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A spatial food web model to investigate potential spillover effects of a fishery closure in an offshore wind farm

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Highlights

- An Ecospace model was developed for the extended Bay of Seine
- Potential effects of a fishery closure in an offshore wind farm were evaluated
- Spillover effect could mitigate the impact of access loss on fishing activities
- The spillover effect is highly localized around the offshore wind farm
- The offshore wind farm could concentrate highly mobile predators

Abstract

There is a growing interest in the development of offshore wind farms to provide a sustainable source of renewable energy and contribute to the reduction of carbon emissions. In parallel, there is a need to better understand the effects of these installations on coastal marine ecosystems and identify potential sea use conflicts, especially when the area is subject to access restrictions. This study investigated the

40 effects of a spatial closure during the exploitation phase of an offshore wind farm in the
41 extended Bay of Seine (English Channel, France) using Ecospace, a spatially and
42 temporally explicit module of Ecopath with Ecosim. To address this question,
43 simulations were conducted through the evaluation of “what-if scenarios” to assess the
44 effectiveness of a fishing exclusion zone inside and surrounding the offshore wind
45 farm. Several biomass, catch and trophic level-based indicators were calculated to
46 evaluate how the exclusion zone could affect fishing activities and main components
47 of the food web. All the indicators were estimated in the extended Bay of Seine and
48 summarized by sub-area. Findings suggested that the spillover effect could mitigate
49 the negative impact of access loss on fishing activities, in a scenario of simulated
50 closure of the area of the wind farm. The Ecospace model predicted an increase of
51 catches (up to 7% near the wind farm) and a slight increase in the proportion of high
52 trophic level species. However, the influence of spillover effects is limited in space and
53 the expected increase of biomass and catches are highly localized in areas around the
54 offshore wind farm installations. At the scale of the Bay of Seine, further analysis of the
55 spillover effects revealed a spatial pattern and suggested that the implementation of
56 an exclusion zone inside the offshore wind farm could concentrate highly mobile
57 predators.

58 **Keywords:** Ecopath with Ecosim, Ecospace, Marine Renewable Energy, Ecosystem-
59 based approach, Fishing, Spillover effects

60 1. Introduction

61 Motivated by the urgent need to reduce the emission of greenhouse gases, Marine
62 Renewable Energy (MRE) development has grown considerably in the last decade
63 (Raoux et al., 2017, 2019). Of these technologies, Offshore Wind Farm (OWF) is a
64 mature technology that has seen consistent growth in capacity and it is by far the most
65 technically advanced of all MRE (Wilding et al., 2017). This rapid growth of OWF has
66 raised concerns over their potential impacts on the ecosystems (Bailey et al., 2014;
67 Bergström et al., 2014). In fact, some studies have highlighted that OWF construction
68 could disturb marine invertebrates, fish, and mammals via the generation of noise and
69 electromagnetic fields (Bergström et al., 2014; Zettler and Pollehne, 2006). On the
70 other hand, OWF construction creates new habitats for sessile benthic species through
71 the introduction of hard substrate (Coolen et al., 2018; Wilhelmsson and Malm, 2008).
72 This observation is known as the “reef effect” and is considered as one of the most
73 important OWF effects on the marine environment (Krone et al., 2017; Wilhelmsson
74 and Malm, 2008). Adding to this reef effect, spatial restrictions such as exclusion zones
75 of fisheries activities (trawl and dredge) are likely to be implemented around turbines
76 and cables for navigation safety, which could lead the operational OWF to act as a
77 marine reserve generating increased biodiversity and abundance for many taxa
78 (Hammar et al., 2015; Shields and Payne, 2014; Yates and Bradshaw, 2018).

79 In this context, the French government has planned the construction of three OWFs in
80 the eastern basin of the English Channel along the Normandy coast (Courseulles-sur-
81 Mer, Fécamp and Dieppe-Le Tréport). As in most other European countries, these
82 future OWFs are subjected to environmental impact assessment and monitoring
83 studies to investigate the impacts of these new structures on ecosystems (Wilding et
84 al., 2017). However, OWF impact assessment and monitoring protocols are still under
85 development and several studies have pointed out significant shortcomings
86 (Lindeboom et al., 2011; Wilding et al., 2017; Pezy et al., 2018). For instance, although
87 the call for holistic approaches and Ecosystem-Based Management (EBM) of marine

88 ecosystems is well-established, attention has tended to focus on some iconic species
89 because of their protection status or public acclaim (Wilding et al., 2017). Thus, the
90 OWF impacts on the whole ecosystem remain insufficiently known and these studies
91 could fail to detect serious impacts on the ecosystem (Bailey et al., 2014; Pezy et al.,
92 2018). In accordance with EBM and environmental legislation requirements, Raoux et
93 al. (2017, 2019) highlighted the need to adopt a holistic approach to the impact of OWF
94 on ecosystem functioning with trophic web modelling tools as a complementary
95 approach to the traditional impact assessments. Such trophic web models have been
96 applied to provide global system indicators reflecting the structure and functioning of
97 ecosystems. In addition, they can provide information on the overall ecosystem status
98 and could be used as a baseline for EBM decisions (Raoux et al., 2019, 2017; Safi et
99 al., 2019).

100 In 2017, Raoux et al. investigated the applicability of the Ecopath with Ecosim (EwE)
101 approach coupled with Ecological Network Analysis (ENA) indices in the context of
102 OWF construction of the Courseulles-sur-Mer (CSM) area in the Bay of Seine, France.
103 An Ecopath model composed of 37 compartments, from phytoplankton to seabirds,
104 was built to describe the situation “before” the construction of the CSM wind farm. The
105 model was then run to predict the positive impact of the wind farm on the biomass of
106 targeted benthic and fish compartments subjected to the reef effect produced by the
107 foundations, scour protections and cable routes. ENA indices were calculated under
108 two scenarios (“before” and “after”) corresponding to the current state and the
109 operational phase of the OWF to analyze food web properties. One of the main results
110 was that total ecosystem activity, recycling and ecosystem maturity increased after the
111 construction of OWF (Raoux et al. 2017, 2019).

