)$, in tonnes, and revenue $R(i)$, in euros, were computed for each métier i at the DCF level 5.
138 Average annual discards $D(i)$, in tonnes, were estimated from the observed discarded proportions
139 $\delta'(i)$, which were assumed close to the true values $\delta(i)$:

$$\delta(i) \sim \delta'(i) = d(i) / c(i) \quad (1)$$

$$D(i) = [\delta(i) \times L(i)] / [1 - \delta(i)] \quad (2)$$

140 where $d(i)$ and $c(i)$ are discard and catch estimated from the FOs observed on-board trawlers.
 141 Given that discards might be overestimated for species with a discarded proportion larger than
 142 0.9, an alternative method of calculation was used as in Pointin et al. (2018).

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

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

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

149 Fixed costs $C_f(i)$ were yearly distributed among metiers based on the time spent on each
 150 metier per year. For convenience, the number of days-at-sea was used as in Eq. (3). Landing costs
 151 $C_l(i)$ were assumed proportional to revenue (Daurès *et al.*, 2013):

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

152 where C_l is landing cost.

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

$$\theta_c = C_c / (R - C_o - C_l) \quad (5)$$

$$C_c(i) = [R(i) - C_o(i) - C_l(i)] \times \theta_c \quad (6)$$

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

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

$$\pi(i) = R(i) - C_o(i) - C_l(i) - C_c(i) - C_f(i) \quad (7)$$

157 **Evaluating economic impacts of the LO implementation**

158 Under the LO, the previously discarded species subject to quota should be landed and sold
 159 either for human (i.e., marketable bycatch) or non-human (i.e., unmarketable bycatch)
 160 consumption. Accordingly, catches to be landed, landing costs, crew costs, revenue and net profits
 161 were re-evaluated under the LO. Fixed costs were assumed unchanged, and other variable costs

162 (except for costs for ice and fishing boxes) were also assumed unchanged as far as fishing effort
 163 remained stable (i.e., no choke species). The economic incentives for fishers to reduce bycatch
 164 were finally assessed by comparing net profits with or without the use of more selective fishing
 165 practices.

166 ***Costs and revenue under the LO***

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

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

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

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

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

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

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

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

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

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

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

$$\Delta\pi(i) = \pi(i) - \pi^*(i) = \pi(i) - [R^*(i) - C_l^*(i) - C_c^*(i) - C_o(i) - C_f(i) + \beta] \quad (12)$$

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

182 ***Measurement of economic incentives***

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

189 ***Choke species***

190 Net profits are expected to fall under the LO because 1/ catch limits may be reached more
191 quickly for choke species and 2/ target species catches may be substituted by lower-value ones,
192 as a result of limited storage capacity. Since the storage capacity should rarely be limiting for
193 trawlers (Balazuc *et al.*, 2016), the choke species problem was only considered in the present
194 paper.

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

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

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

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

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

206 Since species quotas were different between years and fishing zones², the occurrence of choke
207 species and the economic incentives for fishers to reduce bycatch were evaluated separately in
208 each fishing zone according to each year. Moreover, the economic incentives were analysed under
209 two different quota top-up levels, for which changes were calculated from a baseline non-LO
210 scenario: 0% and 75% of the estimated stock discards. Species quotas were thus assumed to be
211 either not changed (worst-case scenario), or lifted by the highest possible level (best-case
212 scenario) (Course *et al.*, 2011; Condie *et al.*, 2014).

213 **Identifying specific avoidance behaviours**

214 Based on the main choke species identified from the previous section, the spatial and temporal
215 distribution of landings and discards were explored for the métiers most likely to be impacted by
216 the LO. In doing so, the nested grid method was used to map landings and discards over the period
217 2011-2016 using the R software (Pointin *et al.*, 2018). This method adjusts the size of each grid
218 cell as a function of the number of observations therein: small cell sizes are used in areas with
219 many observations, and vice versa.

