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

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

1. Introduction

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

In this context, the French government has planned the construction of three OWFs in the eastern basin of the English Channel along the Normandy coast (Courseulles-sur-Mer, Fécamp and Dieppe-Le Tréport). As in most other European countries, these future OWFs are subjected to environmental impact assessment and monitoring studies to investigate the impacts of these new structures on ecosystems (Wilding et al., 2017). However, OWF impact assessment and monitoring protocols are still under development and several studies have pointed out significant shortcomings (Lindeboom et al., 2011; Wilding et al., 2017; Pezy et al., 2018). For instance, although the call for holistic approaches and Ecosystem-Based Management (EBM) of marine ecosystems is well-established, attention has tended to focus on some iconic species because of their protection status or public acclaim (Wilding et al., 2017). Thus, the OWF impacts on the whole ecosystem remain insufficiently known and these studies could fail to detect serious impacts on the ecosystem (Bailey et al., 2014; Pezy et al., 2018). In accordance with EBM and environmental legislation requirements, Raoux et al. (2017, 2019) highlighted the need to adopt a holistic approach to the impact of OWF on ecosystem functioning with trophic web modelling tools as a complementary approach to the traditional impact assessments. Such trophic web models have been applied to provide global system indicators reflecting the structure and functioning of ecosystems. In addition, they can provide information on the overall ecosystem status and could be used as a baseline for EBM decisions (Raoux et al., 2019, 2017; Safi et al., 2019).

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

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

2. Material and Methods

2.1. The study area

The extended Bay of Seine (eBoS) is a shallow coastal ecosystem located on the northwestern French coast and opening onto the Eastern English Channel to the limit of the French Exclusive Economic Zone (Fig. 1). The eBoS covers approximately 13500 km^2 and it is generally composed of soft sediment (i.e. coarse sands, fine sands and muddy fine sands) (Dauvin, 2015). The mean depth of the study area is about 35 m with a maximum tidal amplitude up to 7.5 m height near the mouth of the Seine estuary. The intertidal zone and the shallowest subtidal zone (i.e. 0 – 5 m depth) was not considered given the specificity of its ecological functioning. In its eastern south part, the eBoS receives the Seine river which is highly loaded with nutrients (Guillaud et al., 2000). Furthermore, the eBoS constitutes an important nursery, feeding, and breeding ground for several marine species (Rochette et al., 2010).

The Bay of Seine concentrates high fishing effort and is one of the main King scallop (*Pecten maximus*) producing areas in France. Commercial fisheries operating in the eBoS area are diversified and include several métiers. The main fleets and gears considered in this study are nets targeting demersal fish, pelagic and bottom trawls targeting small pelagic fish, bottom trawls targeting demersal fish and cephalopods, pelagic trawls targeting demersal fish, dredge targeting king scallop and other fishing gears (Carpentier et al., 2009).

