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Original Article

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An ecosystem modelling approach to assess potential impacts of offshore wind farms

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Abstract

Offshore wind energy is in great expansion around the world. Considerable gaps in scientific knowledge on ecological impacts of offshore wind farms (OWFs), including the lack of standardized operational tools to conduct cumulative impact assessment, could lead to delays in the consent process. Ecosystem models are useful tools for cumulative impact assessments because they consider various ecosystem components and their interactions, and therefore are able to provide integrative evaluations. In this study, we improved an existing individual-based ecosystem model (OSMOSE), aiming to assess the cumulative effects of OWFs on various biological groups and fishing activities in the Eastern English Channel (EEC). This work presents substantial technical developments on the existing OSMOSE model application, enhancing its capability to evaluate OWF effects. Technical model improvements included new species, a better representation of the fishing process, prey field forcing updates to include climate change projections, and inter-annual calibration over the period 2002–2021. These developments were essential for improving the depiction of OWFs cumulative impacts, encompassing effects from underwater noise emission, sediment resuspension, and fishing access restriction. We simulated the EEC ecosystem during construction and operational phases under a factorial plan combining OWFs deployment and fishing regulation scenarios. At the scale of the entire EEC ecosystem, total fish biomass and catch were slightly reduced under all scenarios. The most significant biomass declines were observed for cuttlefish, herring, and red mullet, primarily driven by changes in predation and fishing pressure, especially during the construction phase. However, at the local scale (model grid resolution), these changes appear to be OWF-specific, as no consistent spatial patterns in fish biomass were observed across OWFs deployment sites. The differences among scenarios suggest a trade-off between energy production, fishery resource exploitation, and environmental protection goals. The most probable OWF spatial deployment scenario that balanced on regulatory and socio-economic considerations also represented a balance of ecological factors.

Keywords: individual-based model; ecosystem model; offshore wind farm; cumulative impact assessment; scenario; Eastern English Channel

Introduction

One of the future major renewable energy supplies, offshore wind energy, has seen consistent growth in its capacity (Williams and Feng 2024). In Europe, the objectives are fixed at 60 GW by 2030 and 300 GW by 2050, representing 25% of the continent's electricity production (European Commission 2020). In France, the government has fixed an objective of 18GW by 2035 and 45GW by 2050, with the current capacity being 2GW (Ministère chargé de la Mer et de la Pêche 2024). Technical advances are allowing massive upscaling of this form of renewable energy. However, larger areas of development with more and bigger turbines increase the potential environmental risk and therefore significantly delay this expansion (Bailey et al. 2014, Salvador et al. 2018). As a result, assessing the environmental impact of offshore wind farms (OWFs) is becoming increasingly important. Willsteed et al. (2018) pointed out that current assessments cannot meet the needs of decision-making. Major problems among current assessments include, *inter alia*, unclear temporal extent of pressures, difficulties in pressures identification, lack of cumulative effects analysis and lack of uncertainty analysis.

OWFs interact with marine ecosystems throughout their lifecycle, from development, to construction, operation and decommissioning. Potential pressure sources include noise emission (Mooney et al. 2020), electromagnetic emission (Taormina et al. 2018, Hermans et al. 2024), hydrodynamic condition modification (Daewel et al. 2022), and benthic habitat modification (Buyse et al. 2023, 2022). These pressures could directly impact several biological groups including planktons (Daewel et al. 2022), invertebrates (Cones et al. 2022, Jézéquel et al. 2022, Solé et al. 2023), and fish (Mooney et al. 2020). Moreover, these impacts propagate in the ecosystem through trophic interactions (Halouani et al. 2020, Püts et al. 2023).

In addition, OWFs could interact with other marine uses such as shipping, offshore aquaculture or fishing activities. Measures of co-existence between OWFs, fishing and other uses have been discussed for the North Sea (Austrheim et al. 2022). Given the diversity and complexity of these effects and their interactions, it is essential to consider the cumulative effects of OWFs within a unified framework.

Ecosystem-based management (EBM) has emerged as a response to the limitations of single-species management, particularly its inability to account for species interactions and integrative system-level evaluations (Hilborn 2011). It has gained increasing prominence in assessing human impacts and informing management decisions, particularly in global fisheries contexts (Safi et al. 2019, Fulton et al. 2019). Unlike traditional single-focus strategies, EBM allows for the integration of multiple pressure sources and supports the balancing of ecological, economic, and social objectives (Fulton et al. 2014). Ecosystem models are essential tools within the EBM framework (Plagányi 2007). By integrating multiple ecosystem components and their interactions into a single modelling platform (Geary et al. 2020), these models can generate outputs that inform ecological, socio-economic, and socio-cultural evaluations of management scenarios (Willis-Norton et al. 2024). Among ecosystem models, the mass balance model EwE (Ecopath, Ecosim and Ecospace; Christensen and Walters 2004) is one of the most applied ones regarding the impact assessment of human activities. Several studies have explored no-fishing zone effects (Halouani et al. 2020, Püts et al. 2023), artificial reef and aggregation effects (Raoux et al. 2019, 2017), as well as behaviour changes due to the presence of artificial structures and acoustic disturbance (Serpetti et al. 2021).