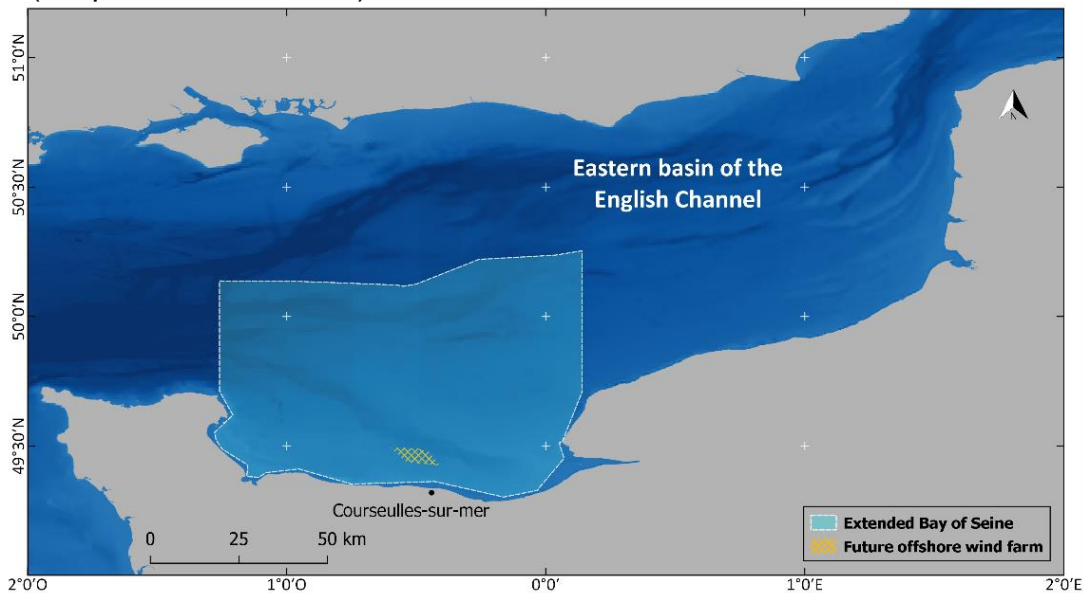
112 The purpose of the present study is to investigate the potential spillover effects of a
113 fishery closure in an offshore wind farm. To achieve this, a spatially explicit model of
114 the extended Bay of Seine was built, based on the use of the Ecospace module of the
115 EwE software. This module simulates the spatial and temporal dynamics of the food
116 web (Christensen and Walters, 2004a; Walters et al., 1999). In order to reach a point
117 of sensitivity where the effects would be observable, the spatial model includes a total
118 fishing exclusion zone in the area intended for wind farm constructions and evaluates
119 potential effects of the wind farm exploitation phase at ecosystem and fishery levels.
120 The overall goal of this research is to consider both ecosystem complexity and fishing
121 activities to address questions related to the spatial effects of setting an offshore wind
122 farm infrastructure as an exclusion zone, and the potential adjacent benefits due to the
123 spillover effect.

124 2. Material and Methods

125 2.1. The study area

126 The extended Bay of Seine (eBoS) is a shallow coastal ecosystem located on the
127 northwestern French coast and opening onto the Eastern English Channel to the limit
128 of the French Exclusive Economic Zone (Fig. 1). The eBoS covers approximately
129 13500 km² and it is generally composed of soft sediment (i.e. coarse sands, fine sands
130 and muddy fine sands) (Dauvin, 2015). The mean depth of the study area is about 35
131 m with a maximum tidal amplitude up to 7.5 m height near the mouth of the Seine
132 estuary. The intertidal zone and the shallowest subtidal zone (i.e. 0 – 5 m depth) was
133 not considered given the specificity of its ecological functioning. In its eastern south
134 part, the eBoS receives the Seine river which is highly loaded with nutrients (Guillaud

135 et al., 2000). Furthermore, the eBoS constitutes an important nursery, feeding, and
 136 breeding ground for several marine species (Rochette et al., 2010).
 137 The Bay of Seine concentrates high fishing effort and is one of the main King scallop
 138 (*Pecten maximus*) producing areas in France. Commercial fisheries operating in the
 139 eBoS area are diversified and include several métiers. The main fleets and gears
 140 considered in this study are nets targeting demersal fish, pelagic and bottom trawls
 141 targeting small pelagic fish, bottom trawls targeting demersal fish and cephalopods,
 142 pelagic trawls targeting demersal fish, dredge targeting king scallop and other fishing
 143 gears (Carpentier et al., 2009).



144
 145 Fig. 1. Map of the study area “extended Bay of Seine” (eBoS) and the location of the
 146 future Courseulles-sur-Mer offshore wind farm.

147 2.2. Model development

148 This work was based on the widely used Ecopath with Ecosim (EwE) software (version
 149 6.5; www.ecopath.org) for the modelling of aquatic food webs (Christensen and
 150 Walters, 2004a; Polovina, 1984). Basic concepts, capabilities and limitations of this
 151 modelling approach are described in detail in Christensen et al. (2008) and
 152 Christensen and Walters (2004a). The spatial simulations presented in this study
 153 required the implementation of Ecopath, Ecosim and Ecospace modules in the eBoS
 154 ecosystem. Details on the input data and computational aspect of these modules are
 155 described in the Appendix (A). Spatial data maps were constructed using R (R Core
 156 Team, 2019).

157 2.2.1. Ecopath model

158 The parameterization of a mass-balanced Ecopath model is based on two master
 159 equations and a resulting set of linear equations to describe the trophic interactions
 160 among functional groups of organisms. The first one describes the production term
 161 (Eq.1):

$$162 \quad \text{Production} = \text{Catch} + \text{Predation} + \text{Biomass accumulation} + \text{Net migration} \\
 163 \quad \quad \quad + \text{Other mortality}$$

164 The second equation ensures energy balance for each functional group (Eq. 2):

$$\text{Consumption} = \text{Production} + \text{Respiration} + \text{Unassimilated food}$$

165

166 The Ecopath model of eBoS is an update of a previously constructed Ecopath model
 167 developed by Raoux et al. (2017) for the future site of the offshore wind farm of CSM.
 168 The main differences of the model developed in this work are: 1/ the enlargement of
 169 the geographical area covered by the Ecopath model of eBoS. Indeed, a larger area
 170 better reflect a closed system when there is lack of accurate information about the
 171 dynamic of migratory species, 2/ the addition of six new functional groups, and 3/ the
 172 definition of new fishing fleets. The eBoS Ecopath model was balanced by slightly
 173 modifying the model inputs (especially diet composition). This step aims to satisfy the
 174 constraint of mass balance and an Ecotrophic Efficiency lower than one since the main
 175 input parameters (i.e. biomass, production/biomass, and consumption/biomass) were
 176 re-estimated in this model. All the details related to the update of the Ecopath model
 177 of Raoux et al. (2017) are presented in the Appendix (A).

178 The mass-balanced model of eBoS represents the situation of the ecosystem in 2000,
 179 (the first year of the dataset (Table 1)), and comprises 43 functional groups composed
 180 of more than 72 species including phyto- and zooplankton (4), benthos (7), exploited
 181 bivalves (1), fish (20), cephalopods (2), seabirds (3), marine mammals (3), discards
 182 (1), detritus (1).

183 2.2.2. Ecosim model

184 An Ecosim model was implemented based on parameters inherited from the eBOS
 185 Ecopath model in order to provide temporal dynamic simulation capabilities at the
 186 ecosystem level (Christensen and Walters, 2004a). The time-dynamic simulations of
 187 the food web result from two main equations, one of which to express the biomass
 188 dynamic:

$$189 \quad \frac{dB_i}{dt} = g_i \sum_{j=1}^n Q_{ji} - \sum_{j=1}^n Q_{ij} + I_i - (M_i + F_i + e_i)B_i$$

190 Where $\frac{dB_i}{dt}$ represents the growth rate of group i during the time interval dt in terms of
 191 biomass, g_i is the net growth efficiency, Q_{ij} is the consumption rate of group i by group
 192 j , I_i is the immigration rate, e_i is the emigration rate, M_i corresponds to the other natural
 193 mortality rate and F_i is the fishing mortality rate. The second equation defines the
 194 consumption of a predator i on its prey j for each time step.