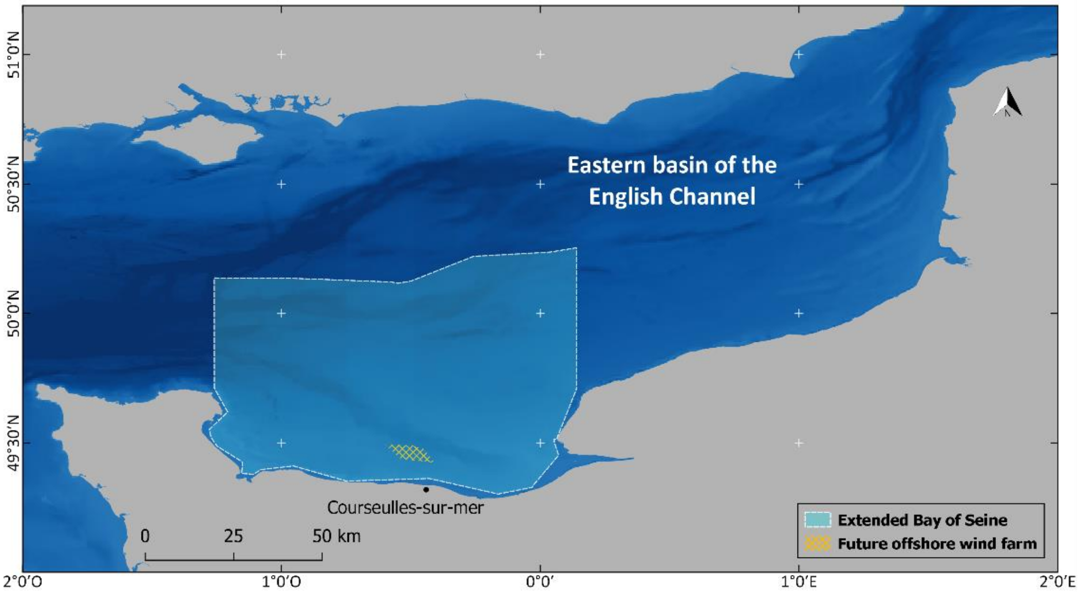

Fig. 1. Map of the study area “extended Bay of Seine” (eBoS) and the location of the future Courseulles-sur-Mer offshore wind farm.

2.2. Model development

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

2.2.1. Ecopath model

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

$$Production = Catch + Predation + Biomass\ accumulation + Net\ migration + Other\ mortality$$

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

$$Consumption = Production + Respiration + Unassimilated\ food$$

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

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

2.2.2. Ecosim model

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

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

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

$$Q_{ij} = \frac{a_{ij} v_{ij} B_i B_j}{2v_{ij} + a_{ij} B_j}$$

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

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

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	• 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)		• 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 ($t.km^{-2}$)		• King scallop	Stock assessment data from COMOR campaign report (Foucher, 2013)	Relative biomass
		• 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)	
		• Fish rays • Fish atlantic horse mackerel		Forcing biomass
Fishing mortality		• Fish european plaice • Fish rays • Fish atlantic cod		Fishing mortality
Primary production ($t.km^{-2}$)	2000 - 2010	• 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)	

2.2.3. Ecospace model

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

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

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

In Ecospace eBoS, the species distribution is driven by the environmental preference function to bathymetry for fish, cephalopods, dolphins and benthic feeders seabirds (estimated from CGFS occurrence data) (Appendix C.2) and the habitat foraging usage for benthic species (Appendix C.3). A fraction of the biomass of each functional group moves into adjacent cells according to random walk movements. This movement is governed by the dispersal rate parameter, which represents the ability of functional groups to move within the base map. The values of dispersal rates recommended by Christensen et al. (2008) were applied for the majority of the functional groups, which are of three magnitudes (i.e. 300 km.year^{-1} for pelagic species, 30 km.year^{-1} for demersal species, and 3 km.year^{-1} for non-dispersing species). These values were adjusted manually for some functional groups during the validation of Ecospace (e.g the dispersal rate of marine mammals and birds is equal to 500 km.year^{-1} (Appendix C.1). When an organism moves to an "unsuitable" (non-assigned) habitat, the values of the basic dispersal rate were multiplied by a factor ranging from 1 to 3 (Appendix C.1). Concerning the relative vulnerability to predation, for benthic groups (e.g. suprabenthos, benthic invertebrate filter feeders, and benthic invertebrate predators), due to their low mobility, their relative vulnerabilities are three times higher in unsuitable habitats. All the other groups are twice more vulnerable to predation in unsuitable habitat, and they are less likely to consume and find appropriate food (Christensen et al., 2008) (Appendix C.1).