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

230 The resulting maps relied on several indicators to evaluate the sample representativeness.
231 Trawlers were found satisfactorily covered by the Obsmer programme (Fig. S1A). Despite some

² EEC vs SNS

232 significant differences, sampling effort was found temporally consistent with fishing effort
233 between years (Fig. S1B) and between quarter (Fig. S1C). Sampling effort was also found
234 spatially consistent with fishing effort (Fig. S2A) and landings (Fig. S2B), as measured by the
235 global collocation index ($GIC > 0.95$) and local collocation index ($LIC = 0.92$) (Bez and
236 Rivoirard, 2000). To minimise potential discrepancies within years, data were pooled over 2011-
237 2016.

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

244 **Results**

245 **Métiers, catch profiles and economic performances**

246 In total, 16 trawlers were selected with similar technical characteristics (Table 2). Crew size
247 was relatively constant over the year. Fishing trips lasted on average 3 to 5 days according to the
248 distance from the fishing areas: the longest trip duration occurred in the SNS (latitude greater than
249 52.5°N). During the year, fishers on-board trawlers practised several métiers consisting of
250 changes in target species, gear used and/or fishing areas. Three main métiers composed their
251 fishing strategy: 1/ bottom otter trawl for cephalopod (hereafter denoted as OTB_CEP), 2/ bottom
252 otter trawl for demersal fish (OTB_DEF), and 3/ bottom/mid-water otter trawl for small pelagic
253 fish (OTBM_SPF). The OTB_CEP métier accounted for 37% of days-at-sea in a year, which were
254 spent mainly in the EEC (ICES statistical rectangles 29F0, 30F0, 29F1, 30F1) from August to
255 March (Fig. 2 and S3). The OTB_DEF métier (50% of days-at-sea) were practised mainly in the
256 EEC (29F0, 30F0, 30F1), and to a more limited extent, in the SNS (31F1, 37F0) depending on
257 the period of the year (Fig. 2 and S4). Lastly, the OTBM_SPF (only 13% of days-at-sea) occurred

258 predominantly in the EEC (29F0, 30F0, 30F1) from April to May, and may be pursued in the SNS
259 (37F0) from May to June (Fig. 2 and S5).

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

267 **Economic impacts of the LO implementation**

268 *Top-up versus no change in quotas*

269 Under the LO, fishers would reach several species quotas within a restricted number of days-
270 at-sea depending on the fishing zone (Fig. 4). In most scenarios, the main choke species would
271 be horse mackerel as it would be associated with the most restricted numbers of days-at-sea,
272 except under a 75% top-up scenario, in which the main choke species would be mackerel in the
273 SNS. Based on existing (i.e., as usual) fishing behaviours, the numbers of days spent at sea by
274 trawlers would decrease by approximately 15 to 85 days depending on the fishing zone and quota
275 top-up level. Under a 0% top-up scenario, the number of days-at-sea would drop from 135 to 50
276 days in the EEC, and from 39 to 14 days in the SNS. It would decrease to a much lesser degree
277 under a 75% top-up scenario: from 135 to 105 days in the EEC, and from 39 to 24 days in the
278 SNS.

279 The loss of profits would be proportional to the reduction of days-at-sea (Fig. 5). Based on
280 existing fishing behaviours, net profits would decrease greatly under a 0% top-up scenario. For
281 all métiers combined, fishers would lose approximately 46,000 euros in the EEC and 20,000 euros
282 in the SNS, while they would lose approximately 13,000 euros in the EEC and 7,000 euros in the
283 SNS under a 75% top-up scenario. The most affected métier would be the OTB_CEP métier (total
284 losses of about 34,000 and 10,000 euros under the 0% and 75% top-up scenarios, respectively),

285 followed by the OTB_DEF métier (22,000 and 7,000 euros) and OTBM_SPF métier (10,000 and
286 3,000 euros).

287 ***With uniform bycatch reduction of 30%***

288 Considering fishers would be able to reduce their bycatch by 30%, the number of days-at-sea
289 (Fig. 4) and the related net profits (Fig. 5) would be less restricted compared with the previous
290 scenarios. Under a 0% top-up scenario, fishers would be allowed to spend more days at sea (9
291 days in the EEC and 4 days in the SNS), resulting in an increase in net profits (5,000 euros in the
292 EEC and 2,000 euros in the SNS). A 75% top-up scenario would produce more significant
293 increases: 21 days for 11,000 euros in the EEC, and 6 days for less than 1,000 euros in the SNS.
294 Under a 75% top-up scenario, fishers would be slightly affected by choke species because quotas
295 would be exceeded late in the year. They would thus benefit from the landings of marketable and
296 unmarketable bycatch of regulated species, explaining changes in net profits would be positive in
297 the EEC.