195

$$196 \quad Q_{ij} = \frac{a_{ij}v_{ij}B_iB_j}{2v_{ij} + a_{ij}B_j}$$

197 Where a_{ij} is the effective search rate of predator j for prey i , v_{ij} is the transfer rate
 198 between vulnerable and an invulnerable component, B_i is the biomass of the prey and
 199 B_j is the biomass of the predator. The consumption rates of the modelled species are
 200 computed based on the concept of “Foraging arena”. The biomass of each prey i is
 201 divided into vulnerable V_i and invulnerable components ($B_i - V_i$). The exchange rate
 202 between the two components depends on the transfer rate v_{ij} (Christensen and
 203 Walters, 2004b; Walters et al., 1997) and only the biomass of the vulnerable
 204 component is available to predators. The transfer rate v_{ij} represents the impact of
 205 predator’s biomass on the predation mortality of a given prey since it determines if the
 206 control is top-down, bottom-up or wasp-waist (Christensen et al., 2008). During the
 207 calibration procedure, the best values of vulnerability were estimated in such way to

208 improve the fit of Ecosim predictions to the observed data by using the same value for
 209 all prey to a single predator. In this study, the eBoS Ecosim model was constructed to
 210 predict the ecosystem effects of fishing over the period 2000 – 2015 in order to
 211 reproduce the historical patterns of landings (Appendix B). During the calibration
 212 procedure, the Ecosim model of the Bay of Seine was fitted to the available time series
 213 of landings (2000 – 2015) obtained from the IFREMER database SACROIS (Système
 214 d'Information Halieutique, 2017). For this purpose, several time series were
 215 implemented in the model (e.g. time series of catches, fishing effort by métiers, primary
 216 production); more details are available in Table 1.
 217 The time-dynamic simulations created by Ecosim were calibrated with an automated
 218 stepwise procedure, which searches for vulnerability parameters that minimize
 219 differences between predicted outputs and observed time series of catches. The
 220 procedure is derived from the one described in Piroddi et al., (2016) in turn based on
 221 Mackinson et al., (2009). The goodness of fit was evaluated by calculating the total
 222 sum of squared deviations (SS) and the Akaike's Information Criterion (AIC). The
 223 calibration was carried out using the module "Fit to time Series" of Ecosim (EwE. 6.5).
 224 The estimation of the primary production anomaly contributed to the reduction of
 225 deviations between model predicted catches and observed catches and thereby to the
 226 improvement of model performance.
 227

228 Table 1. Time series data used to fit the Ecosim model of the Bay of Seine

Time series	Period	Target group	Sources	Type (in Ecosim)
Catches (t.km ⁻²)	2000 - 2015	<ul style="list-style-type: none"> • King scallop • Fish limande • Fish flounder • Fish european plaice • Fish sole • Fish sea bream • Fish benthos feeders • Fish planctivorous • Fish piscivorous • Fish european pilchard • Fish pouting • Fish gurnard • Fish atlantic horse mackerel • Fish whiting • Fish atlantic cod • Fish sharks • Fish rays • Fish european seabass • Fish mackerel • Benthic cephalopods • Benthopelagic cephalopods 	SACROIS data (Système d'Information Halieutique, 2017) http://sih.ifremer.fr/	Catch (reference)

Time series	Period	Target group	Sources	Type (in Ecosim)
Fishing effort (per unit of time)		<ul style="list-style-type: none"> Nets targeting demersals and crustaceans Pelagic and bottom trawls targeting small pelagics Bottom trawls targeting demersals and cephalopods Pelagic trawls targeting demersals Other fishing gears Dredge 		Fishing effort
Biomass (t.km ⁻²)		<ul style="list-style-type: none"> King scallop 	Stock assessment data from COMOR campaign report (Foucher, 2013)	Relative biomass
		<ul style="list-style-type: none"> Fish flounder Fish european plaice Fish whiting Fish pouting Fish piscivorous 	Estimated from a surplus-production model (SPiCT) (Pedersen and Berg, 2017) using abundance indices from CGFS campaign in the Eastern English Channel (Coppin et al., 1989) and the French landings data from SACROIS (Système d'Information Halieutique, 2017)	
		<ul style="list-style-type: none"> Fish rays Fish atlantic horse mackerel 		Forcing biomass
Fishing mortality _y	<ul style="list-style-type: none"> Fish european plaice Fish rays Fish atlantic cod 		Fishing mortality	
Primary production (t.km ⁻²)	2000 - 2010	<ul style="list-style-type: none"> Primary production 	Satellite ocean data (SeaWifs): SeaWifs Level3, Annually mapped, 9km resolution, Chlorophyll a (NASA Goddard Space Flight Center and Ocean Biology Processing Group, 2014)	Primary production forcing function
	2011 - 2015		Satellite ocean data (MODIS): MODIS Aqua, Level 3 Global Monthly Mapped 4 km Chlorophyll a (Hu et al., 2012)	

229

230 2.2.3. Ecospace model

231 Ecospace is the spatial and time dynamic module of the EwE software. It inherits all
232 the key elements of Ecopath and Ecosim models. Ecopath baseline biomasses and
233 Ecosim fitted time series were used as starting point to initialize the spatial simulations
234 (Walters et al., 1999). In Ecospace, the biomass of each functional group is allocated
235 across two-dimensional spatial grid with equally sized homogenous cells. This base
236 map is divided into different habitats to which functional groups and fishing fleets are
237 assigned. The biomass pools linked by trophic flows, can move among fixed spatial
238 reference points according to the “Eulerian” approach which treats movement as flows
239 of organisms without retaining information about their movement history (origin and
240 past features) (Walters et al., 1999).

241 The implementation of an Ecospace model starts by defining a grid of spatial cells.
242 Each cell of the base map is assigned to a land or water value and to a specific habitat
243 type. The distribution of the functional groups across the spatial domain is governed
244 by the habitat assignment, the environmental preference function, dispersal rates and
245 foraging behavior. Despite the fact that the extended Bay of Seine is an open
246 ecosystem, the species migration was not considered due to the lack of data, therefore
247 net inputs or outputs of organisms in the considered zone in terms of trophic flows are
248 neglected. For each cell, biomass and consumption rates of functional groups are
249 driven by the trophic interactions inherited from Ecopath and through Ecosim
250 differential equations described in details by Walters et al. (2000, 1997). After the
251 assignment of fishing fleets to the existing habitats, the fishing mortality is distributed
252 by fleet over the spatial domain based on a relatively simple “gravity model”. Ecospace
253 represents spatial distribution of fishing mortality in such way that the amount of effort
254 allocated to each cell is assumed to be proportional to the relative profitability rate in
255 that same cell (Christensen et al., 2008; Walters et al., 1999). This representation
256 allows the model to predict the fishing effort by fleet in a more realistic way. The base
257 map of the Ecospace eBoS consists of a raster grid map of 70 rows and 101 columns,
258 each cell is 0.015° x 0.015° latitude-longitude resolution (≈ 1.6 km side). Several layers
259 of information have been implemented to define the distribution of functional groups
260 and fishing effort:

- 261 - The map of the study area: definition of land and water cells and the position of
262 the main ports.
- 263 - The bathymetry of the study area extracted from the GEBCO (General
264 Bathymetric Chart of the Oceans) database at 15 arc-second intervals,
265 downloaded from (<https://www.gebco.net/>).
- 266 - The area of the future CSM offshore wind farm implemented as a Marine
267 Protected Area (MPA).
- 268 - Two sub-areas around the offshore wind farm: a first sub-area adjacent to the
269 wind farm 3.2 km wide and a second sub-area adjacent to first one also 3.2 km
270 wide.
- 271 - The map of the primary production extracted from the SeaWifs satellite data
272 (processing level: Level 3, resolution: 0.083 ° (Lat) x 0.083 ° (Long)). This map
273 represents the relative concentration of chlorophyll a in the Bay of Seine for the
274 year 2000 (<https://podaac.jpl.nasa.gov/>).
- 275 - The map of the main benthic habitats of the Bay of Seine based on the seafloor
276 type, namely, gravels, sandy gravel, coarse sands, *Ophiotrix fragilis* patches,
277 fine sand more or less silted, middle dune sands, scallop shell deposit (derived
278 from several benthos campaigns: LANICE, GIE-GMO, PECTOW and
279 Benthoseine) (Baffreau et al., 2017)