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

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

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

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

2.3. Offshore wind farm simulations

The future wind farm composed of 64 turbines will be located 10 – 16 km offshore from Courseulles-sur-Mer (Fig. 1). During the exploitation phase of turbines, around 20% of the installation area is scheduled to be closed to all fishing activities (EDF personal communication). In the present study, two simulations were run for a period of 15 years to assess the Marine Protected Area (MPA) effect through the evaluation of "what if scenarios". A reference scenario, which corresponds to the observed ecosystem for the period 2000 – 2015 with no changes and an "exclusion" scenario in which a MPA is assigned to the offshore wind farm area (≈ 70 km^2). The scenario corresponding to a closure of 20% of the wind farm area was not presented in this article because the resolution is not fine enough to detect any changes.
Several biomass, catch and trophic level-based indicators were calculated to quantify the impact of the installation of the wind farm (e.g. biomass, catches and discards of exploited groups, Marine Trophic Index (MTI) defined as the mean trophic level (TL) of fisheries landings of species with trophic levels > 3.25, trophic level of catches, trophic level of the community at two different cut-offs (3.25 and 4) corresponding the lowest TL values used in the computation of the indicator (it considers all organisms above $^{\text{cut-off}}$ TL). In order to investigate the potential spillover effects from the exclusion area,

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

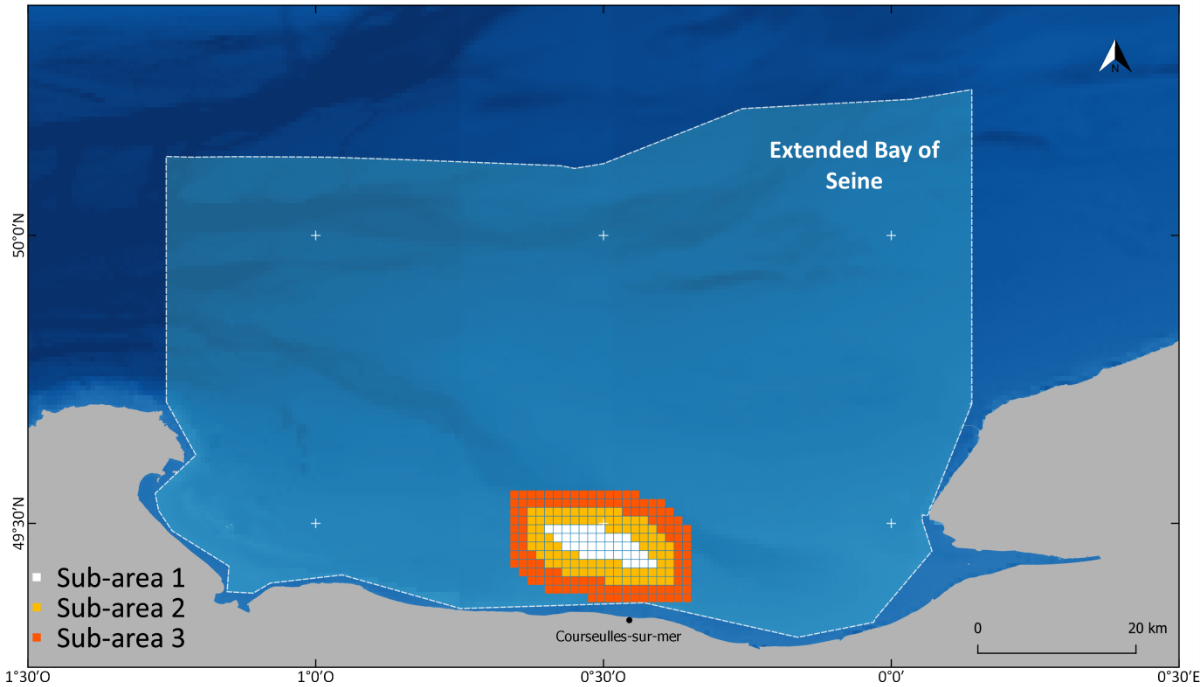

Fig. 2. Map of sub-areas of interest inside the study area of eBoS Ecospace model. Sub-area 1 (white) corresponds to the location of the future offshore wind farm of Courseulles-sur-Mer (CSM).