298 **Specific avoidance behaviours**

299 In most scenarios, the most profitable behaviours for fishers would be to avoid horse mackerel
300 bycatch while practising the OTB_CEP and OTB_DEF métiers in the EEC. Under a 0% top-up
301 scenario, horse mackerel quota would be reached after only 50 days-at-sea (compared to the initial
302 135 days-at-sea), so the trawl fishery would close during the first half of the year. Fishers would
303 thus be incentivised to avoid horse mackerel bycatch beforehand. As a consequence, three isolated
304 areas with high discarded proportions (>0.8) should be avoided in the EEC from January to
305 March, and along the south coast of England from April to June (Fig. 6). These avoidance
306 behaviours would apply primarily to the OTB_DEF métier. Under a 75% top-up scenario, fishers
307 would be incentivised to avoid bycatch during the second half of the year as the fishery would
308 close later (after 120 days-at-sea). Fishers should therefore avoid operating in the southern EEC
309 from July to September (especially when practising the OTB_CEP métier), and in the mid-part of
310 the EEC and in the region off Boulogne-sur-Mer from September to December (Fig. 6).

311 **Discussion**

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

321 **LO direct economic impacts**

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

335 In most scenarios, horse mackerel is the main choke species for the studied trawlers, while in
336 the literature, cod, plaice and whiting are usually cited as the main ones for similar fisheries
337 (Russel *et al.*, 2015; Catchpole *et al.*, 2017; Mortensen *et al.*, 2018). The reasons for this are: (1)

338 horse mackerel quotas were divided by more than two from 2011 to 2016, resulting in low
339 available quotas for trawlers; (2) available quotas for the other species remained steady or
340 increased because fish stocks were in good conditions (e.g., ICES, 2017a, 2017b). It is also
341 important to notice that different countries fishing in this area are subject to different quotas
342 (which means different choke species) and so the decisions that other fleets will have to make
343 will differ from French vessels.

344 **Little economic incentives for uniform bycatch reduction**

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

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

361 The economic impacts of the LO may be underestimated as the additional effort and costs
362 incurred for handling, sorting and storing bycatch have not been considered in the analysis. In
363 reality, fishers on-board trawlers are expected to work more hours during a fishing trip, leading
364 to an increase in labour costs (Balazuc *et al.*, 2016). They are thus likely to be more strongly

365 incentivised to reduce the time required to handle, sort and store bycatch by fishing more
366 selectively, as suggested by Johnsen and Eliassen (2011). Negative economic impacts may also be
367 worse due to increased landing costs because of new equipment and infrastructures required at
368 fishing port to deal with bycatch landings.

369 **Limitations of this approach**

370 This study explores the degree of incentives for fishers to reduce bycatch under the LO.
371 Besides, it identifies métiers, fishing areas and/or seasons for which fishers are mostly
372 incentivised to avoid bycatch. These aspects are however very sensitive to a number of
373 assumptions. First, the assumption that species quotas were distributed equally between all
374 members of a producer organisation (i.e., each member held its own quotas), although they should
375 be available for all members, in which case the system is competitive (generating a race for fish;
376 Batsleer *et al.*, 2013). In such systems, fishers attempt to maximise landings before species quotas
377 are reached. As a result, it is more difficult to incentive fishers to use more selective fishing
378 practices as individual vessels have their own free will (e.g., if one fisher decides not to fish more
379 selectively, it will eventually go against all others). Second, fish prices are assumed to be fixed,
380 while these are known to vary depending on the time, and the quality and size of individual fish
381 (e.g., Meuriot and Gilly, 1987). Third, the LO exemptions are disregarded, such as for fish
382 damaged by predator, with high survival rate, or included in *de minimis* exemptions (Regulation
383 (EU) N°1380/2013). The estimated quantities of marketable and unmarketable bycatch are thus
384 slightly over-estimated.