280
281 In Ecospace eBoS, the species distribution is driven by the environmental preference
282 function to bathymetry for fish, cephalopods, dolphins and benthic feeders seabirds
283 (estimated from CGFS occurrence data) (Appendix C.2) and the habitat foraging usage
284 for benthic species (Appendix C.3). A fraction of the biomass of each functional group
285 moves into adjacent cells according to random walk movements. This movement is
286 governed by the dispersal rate parameter, which represents the ability of functional
287 groups to move within the base map. The values of dispersal rates recommended by
288 Christensen et al. (2008) were applied for the majority of the functional groups, which
289 are of three magnitudes (i.e. 300 km.year⁻¹ for pelagic species, 30 km.year⁻¹ for
290 demersal species, and 3 km.year⁻¹ for non-dispersing species). These values were

291 adjusted manually for some functional groups during the validation of Ecospace (e.g.
 292 the dispersal rate of marine mammals and birds is equal to 500 km.year⁻¹ (Appendix
 293 C.1). When an organism moves to an “unsuitable” (non-assigned) habitat, the values
 294 of the basic dispersal rate were multiplied by a factor ranging from 1 to 3 (Appendix
 295 C.1). Concerning the relative vulnerability to predation, for benthic groups (e.g.
 296 suprabenthos, benthic invertebrate filter feeders, and benthic invertebrate predators),
 297 due to their low mobility, their relative vulnerabilities are three times higher in unsuitable
 298 habitats. All the other groups are twice more vulnerable to predation in unsuitable
 299 habitat, and they are less likely to consume and find appropriate food (Christensen et
 300 al., 2008) (Appendix C.1).

301 The spatial fishing mortality depends on fishing fleet distribution. The gravity model
 302 spreads the fishing effort inherited from Ecosim across all habitats open to fishing. In
 303 the reference scenario, all fleets could fish everywhere except for “Dredge” which
 304 assigned to a specific area limited to the stock of King scallop. The fishing effort is
 305 distributed proportionally to the “attractiveness” of each cell $A_{n,k}$.

$$306 \quad A_{n,k} = \left(\frac{\sum_{i=1}^I p_{k,i} \cdot q_{k,i} \cdot B_{i,n}}{C_{n,k}} \right)^{\frac{1}{\sigma}}$$

307 Where n is the cell, k is the fleet, $p_{k,i}$ is the price of functional group i for fleet k , $q_{k,i}$ is
 308 the catchability of functional group i by fleet k , $B_{i,n}$ is the biomass of group i in cell n ,
 309 $C_{n,k}$ is the cost for fleet k of fishing in cell n and σ measures variation among fishermen
 310 in the perception of profit from fishing in cell n (Romagnoni et al., 2015).

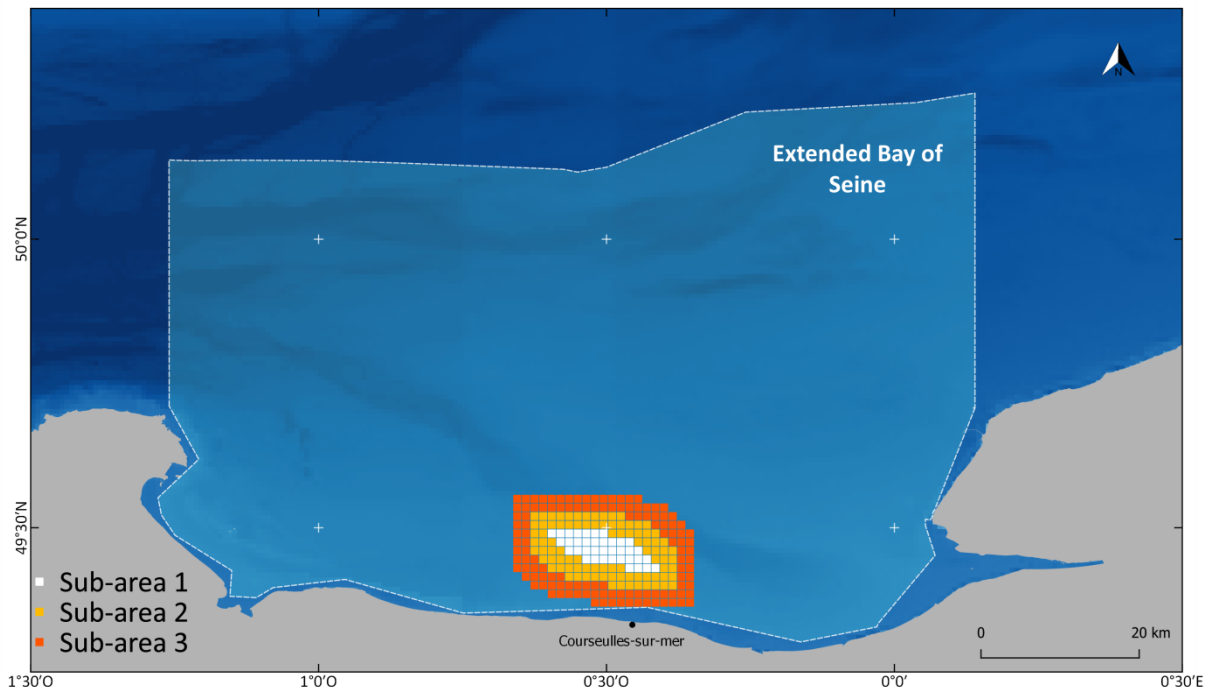
311 In Ecospace eBoS, costs are based on the map of sailing costs calculated from the
 312 “distance from port” map and effort related cost (Ecopath default value for all fleets).
 313 The effective power $\frac{1}{\sigma}$ controls fleets distribution, high value of σ correspond to a
 314 smoother distribution of the fishing effort throughout the map. The effective power and
 315 the total efficiency multiplier (the multiplier factor for effort) were set to the default value
 316 1.

317 2.3. Offshore wind farm simulations

318 The future wind farm composed of 64 turbines will be located 10 – 16 km offshore from
 319 Courseulles-sur-Mer (Fig. 1). During the exploitation phase of turbines, around 20% of
 320 the installation area is scheduled to be closed to all fishing activities (EDF personal
 321 communication). In the present study, two simulations were run for a period of 15 years
 322 to assess the Marine Protected Area (MPA) effect through the evaluation of “what if
 323 scenarios”. A reference scenario, which corresponds to the observed ecosystem for
 324 the period 2000 – 2015 with no changes and an “exclusion” scenario in which a MPA
 325 is assigned to the offshore wind farm area ($\approx 70 \text{ km}^2$). The scenario corresponding to
 326 a closure of 20% of the wind farm area was not presented in this article because the
 327 resolution is not fine enough to detect any changes.