3. Results and discussion

3.1. Reference scenario

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

Most of the functional groups and especially demersal species (details of grouping are given in Appendix A.0) display a clear coast-offshore gradient since their distributions are driven by the bathymetry (e.g. fish plaice, fish rays, fish whiting). The observed gradient could also be explained by the fact that estuarine habitats of the eBoS represent an important nursery area during the autumn for juvenile marine fishes (e.g. the common dab (*Limanda limanda*), the European seabass (*Dicentrarchus labrax*), the Whiting (*Merlangius merlangus*), and the Surmullet (*Mullus surmuletus*) (Le Pape et al., 2007). In contrast, the distribution of sedentary benthic invertebrates (e.g. benthic inv. bivalve's filter feeders, benthic inv. predators, benthic inv. deposit feeders (surface)) is mainly driven by the type of sediment.

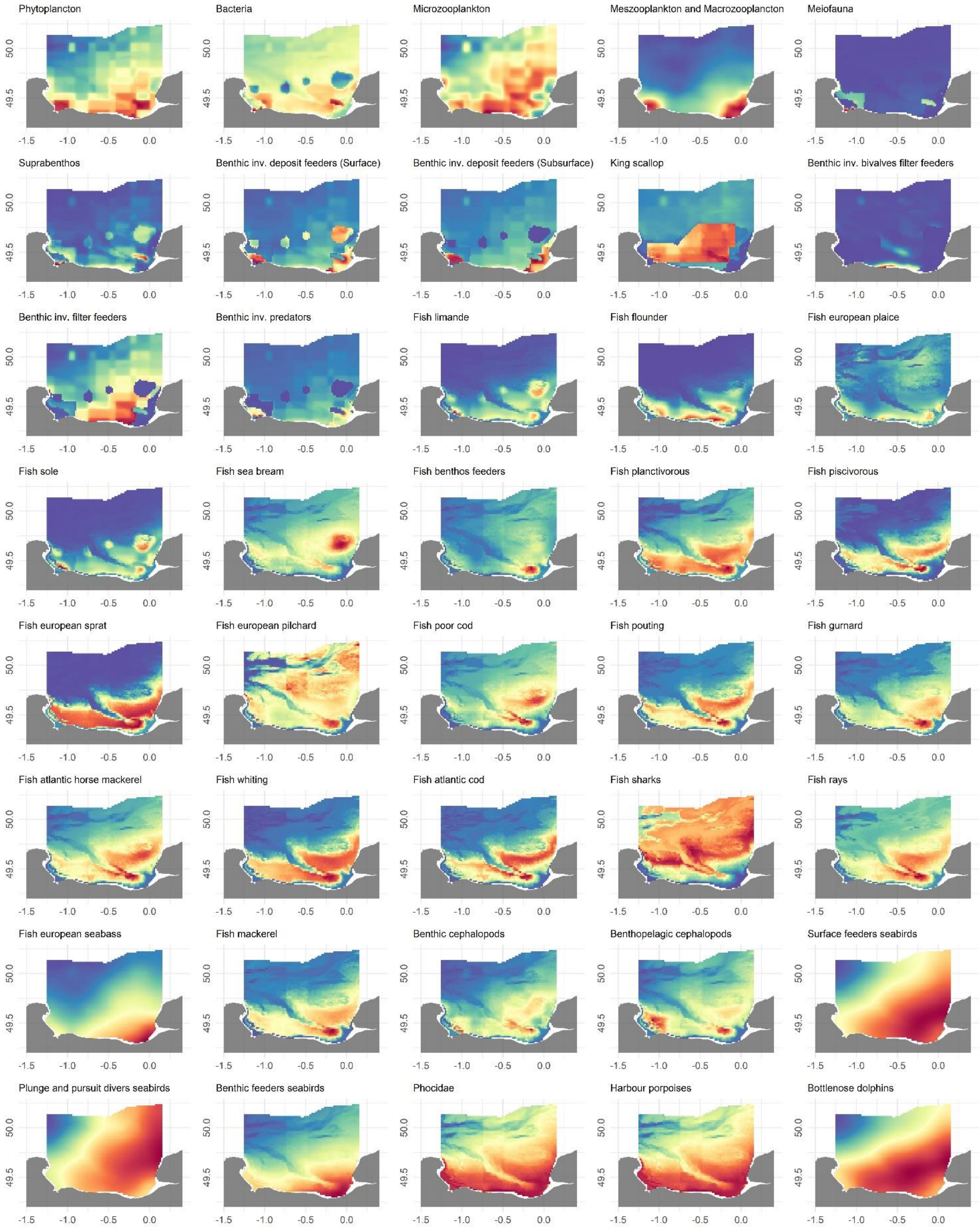

Fig. 3. Biomass distribution of 40 functional groups predicted by Ecospace eBoS under the reference scenario representing the mean state of the Bay of Seine ecosystem during the period 2000 – 2015, (red: high biomass, blue: low biomass).

3.2. Analysis of the spillover effects

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