385 **Specific avoidance behaviours supported by on-board observer data and mapping** 386 **tools**

387 Rochet *et al.* (2014) recommended that fishers adopt a combination of mitigation strategies if
388 they want to comply with all LO regulations, including avoidance behaviours. By contrast with a
389 uniform reduction of bycatch, specific avoidance behaviours, which can be explored and
390 identified using nested grids, could benefit more fishers. Provided that all quality indicators are

391 met, the resulting maps are thus considered meaningful for fishers to visualise how best to
392 reallocate effort when faced with the problems associated with choke species. Such mapping tools
393 could be used by other fisheries successfully. It is important to mention that this could also be
394 achieved with mapping methods developed in other studies with regard to discard hotspots (e.g.
395 Vilela and Bellido, 2015).

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

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

412 **Perspectives**

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

416 In cases where data on landings and discards are shared in near-real time between vessels, the
417 nested grid method could be used to identify more efficiently avoidance behaviours, as suggested

418 by Eliassen and Bichel (2016). One possible application would thus consist in creating an
419 automatic calculation and visualisation tool for fishers (e.g. Vilela and Bellido, 2015). The
420 objectives of such a tool would be to ease data processing (e.g., reduce calculation time), to
421 perform detailed analyses of fishing métiers (e.g., at port and/or fleet's scale), and to produce a
422 large number of maps. These maps would then be shared with fishers. Currently, this is feasible
423 only if a 100% observer coverage is applied, or if the LO is fully implemented and accepted by
424 fishers.

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619

620

621 **Tables**

622 **Table 1:** List of the main species landed and discarded by trawlers from 2011 to 2016. Contrib.,
 623 the percentage of revenue derived for each species all métiers combined; MCRS, Minimum
 624 Conservation Reference Size; DEF, demersal fish; CEP, cephalopod; SPF, small pelagic fish.

FAO Code	English name	Scientific name	DCF level 5	MCRS (cm)	Price ³ (€/kg)	Contrib. (%)
BSS ¹	Sea bass	<i>Dicentrarchus labrax</i>	DEF	–	6.95	7.5
COD	Cod	<i>Gadus morhua</i>	DEF	35	2.49	5.1
CTC ^{1,2}	Common cuttlefish	<i>Sepia officinalis</i>	CEP	–	2.05	8.5
DAB	Dab	<i>Limanda limanda</i>	DEF	–	0.51	1.1
HER	Herring	<i>Clupea harengus</i>	SPF	–	0.24	1.0
HOM	Horse mackerel	<i>Trachurus trachurus</i>	SPF	15	0.28	0.5
MAC ¹	Mackerel	<i>Scomber scombrus</i>	SPF	20 [†]	0.72	12.1
PLE	Plaice	<i>Pleuronectes platessa</i>	DEF	27	0.92	1.4
SQZ ^{1,2}	Various squids	<i>Loliginidae</i>	CEP	–	4.03	26.2
WHG ¹	Whiting	<i>Merlangius merlangus</i>	DEF	27	1.36	16.3

625 ¹Main target species; ²Non-quota species; ³ Lowest price level from 2011 to 2016 (source:
 626 EUMOFA); [†] 30 cm in the southern North Sea.

627 **Table 2:** Average technical characteristics for trawlers. Values in parentheses are coefficients of
628 variation (%) between vessels.

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)

629

630 **Table 3:** Summary of métier characteristics, and the average annual landings, discards, revenue¹
 631 and costs per vessel from 2011 to 2016.

Variable	Métiers		
	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 ¹ 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

632 ¹ No information was available on fishing subsidies, so a significant portion of revenue was
 633 ignored.
 634

635 **Figure Legends**

636 **Figure 1:** Map of the study area in the eastern English Channel (EEC) and southern North Sea
637 (SNS). The ICES statistical rectangles are referenced by their codes.