328 Several biomass, catch and trophic level-based indicators were calculated to quantify
 329 the impact of the installation of the wind farm (e.g. biomass, catches and discards of
 330 exploited groups, Marine Trophic Index (MTI) defined as the mean trophic level (TL) of
 331 fisheries landings of species with trophic levels > 3.25 , trophic level of catches, trophic
 332 level of the community at two different cut-offs (3.25 and 4) corresponding the lowest
 333 TL values used in the computation of the indicator (it considers all organisms above
 334 ^{cut-off} TL). In order to investigate the potential spillover effects from the exclusion area,

335 these indicators were calculated in three sub-areas, i/ sub-area 1: the MPA area (also
336 called “no fishery area” or “exclusion area”), ii/ sub-area 2: a first area 3.2 km wide
337 surrounding sub-area 1 and, iii/ sub-area 3: a second area 3.2 km wide surrounding
338 sub-area 2 (Fig. 2).
339



340 Fig. 2. Map of sub-areas of interest inside the study area of eBoS Ecospace model.
341 Sub-area 1 (white) corresponds to the location of the future offshore wind farm of
342 Courseulles-sur-Mer (CSM).
343

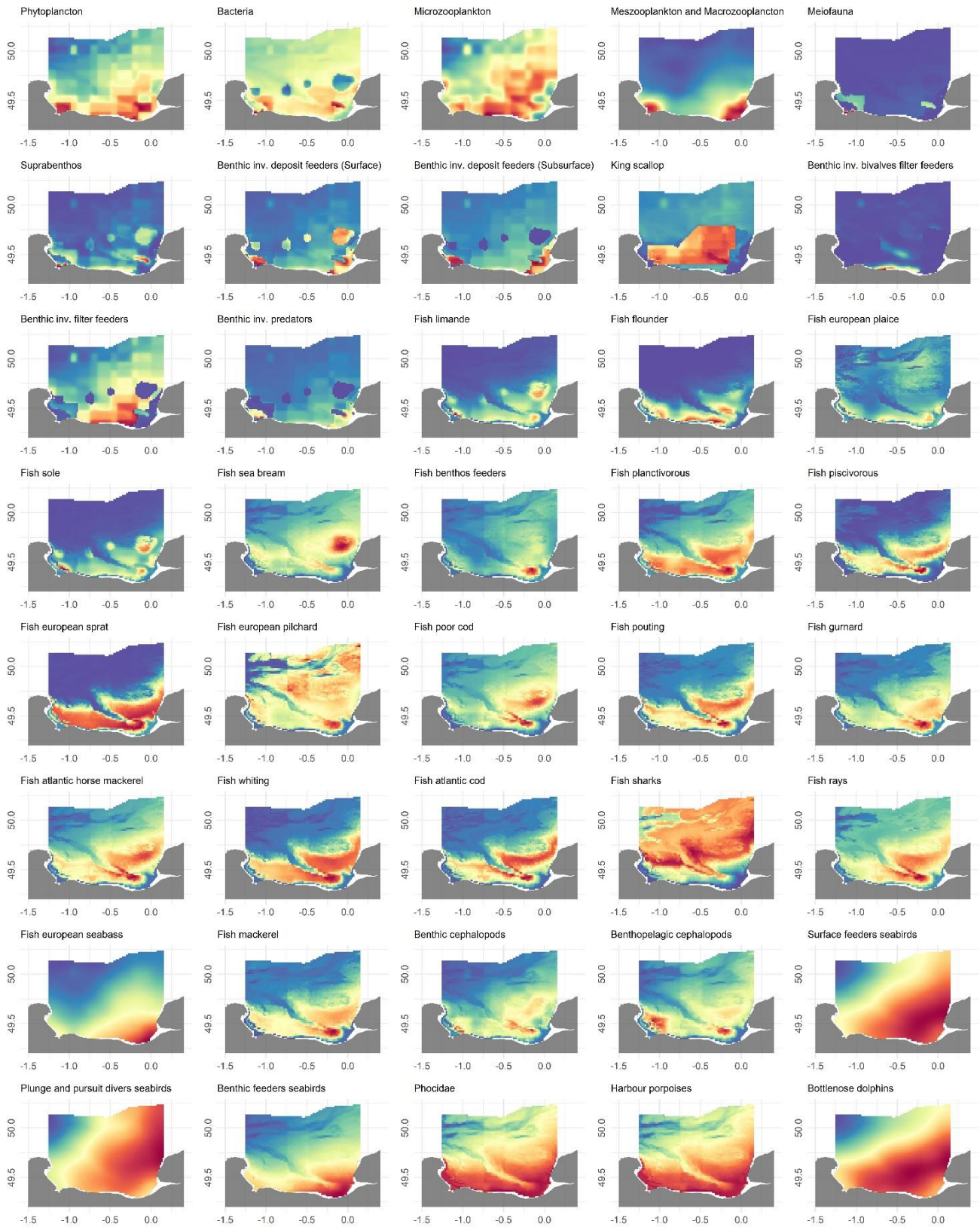
344 3. Results and discussion 345 3.1. Reference scenario

346 The reference scenario maps were averaged to capture the mean state of the eBoS
347 ecosystem during the period 2000 – 2015. In Ecospace eBoS, CGFS data served to
348 define species preferences in terms of habitat. Since CGFS fisheries surveys are
349 conducted yearly in the eastern English Channel in October the predicted maps of
350 biomass should be considered as an autumnal representation of the ecosystem (Fig.
351 3). In order to assess the accuracy of Ecospace outputs and avoid a misrepresentation
352 of the geographic distribution of modelled groups, predicted maps were compared to
353 species distribution maps from Channel Habitat Atlas for marine Resource
354 Management (Carpentier et al., 2009) and COMOR reports of IFREMER for the King
355 scallop. The spatial predictions were evaluated by visual comparison and the results
356 were corroborated by expert opinion elicited during dedicated ad-hoc workshops. The
357 comparison between observed and predicted spatial distribution was considered
358 satisfactory.

359 Most of the functional groups and especially demersal species (details of grouping are
360 given in Appendix A.0) display a clear coast-offshore gradient since their distributions
361 are driven by the bathymetry (e.g. fish plaice, fish rays, fish whiting). The observed
362 gradient could also be explained by the fact that estuarine habitats of the eBoS
363 represent an important nursery area during the autumn for juvenile marine fishes (e.g.
364 the common dab (*Limanda limanda*), the European seabass (*Dicentrarchus labrax*),
365 the Whiting (*Merlangius merlangus*), and the Surmullet (*Mullus surmuletus*) (Le Pape

366 et al., 2007). In contrast, the distribution of sedentary benthic invertebrates (e.g.
367 benthic inv. bivalve's filter feeders, benthic inv. predators, benthic inv. deposit feeders
368 (surface)) is mainly driven by the type of sediment.

369



370

371 Fig. 3. Biomass distribution of 40 functional groups predicted by Ecospace eBoS under
372 the reference scenario representing the mean state of the Bay of Seine ecosystem
373 during the period 2000 – 2015, (red: high biomass, blue: low biomass).