In previous studied mentioned above, the response of biological groups to OWFs is directly defined at population level, due to the limited individual-level biological processes in EwE. Moreover, the lack of age and size structure in EwE could limit scenario design and indicator output. To overcome these limitations, we chose an individual-based model (IBM)—OSMOSE (Object-oriented Simulator of Marine ecOSystEms; Shin and Cury 2004, 2001). As in other IBMs (Jørgensen and Fath 2011), fish agents in OSMOSE exhibit variability across individuals and life stages, reflecting differences in size, age, and behaviour. Higher-level properties (at the population, community, and ecosystem scales) emerge from individual-level interactions and their dynamic responses to the environment (Shin and Cury 2004, 2001). Such individual-level resolution enables the simulation of behavioural responses to OWFs, including attraction, avoidance, and altered spatial distribution. To apply these features in a real-world context, we improved an existing Eastern English Channel configuration of OSMOSE (OSMOSE-EEC, Travers-Trolet et al. 2019) and applied it to assess the cumulative ecological impacts of OWFs.

First, we updated the OSMOSE-EEC model using biomass, yield and catch-at-length data between 2002 and 2021. A temporal dimension was integrated into the model to include the effects during the construction phase and the operational phase of OWFs. We also improved the representation of fishing to accommodate the effects of OWF implementation. We then simulated the EEC ecosystem through 2050 under different cumulative effect scenarios, based on a factorial plan, and finally analysed the impact of OWFs using ecological indicators. The results were also compared to the results in previous studies based on the EwE model.

Materials and methods

Study area

The Eastern English Channel (EEC, ICES Division 27.7d) is a shallow sea delineated by latitudes 49.3°N and 51°N and longitudes 2°W and 2°E. It is subject to intense and diversified human activities such as fishing, maritime traffic, and mineral extraction (Martin et al. 2009). This area also has multiple OWFs projects ongoing and upcoming (Fig. 1). By 2050, a capacity of 12–15.5 GW of offshore wind energy will be installed in the French exclusive economic zone of the EEC and the North Sea (Ministère chargé de la Mer et de la Pêche 2024).

OSMOSE model

OSMOSE is a multi-species and IBM that focuses on fish (https://osmose-model.org/). The principal hypothesis of the model, opportunistic predation, relies on the size adequacy and the spatial co-occurrence between a predator and its prey. An agent in the OSMOSE model corresponds to a fish school. Each fish school has its own properties, such as abundance, size, weight, trophic level, and geographic location. OSMOSE is dynamic and spatially explicit. Each time step implements several processes: growth, mortality (including explicit predation, starvation, fishing), reproduction, and movement (Shin and Cury 2004, 2001).

At the beginning of each time step, fish schools are distributed across a 2D spatial grid. They may move to adjacent cells in a random direction, while remaining within the boundaries of their predefined distribution range. This range is specified through input presence/absence maps that define the spatial domain accessible to each species. These maps can be stratified by life stage and/or season, thereby accounting for ontogenetic and temporal variability in spatial distribution.

The opportunistic predation is based on spatio-temporal co-occurrence and size adequacy between predator and prey. A fish school can predate either on another fish school or a prey field group that is within the predation size range. The size range is defined by the size of predator, and maximal and minimal predation size ratios. The spatial co-occurrence is determined by the location of fish schools in the 2D map, as well as the accessibility coefficient that represents the vertical position in the water column of each species.

Growth depends on the food effectively consumed by a predator compared to the food requirement for maintenance. If predation achieves the threshold of maintenance, fish grow more or less (depending on predation success) following the von Bertalanffy growth model.

Next, various sources of mortality are applied to fish schools in a random order. Predation mortality is applied to the prey fish school, according to the opportunistic predation described above. Starvation mortality is applied when predation efficiency is smaller than the maintenance threshold. Fishing mortality is implemented by fishing fleets and is detailed in the next section. Mortalities due to other sources are implemented by an additional mortality rate.

Finally, for the reproduction process, sexually mature fish release eggs that produce new fish schools in the system. The number of new fish depends on the relative fecundity, the spawning seasonality and the spawning biomass.