It is likely that the increase of catches does not balance the decline of total landings following the closure of sub-area 1 to fishing activities. However, the shortfall in catches could be mitigated by the predicted change of catch composition. Indeed, the slight increase of the trophic level of catches and the Marine Trophic Index in the areas surrounding the wind farm indicates an increase in the proportion of high trophic level species in the catch composition, which generally have high economic value (e.g. European seabass, benthic cephalopods, and Atlantic cod). For the trophic level of the community at thresholds 3.25 and 4, the predicted increase in sub-areas 1 and 2 is attributed to an increase of the proportion of top predators. This result highlights that high trophic level species (TL>3.25) could benefit from the installation of the offshore wind farm and the resulting fishing ban in sub-area 1. Higher trophic level species also benefit in sub-areas 2 and 3 even despite the increase of fishing mortality.

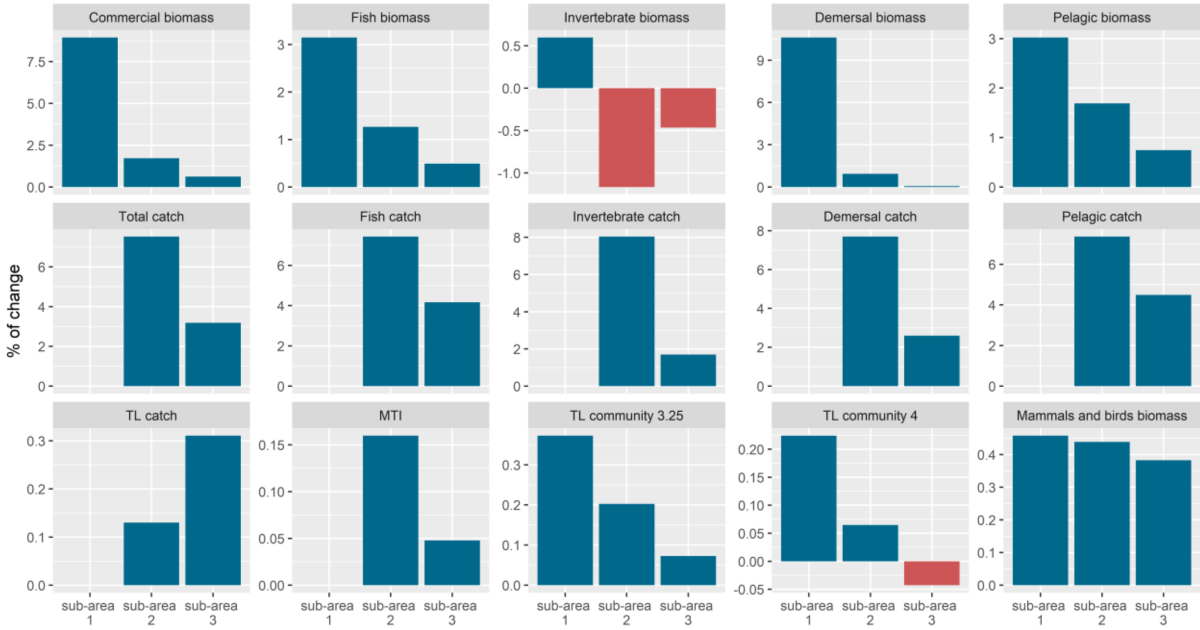

Fig. 4. The percentage of change represents the comparison of the averaged outputs over 15 years of the offshore wind farm scenario with the reference scenario inside each sub-area (sub-area 1: inside the MPA area, sub-area 2: a first area 3.2 km wide around sub-area 1, sub-area 3: a second area 3.2 km wide around sub-area 2) and by ecological indicator.