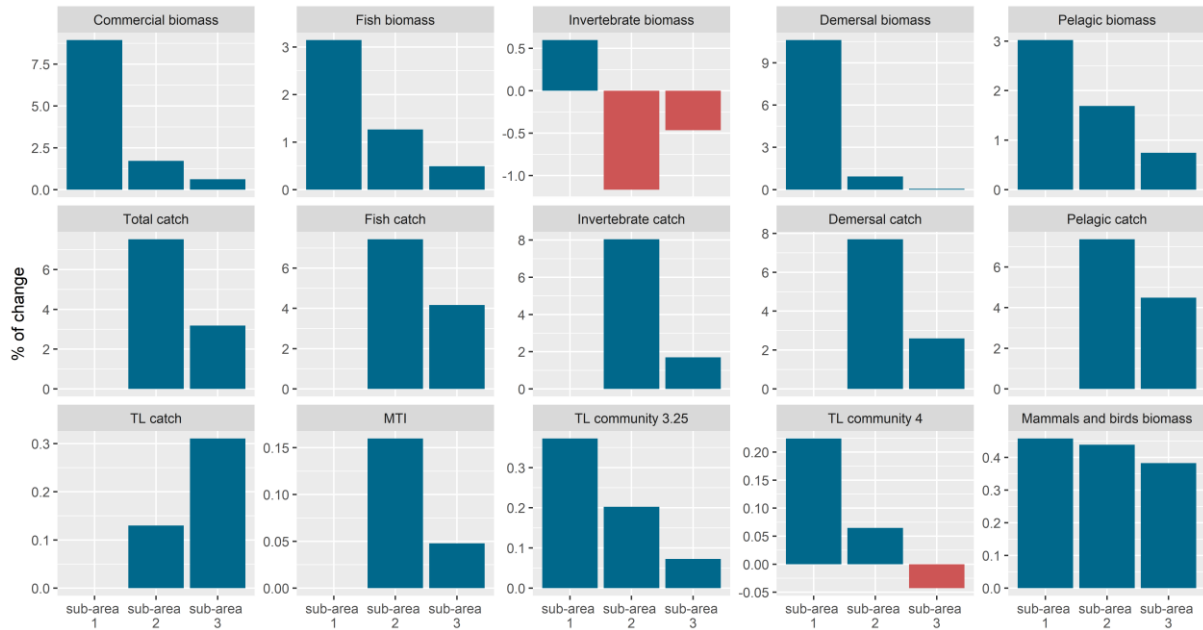
374 3.2. Analysis of the spillover effects

375 In order to analyze the spillover effects, the percentage of change by sub-area was
376 calculated by comparing the averaged outputs over 15 years of the reference scenario
377 with the offshore wind farm scenario. Results of the implementation of the offshore
378 wind farm scenario revealed substantial changes in biomass of demersal species
379 which display a percentage of change higher than 9% in sub-area 1 (Fig. 4, Demersal
380 biomass). Nonetheless, the spillover effects for demersal species in sub-areas 2 and
381 3 is less pronounced than for other functional groups because of their low mobility.
382 Besides, pelagic species characterized by a high dispersal rate could benefit from the
383 spillover effect by increasing their biomass to almost 2%. For invertebrates, the
384 simulation results exhibit a different pattern. Indeed, the implementation of the offshore
385 wind farm has limited effects in the exclusion zone. Figure 4 reveals that the biomass
386 of invertebrates increases only by 0.5% in sub-area 1. However, their biomass could
387 decrease up to 1% in surrounding sub-areas. This result might be explained by the
388 increase of both predation pressure inside the exclusion zone (sub-area 1) and fishing
389 mortality around the wind farm in sub-areas (2 and 3). The intensification of fishing
390 pressure on benthic invertebrates is clearly illustrated by an important increase of
391 catches of King scallop *Pecten maximus* in sub-areas 2 and 3. The changes in catches
392 are similar across the main exploited groups of fish, invertebrate, demersal and pelagic
393 species. Potential catches increase up to 8% in sub-area 2 and 4% in sub-area 3,
394 which could be interpreted as a result of re-allocation of the fishing effort in the cells
395 around the offshore wind farm (since the spillover effect increased the profitability of
396 sub-areas 2 and 3).

397 It is likely that the increase of catches does not balance the decline of total landings
398 following the closure of sub-area 1 to fishing activities. However, the shortfall in catches
399 could be mitigated by the predicted change of catch composition. Indeed, the slight
400 increase of the trophic level of catches and the Marine Trophic Index in the areas
401 surrounding the wind farm indicates an increase in the proportion of high trophic level
402 species in the catch composition, which generally have high economic value (e.g.
403 European seabass, benthic cephalopods, and Atlantic cod). For the trophic level of the
404 community at thresholds 3.25 and 4, the predicted increase in sub-areas 1 and 2 is
405 attributed to an increase of the proportion of top predators. This result highlights that
406 high trophic level species (TL>3.25) could benefit from the installation of the offshore

407 wind farm and the resulting fishing ban in sub-area 1. Higher trophic level species also
 408 benefit in sub-areas 2 and 3 even despite the increase of fishing mortality.

409 Fig. 4. The percentage of change represents the comparison of the averaged outputs
 410 over 15 years of the offshore wind farm scenario with the reference scenario inside
 411 each sub-area (sub-area 1: inside the MPA area, sub-area 2: a first area 3.2 km wide



412 around sub-area 1, sub-area 3: a second area 3.2 km wide around sub-area 2) and by
 413 ecological indicator.

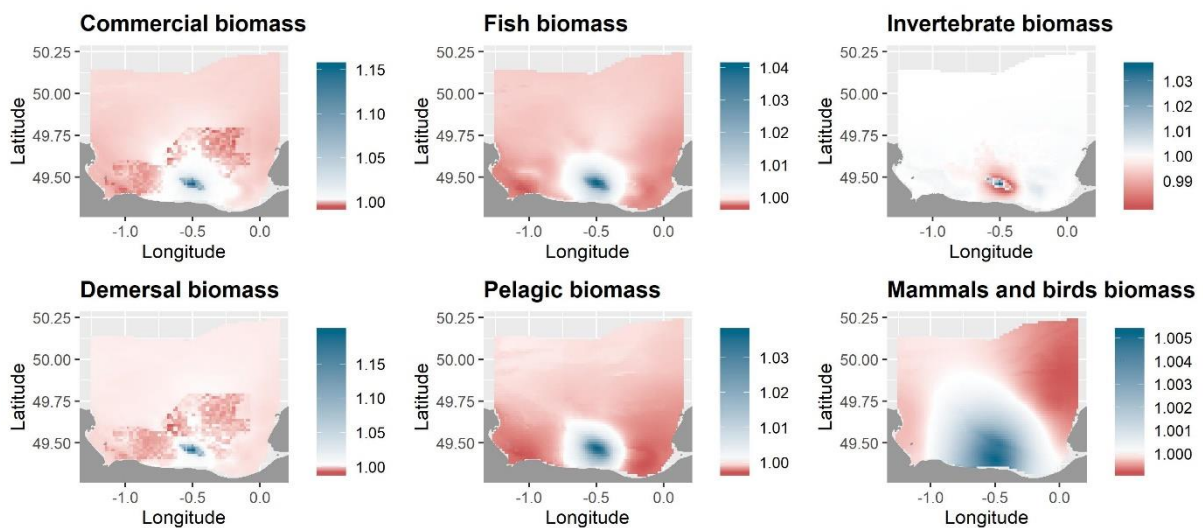
414

415 The spatial analysis of the spillover effects revealed that, for most of the groups, it is
 416 limited to adjacent areas around the offshore wind farm in less than 3 km radius range
 417 and diminish rapidly with increasing distance, especially for commercial and demersal
 418 species (Fig. 5). These findings are in line with previous findings which showed that
 419 spillover is a common phenomenon around no-take marine reserves, but at relatively
 420 small scales (Harmelin-Vivien et al., 2008; Halpern et al., 2009). Furthermore, the
 421 intensity of the spillover effects seems to vary among the different groups. For
 422 example, the group of invertebrates exhibit an opposite trend due to a higher fishing
 423 pressure on King scallop *Pecten maximus* in the sub-area bordering the wind farm.
 424 Moreover, the simulation of a no fishing area suggested that for highly mobile species,
 425 the spillover effect is less intense and more diffused in space, such as for pelagic
 426 species and the group of marine mammals and birds. These predictions are consistent
 427 with previous results which support that the spillover effect differs by species mobility
 428 (Kellner et al., 2007).