There are different sources of stochasticity in the model: the order at which schools interact, the randomization of different sources of mortality (predation, starvation, fishing, other natural mortality) and the random movement of fish within their habitats.

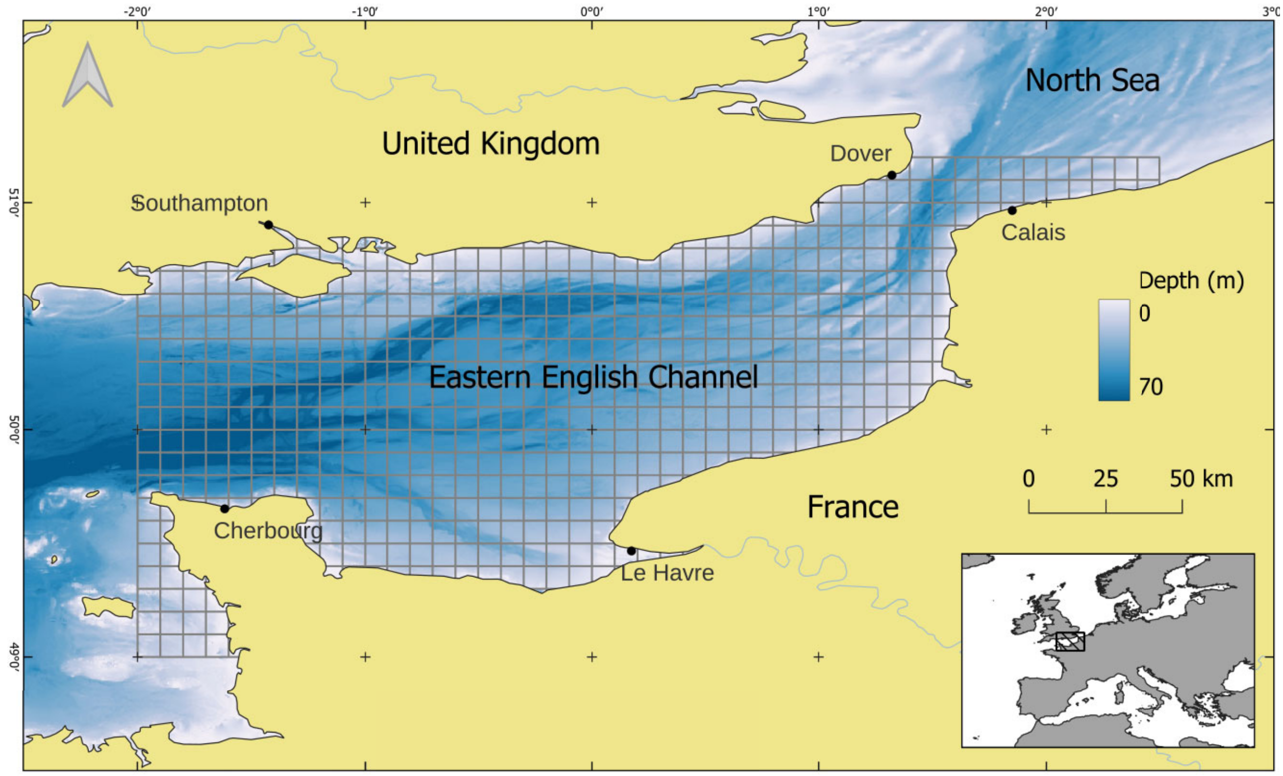


Figure 1. The study area—Eastern English Channel with the OSMOSE-EEC grid (0.1° × 0.1° cells) and bathymetry.

Fishing in OSMOSE

In OSMOSE, fishing could be implemented by either fishing mortalities by species, as was done in the previous study (Travers-Trolet et al. 2019), or, thanks to recent developments, by fishing fleets. In this study, we have chosen the latter to accommodate OWFs fishing regulation scenarios.

Fishing mortality for species caught by each fleet, with size selectivity ($F_{\text{fleet, sp, L}}$) is the product of five components: $S_{\text{fleet, L}}$, Q_{fleet}, $Q_{\text{fleet, sp}}$, $E_{\text{fleet, period}}$, and $E_{\text{fleet, season}}$.

$$F_{\text{fleet,sp,L,}} = S_{\text{fleet,L}} * Q_{\text{fleet}} * Q_{\text{fleet,sp}} * E_{\text{fleet,period}} * E_{\text{fleet,season}}$$

$S_{\text{fleet, L}}$ is the size selectivity of a fleet. Q_{fleet} represents the overall catchability of a fleet. $Q_{\text{fleet, sp}}$ is the catchability of each fleet for each species. $E_{\text{fleet, period}}$ represents the long term (typically interannual) temporal variability of fishing effort. $E_{\text{fleet, period}}$ is a vector, with each value representing a multiplier for one fishing period, typically a year. The number of fishing periods per year is defined by the user. $E_{\text{fleet, season}}$ is the seasonal variability of fishing effort within one fishing period. $E_{\text{fleet, season}}$ should be a vector, its length should be the number of time steps within one fishing period.