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

The model displayed certain spatial patterns in the distribution of the spillover effects over the Bay of Seine (Fig. 5). This is illustrated by the presence of three well defined sub-areas: a first zone adjacent to the offshore wind farm with positive spillover effects (increase of biomass), a second zone bordering the first one with no spillover effects (no change in biomass) and a third zone afterwards with a decrease of biomass). This pattern could be interpreted as being a result of species movement toward more suitable habitats through the net emigration of fish as proposed by Rowley (1994) and the redistribution of the fishing effort over the study area. In fact, the increase of the predicted biomass, in the sub-area 2, could be explained by local movements of functional groups, which tend to spend more time in areas where the conditions are more suitable for two main reasons: 1) the offshore wind farm plays the role of a Marine Protected Area (MPA) after the closure of fishing activities. Hence, the exploited species could benefit from the absence of fishing mortality, and 2) the offshore wind farm and surrounding areas offer more feeding opportunity for all predators given the spillover effects. Therefore, it is very likely that the predicted increase of biomass in sub-areas 1, 2 and 3 is due to the spillover effects and species movements. For invertebrates, the decrease of their biomass only occurs around the no-take area because of a higher fishing pressure on King Scallop, which has a high abundance localized around the future wind farm. Furthermore, the patterns observed in figure 5 show that for less mobile species such as invertebrates the impact of spillover (increase of biomass around the no-take) area is very limited in contrast to more mobile groups (e.g. marine mammals and pelagic fish) for which the effect of the spillover could cover a larger area.

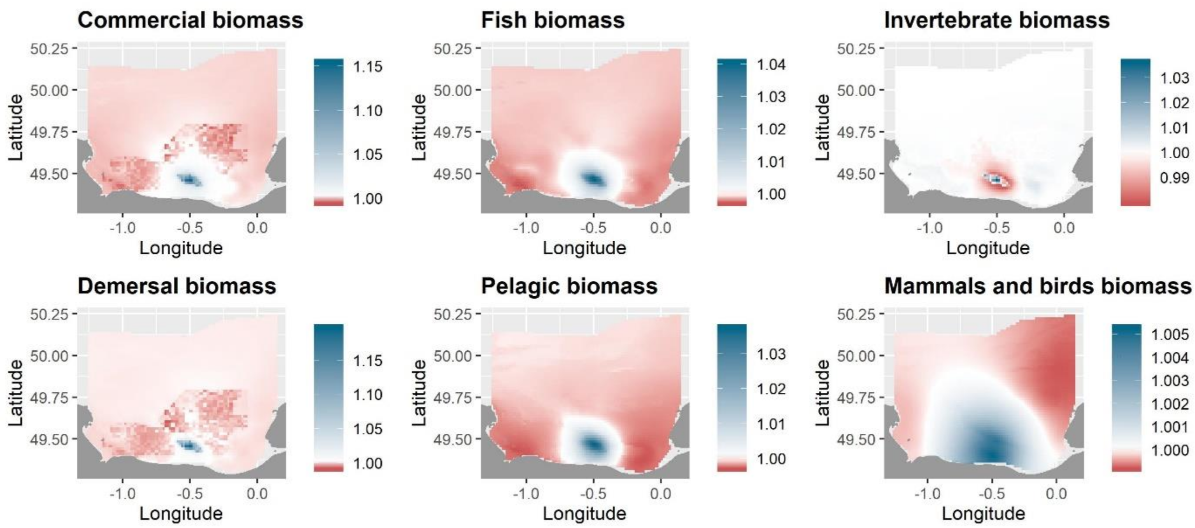

Fig. 5. The spatial relative impact of the implementation of the offshore wind farm on the biomass of commercial species, invertebrates, demersal species, pelagic species, marine mammals and birds (blue: the value of the indicator is higher than the reference scenario, red: the value of the indicator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