429 The model displayed certain spatial patterns in the distribution of the spillover effects
 430 over the Bay of Seine (Fig. 5). This is illustrated by the presence of three well defined
 431 sub-areas: a first zone adjacent to the offshore wind farm with positive spillover effects
 432 (increase of biomass), a second zone bordering the first one with no spillover effects
 433 (no change in biomass) and a third zone afterwards with a decrease of biomass). This
 434 pattern could be interpreted as being a result of species movement toward more
 435 suitable habitats through the net emigration of fish as proposed by Rowley (1994) and
 436 the redistribution of the fishing effort over the study area. In fact, the increase of the

437 predicted biomass, in the sub-area 2, could be explained by local movements of
 438 functional groups, which tend to spend more time in areas where the conditions are
 439 more suitable for two main reasons: 1) the offshore wind farm plays the role of a Marine
 440 Protected Area (MPA) after the closure of fishing activities. Hence, the exploited
 441 species could benefit from the absence of fishing mortality, and 2) the offshore wind
 442 farm and surrounding areas offer more feeding opportunity for all predators given the
 443 spillover effects. Therefore, it is very likely that the predicted increase of biomass in
 444 sub-areas 1, 2 and 3 is due to the spillover effects and species movements. For
 445 invertebrates, the decrease of their biomass only occurs around the no-take area
 446 because of a higher fishing pressure on King Scallop, which has a high abundance
 447 localized around the future wind farm. Furthermore, the patterns observed in figure 5
 448 show that for less mobile species such as invertebrates the impact of spillover
 449 (increase of biomass around the no-take) area is very limited in contrast to more mobile
 450 groups (e.g. marine mammals and pelagic fish) for which the effect of the spillover
 451 could cover a larger area.

452



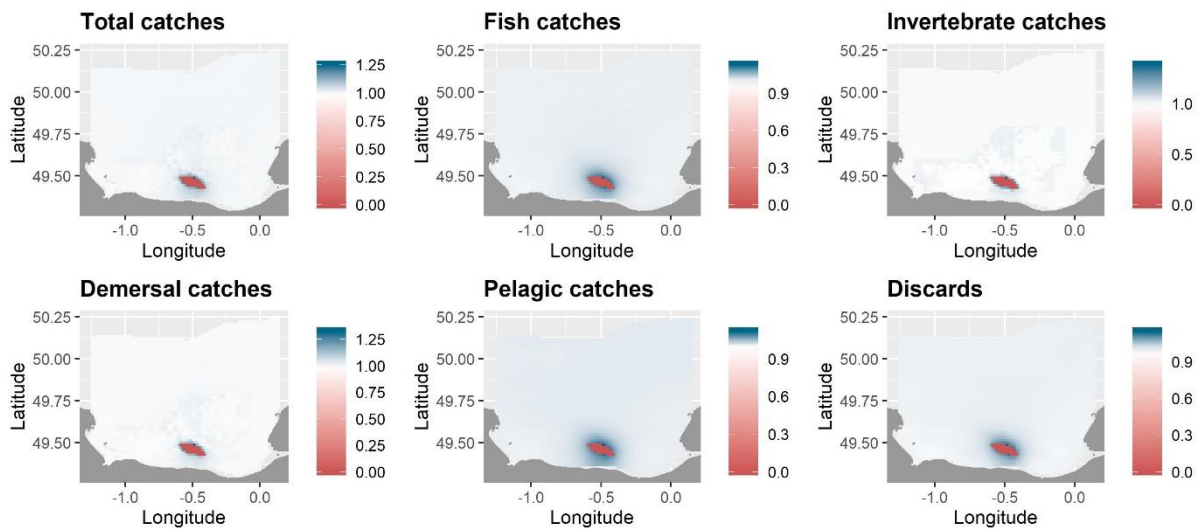
453

454 Fig. 5. The spatial relative impact of the implementation of the offshore wind farm on
 455 the biomass of commercial species, invertebrates, demersal species, pelagic species,
 456 marine mammals and birds (blue: the value of the indicator is higher than the reference
 457 scenario, red: the value of the indicator is lower than the reference scenario). The maps
 458 were averaged over the period 2000 – 2015.

459

460 Figure 6 shows spatial changes, in terms of catches and discards, after the
 461 implementation of the offshore wind farm. The Ecospace model predicted an increase
 462 of catches, up to 20%, in some cells in the areas surrounding the wind farm site. The
 463 pattern of change of catches was very similar to biomass changes (Fig. 6). Ecospace
 464 simulations corroborate the view that the impacts of banning fishing activities within
 465 the wind farm are local (less than 3 km radius range around the wind farm) and they
 466 are not likely to affect the global trophic dynamic of the eBoS ecosystem. These results
 467 are in line with previous findings regarding the potential effects of small sized marine
 468 protected areas on the catches of the Gulf of Gabès, Tunisia (Abdou et al., 2016) and
 469 the net contribution of spillover from marine reserves to fishery catches (Goñi et al.,
 470 2010).

471



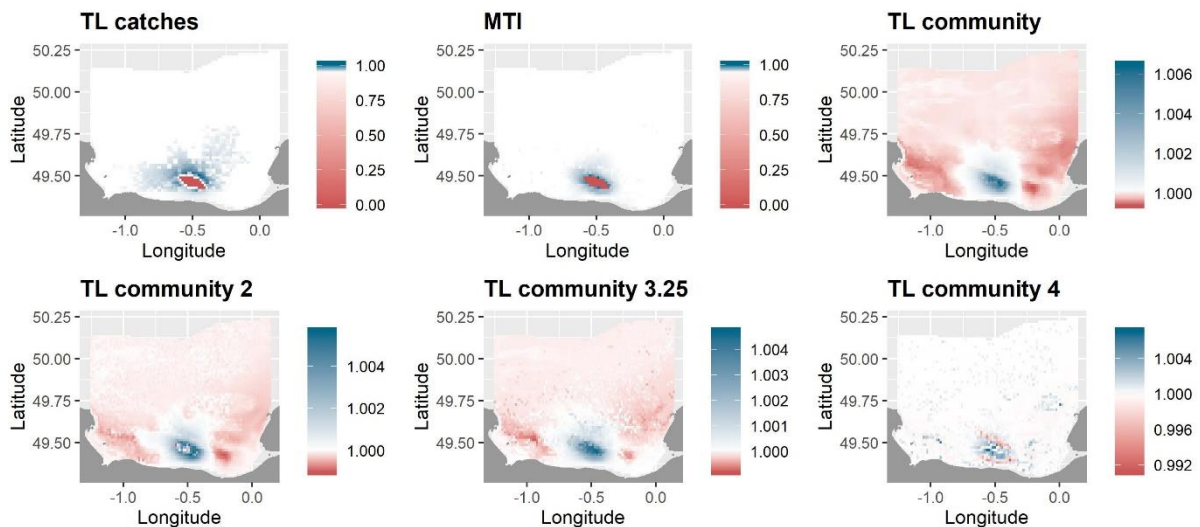
472

473 Fig. 6. The spatial relative Impact of the implementation of the offshore wind farm on
474 total catches, fish catches, invertebrates catches, demersal catches, pelagic catches
475 and total discards (blue: the value of the indicator is higher than the reference
476 scenario, red: the value of the indicator is lower than the reference scenario). The maps
477 were averaged over the period 2000 – 2015.