638 **Figure 2:** Average number of days-at-sea per month (top) and per ICES statistical rectangle
639 (bottom) in a year for each trawler as reported in the fisheries statistics. Each column corresponds
640 to a métier: bottom otter trawl for cephalopod (OTB_CEP) or demersal fish (OTB_DEF), and
641 bottom/mid-water otter trawl for small pelagic fish (OTBM_SPF).

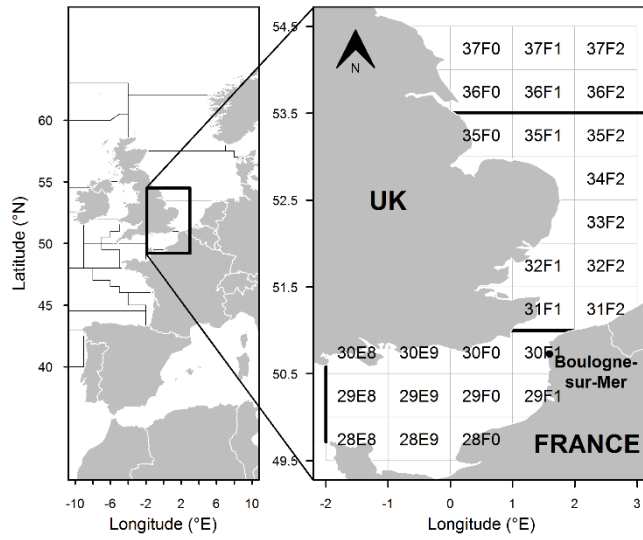
642 **Figure 3:** Average species composition (%) of landings and discards in weight for bottom otter
643 trawlers targeting cephalopod (OTB_CEP) or demersal fish (OTB_DEF), and for bottom/mid-
644 water otter trawlers targeting small pelagic fish (OTBM_SPF). Only the most landed and
645 discarded species are displayed (see Table 1 for species codes).

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

652 **Figure 5:** Change in net profits (10³ euros) from a baseline non-LO scenario compared to a LO
653 scenario combined with either 0% or 75% quota top-ups. Fishing behaviours are assumed as usual
654 (red), or adapted to reduce bycatch by 30% (green). Bars indicate the inter-annual variability from
655 2011 to 2016. Results are shown for bottom otter trawlers targeting cephalopod (OTB_CEP) or
656 demersal fish (OTB_DEF), and for the bottom/mid-water otter trawlers targeting small pelagic
657 fish (OTBM_SPF) in the eastern English Channel (EEC) and southern North Sea (SNS).

658 **Figure 6:** Discarded proportion of horse mackerel for bottom otter trawlers targeting cephalopod
659 (OTB_CEP) or demersal fish (OTB_DEF) from January to March, April to June, July to
660 September and October to December. The proportions are displayed only in cells containing 90%