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

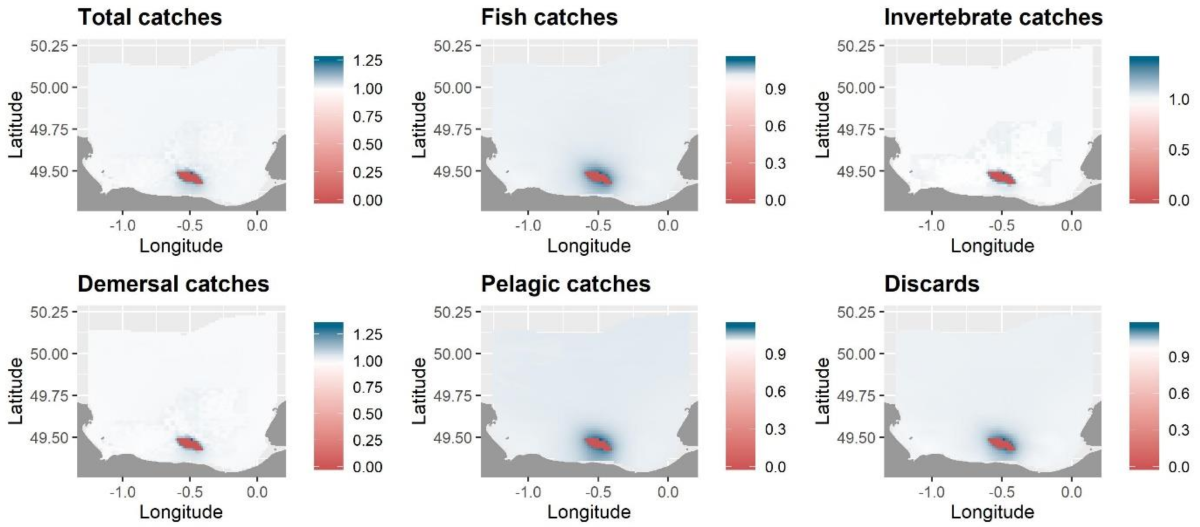

Fig. 6. The spatial relative Impact of the implementation of the offshore wind farm on total catches, fish catches, invertebrates catches, demersal catches, pelagic catches and total discards (blue: the value of the indicator is higher than the reference scenario, red: the value of the indicator is lower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