478

479 The Ecospace modelling of eBoS predicted very low (less than 0.01%) spatial changes
480 in the community trophic level and catch composition that resulted from the fishing ban
481 around the wind farm. However, despite the weakness of the signal to detect
482 ecosystem responses, maps of trophic indicators reveal a very clear and consistent
483 spatial pattern (Fig. 7). Indeed, both trophic level of catches and community illustrate
484 a slight increase of the proportion of higher trophic level organisms inside and
485 bordering the offshore wind farm. The decrease of TL indicators, in more remote areas,
486 confirms the hypothesis that top predators would concentrate around the wind farm
487 site, where they would maximize their feeding opportunities (Pérez-Jorge et al., 2015).
488 A further explanation may also relate to the absence of fishing inside the exclusion
489 area. Indeed, predators in sub-area 1 take advantage of the fishing ban and benefit
490 from the higher survival rate. This finding suggests that the exclusion zone inside the
491 wind farm would result in the concentration of top predators from surroundings areas
492 (Gell and Roberts, 2003). Moreover, the predicted increase in the proportion of top
493 predators concurred with the observations of Ecoutin et al. (2014) on the effects of a
494 fishing ban on fish assemblages in The Sine Saloum Delta in Senegal.

495



496

497 Fig. 7. The spatial relative impacts of the implementation of the offshore wind farm by
 498 trophic level-based indicators: Trophic Level of catches, Marine Trophic Index, Trophic
 499 Level of the community, Trophic Level of the community set at 2, Trophic Level of the
 500 community set at 3.25 and Trophic Level of the community set at 4. (blue: the value of
 501 the indicator is higher than the reference scenario, red: the value of the indicator is
 502 lower than the reference scenario).

503

504 3.3. Uncertainty and limitations of the model

505 Incorporating ecosystem considerations in the analysis of potential effects of the
 506 implementation of offshore wind farms is a relevant approach to understand ecosystem
 507 response and prevent conflict between the main users (i.e. fishing industry and marine
 508 renewable energy) (Alexander et al., 2016). Such approach requires using complex
 509 models like Ecospace in order to represent spatio-temporal dynamics of species
 510 interactions. Therefore, it is a major issue to consider uncertainties and limitations
 511 associated with this modelling approach in the interpretation of results.

512 In fact, some limitations related to both data availability and our understanding of the
 513 ecosystem occurred. For instance, the model was constructed as a “closed” system
 514 because it was not possible to simulate trophic inflows and outflows related to species
 515 migration due to lack of data. Moreover, input parameters in Ecopath, Ecosim and
 516 Ecospace models do not have the same level of uncertainty. Most of the data were
 517 obtained from the Bay of Seine (e.g. biomass, landings, fishing effort) but some
 518 parameters were obtained from adjacent ecosystems (i.e. Western English Channel or
 519 North Sea) or set by default (e.g. dispersal rates). Moreover, the large number of
 520 parameters in ecosystem models makes the sensitivity analysis a complex task to
 521 implement and requires high computational resources (Romagnoni et al., 2015; Song
 522 et al., 2017). Therefore, a simple sensitivity analysis limited to the dispersal rate
 523 parameter was performed to test the robustness of the results by functional group
 524 inside each sub-area (Appendix E). Besides the uncertainties associated with the type
 525 and source of data, there are some limitations inherent to mass-balanced models (e.g.
 526 the diet composition of consumers is fixed during the simulation period). The limitations
 527 related to model hypothesis and assumptions of Ecopath, Ecosim and Ecospace were
 528 discussed in details in Ainsworth and Walters (2015) and Christensen & Walters
 529 (2004a). More discussions about the uncertainty regarding the definition of functional

530 groups are also detailed in Essington (2007) and Plagányi & Butterworth (2004). Given
531 the different sources of uncertainty in the modelling process and the lack of rigorous
532 sensitivity analysis, the present study was based on emerging patterns to reduce the
533 uncertainty relative to the reliability of inputs and model complexity. Furthermore,
534 spatial observations were not sufficient for the majority of functional groups to perform
535 a quantitative validation. Nevertheless, the abundant samples of the King scallop
536 (*Pecten maximus*) could be used to perform a regional validation similar to the method
537 used by De Mutsert et al. (2017) to test the performance of their Ecospace model in
538 the lower Mississippi River Delta.

539 Other limitations are related to the trade-off between the spatial scale and the
540 resolution during the implementation of the Ecospace model. Indeed, although the
541 spatial resolution of Ecospace eBoS was suitable to analyze spillover effects in the
542 extended Bay of Seine, it was not relevant to simulate scenarios at a finer scale such
543 as the 20% closure scheduled by the operator of the wind farm. The spatial resolution
544 of the Ecospace eBoS (each cell $\approx 2.5 \text{ km}^2$) is too coarse to represent the species
545 habitat at the scale of the installations. Indeed, the size of each cell in Ecospace eBoS
546 grid ($0.015^\circ \times 0.015^\circ$) is not fine enough to analyze both the “reef effect” which may
547 be important at local scale and the “spillover effect” which operates at larger scale. In
548 order to overcome this limitation, coupling a 3D hydrodynamic-biogeochemical model
549 to a Dynamic Energy Budget (DEB) model may help to evaluate the impact of wind
550 turbine structure on benthic species (e.g. mussels) at a small scale (Maar et al., 2009).
551 The predictions of this high-resolution model could be then integrated into Ecospace
552 as a forcing function.

553 Given the model structure, this study focuses on the operational phase of an offshore
554 wind farm rather than the whole cycle (prospecting, installation and decommissioning).
555 Therefore, some long-lasting impacts which may have cascading effects on the food
556 web were not included. Furthermore, it is important to interpret the predictions for
557 marine mammals and seabirds carefully since the model do not consider all the drivers
558 which could affect their distribution (e.g. risk of collisions with rotor blades, migration
559 barriers, low frequency noise from operating turbines).

560 4. Conclusions

561 This study represents a first attempt to provide insight into potential impacts of the
562 deployment of an offshore wind farm in the French waters with a special focus on the
563 spillover effect from a spatial closure of the wind farm to fishing activities. The
564 implementation of the Ecospace model allowed investigating ecosystem
565 consequences of turning the offshore wind farm site into a Marine Protected Area.
566 Although, the closure area is scheduled to cover around 20% of the site, the objective
567 of this simulation is to evaluate how a more extended total closure could affect fishing
568 activities and the main components of the ecosystem. Such an analysis could then be
569 useful for spatial planning decision makers about new offshore wind farms.

570 The findings of this study suggest that the spillover effects could mitigate the negative
571 impact on fishing activities because of 1/ an increase of catches (up to 7% close to the
572 wind farm) and 2/ a slight modification in the composition of catches leading to an
573 increase in the proportion of high trophic level species. However, the influence of
574 spillover effects is limited in space and the expected positive effects are highly localized
575 in areas around the offshore wind farm site. The analysis of the spillover effects at the
576 scale of the Bay of Seine suggested a spatial pattern, which shows that the exclusion

577 zone could play the role of a “Fish Aggregating Device” by attracting predators from
578 surrounding areas. Despite the limitations inherited from the underlying Ecopath with
579 Ecosim models and input data used in the parameterization of the Ecospace eBoS,
580 this study serves as a tool of a more holistic approach to address questions regarding
581 the potential effects of the implementation of offshore wind farms. This approach could
582 be used with complementary studies on benthos, marine mammals and seabirds to
583 address potential compatibility and synergies between fishing activities, marine
584 conservation and marine renewable energy and provide a baseline for an assessment
585 tool for Ecosystem Based Management decisions in the Bay of Seine.

586

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