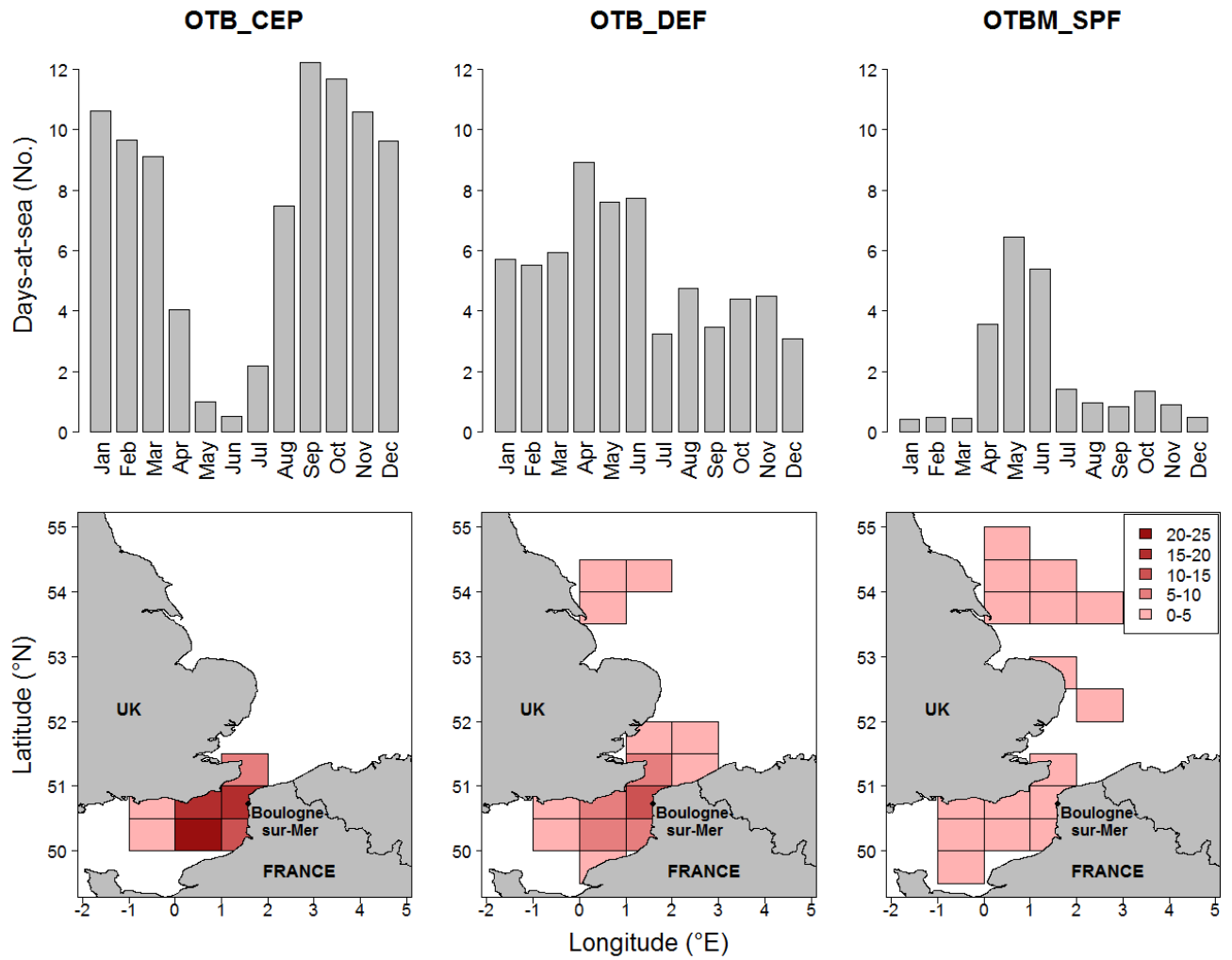
661 of catch-per-unit-effort. Black (grey) lines define cells with (in)sufficient amounts of FOs to make
662 estimates with a precision level of 0.35.