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

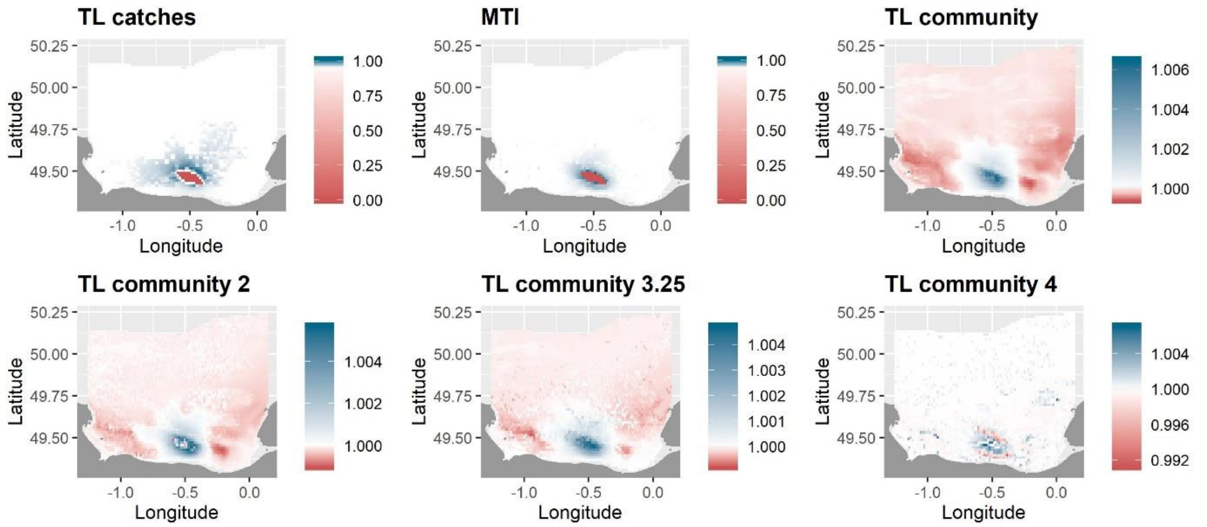

Fig. 7. The spatial relative impacts of the implementation of the offshore wind farm by trophic level-based indicators: Trophic Level of catches, Marine Trophic Index, Trophic Level of the community, Trophic Level of the community set at 2, Trophic Level of the community set at 3.25 and Trophic Level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

3.3. Uncertainty and limitations of the model

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

In fact, some limitations related to both data availability and our understanding of the ecosystem occurred. For instance, the model was constructed as a “closed” system because it was not possible to simulate trophic inflows and outflows related to species migration due to lack of data. Moreover, input parameters in Ecopath, Ecosim and Ecospace models do not have the same level of uncertainty. Most of the data were obtained from the Bay of Seine (e.g. biomass, landings, fishing effort) but some parameters were obtained from adjacent ecosystems (i.e. Western English Channel or North Sea) or set by default (e.g. dispersal rates). Moreover, the large number of parameters in ecosystem models makes the sensitivity analysis a complex task to implement and requires high computational resources (Romagnoni et al., 2015; Song et al., 2017). Therefore, a simple sensitivity analysis limited to the dispersal rate parameter was performed to test the robustness of the results by functional group inside each sub-area (Appendix E). Besides the uncertainties associated with the type and source of data, there are some limitations inherent to mass-balanced models (e.g. the diet composition of consumers is fixed during the simulation period). The limitations related to model hypothesis and assumptions of Ecopath, Ecosim and Ecospace were discussed in details in Ainsworth and Walters (2015) and Christensen & Walters (2004a). More discussions about the uncertainty regarding the definition of functional groups are also detailed in Essington (2007) and Plagányi & Butterworth (2004). Given the different sources of uncertainty in the modelling process and the lack of rigorous sensitivity analysis, the present study was based on emerging patterns to reduce the uncertainty relative to the reliability of inputs and model complexity. Furthermore, spatial observations were not sufficient for the majority of functional groups to perform a quantitative validation. Nevertheless, the abundant samples of the King scallop (*Pecten maximus*) could be used to perform a regional validation similar to the method used by De Mutsert et al. (2017) to test the performance of their Ecospace model in the lower Mississippi River Delta.

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

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

4. Conclusions

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

The findings of this study suggest that the spillover effects could mitigate the negative impact on fishing activities because of 1/ an increase of catches (up to 7% close to the wind farm) and 2/ a slight modification in the composition of catches leading to an increase in the proportion of high trophic level species. However, the influence of spillover effects is limited in space and the expected positive effects are highly localized in areas around the offshore wind farm site. The analysis of the spillover effects at the scale of the Bay of Seine suggested a spatial pattern, which shows that the exclusion zone could play the role of a "Fish Aggregating Device" by attracting predators from surrounding areas. Despite the limitations inherited from the underlying Ecopath with Ecosim models and input data used in the parameterization of the Ecospace eBoS, this study serves as a tool of a more holistic approach to address questions regarding the potential effects of the implementation of offshore wind farms. This approach could be used with complementary studies on benthos, marine mammals and seabirds to address potential compatibility and synergies between fishing activities, marine conservation and marine renewable energy and provide a baseline for an assessment tool for Ecosystem Based Management decisions in the Bay of Seine.

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