663

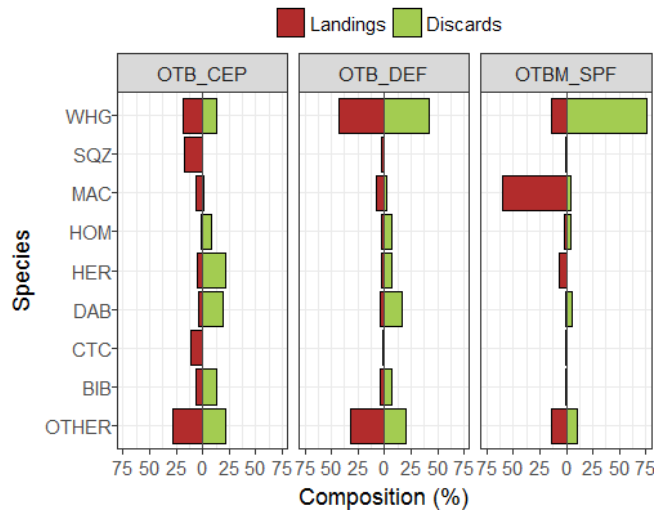
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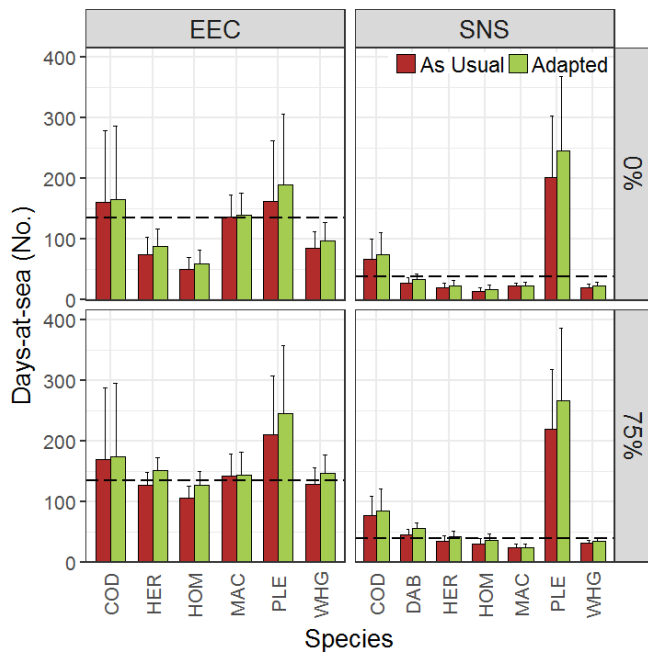
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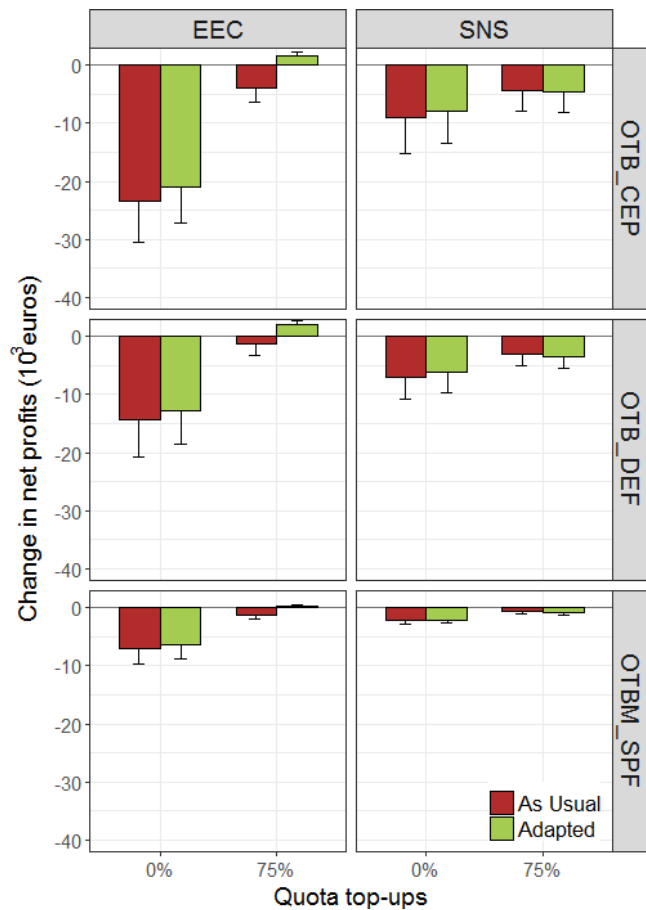
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 674 water otter trawlers targeting small pelagic fish (OTBM_SPF). Only the most landed and
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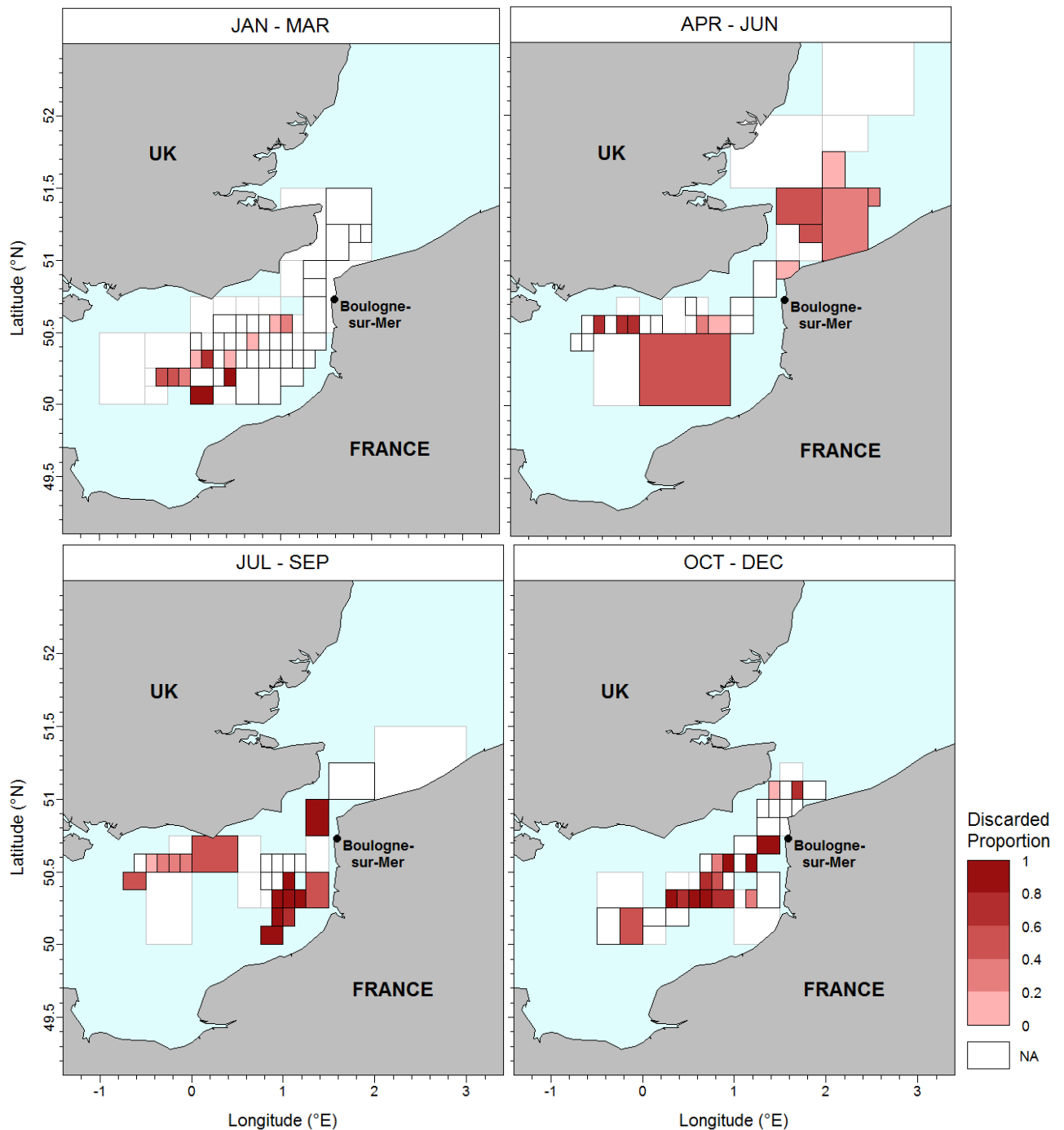
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 678 scenario combined with either 0% or 75% quota top-ups in the eastern English Channel (EEC)
 679 and southern North Sea (SNS). Fishing behaviours are assumed as usual (red), or adapted to
 680 reduce bycatch by 30% (green). The dashed line represents the number of days-at-sea calculated
 681 from a baseline non-LO scenario (135 days in the EEC and 39 days in the SNS). Bars indicate the
 682 inter-annual variability from 2011 to 2016. See Table 1 for species codes.



683

684 **Figure 5:** Change in net profits (10^3 euros) from a baseline non-LO scenario compared to a LO
 685 scenario combined with either 0% or 75% quota top-ups. Fishing behaviours are assumed as usual
 686 (red), or adapted to reduce bycatch by 30% (green). Bars indicate the inter-annual variability from
 687 2011 to 2016. Results are shown for bottom otter trawlers targeting cephalopod (OTB_CEP) or
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 694 estimates with a precision level of 0.35.