In this study, sigmoid and Gaussian size-selectivities were used, defined as follows:

Sigmoid selectivity:

$$S(L) = \frac{1}{1 + e^{S_1 - S_2 * L}}$$

where $S_1 = \frac{L_{50} * ln3}{L_{75} - L_{50}}$ and $S_2 = \frac{S_1}{L_{50}}$

Gaussian selectivity:

$$S(L) = \frac{F(L)}{F(L_{50})}$$

where $F(L) = e^{\frac{-(L-L_{50})}{2\sigma^2}}$ and $\sigma = \frac{L_{75} - L_{50}}{q_{75}}$

L is the average length of the fish of a school, S(L) is the selectivity as a function of length, L_{50} and L_{75} are the length at 50th and 75th percentile, and q_{75} is the inverse cumulative standard normal distribution for the 75th percentile.

Last, a proportion of catch will be discarded, splitting the yield into landings and discards. The proportion of a species catch discarded by fishery is provided as a parameter.

Application to the Eastern English Channel

This work includes an update of the OSMOSE configuration for the Eastern English Channel ecosystem (OSMOSE-EEC, Fig. 1) initially developed by Travers-Trolet et al. (2019). Here, we used version 4.4.0.9004 of OSMOSE.

Several improvements were implemented in OSMOSE-EEC, facilitating ecosystem impact assessment of OWFs. These improvements are related to: (1) addition of new species, (2) prey field forcings, (3) representation of fishing fleets, (4) estimation of the initial state for developing a hindcast model, and (5) inter-annual calibration of the model.

Addition of new species and update of biological parameters

On top of the focal species in the version of Travers-Trolet et al. (2019) and in the version of Bourdaud et al. (2025), we added thornback ray (*Raja clavata*) to the model. This species has seen increasing biomass and catch in recent years. There is currently a need for quota refining of this species in the English Channel. Parameters of the species that existed in the previous versions (Bourdaud et al. 2025, Travers-Trolet et al. 2019) were mostly conserved. Parameters of thornback ray were obtained from various sources. List of 16 focal species, the values

Table 1. Main characteristics of fishing fleets in OSMOSE-EEC.

Fleet name	Q_{fleet} (y^{-1})	Selectivity type	L_{50} (cm)	L_{75} (cm)	Target species
French bottom trawlers	0.19	sigmoid	18	21.5	Lesser spotted dogfish, red mullet, pouting, whiting, cod, sole, plaice, horse mackerel, mackerel, squids, cuttlefish, thornback ray
French mid-water trawlers	0.75	sigmoid	18	22	Horse mackerel, mackerel, herring, sardine
French netters	0.09	gaussian	29	33	Lesser spotted dogfish, cod, sole, plaice
Others (including other French vessels and all vessels from other countries)	0.06	sigmoid	18.5	22	All species but poor cod and dragonet

F_{base} represents average fishing effort over the simulation period. Selectivity type defines the shape of the size selectivity curve. L_{50} and L_{75} are parameters of the selectivity curve. Other parameters can be found in the supplementary material (Table S4, S6, and S7).

and sources of key biological parameters can be found in the supplementary material (Table S1, S2).

Prey field groups forcing

The prey field is composed of 11 groups. A biogeochemical model coupled to a physical model, POLCOMS-ERSEM, provides biomass projections of the five pelagic prey field groups (diatoms, micro-phytoplankton, heterotrophic flagellates, micro-zooplankton, meso-zooplankton) and three benthic groups (suspension feeders, deposit feeders, and meiobenthos) under the RCP8.5 IPCC scenario, incorporating the impact of climate change (Holt et al. 2001, Giorgetta et al. 2013, Butenschön et al. 2016; Fig. S5). One pelagic group (macrozooplankton) and two benthic groups (large benthos of 5–10 cm and very large benthos of 10–15 cm) were kept as homogeneous prey fields in space and time as in the previous version, due to the absence of data. The parameters of prey field groups are based on other OSMOSE configurations (Travers-Trolet et al. 2019, Morell et al. 2023; Table S3).

Fishing fleets

Here, we have refined the fishing representation to allow for different fishing regulation scenarios inside OWFs, such as fishing closure for vessels that practice active fishing gears.

We decided to separate only the French vessels into different fleets because of the data availability. Among the French vessels, the main gears that target focal species of OSMOSE-EEC during 2002–2021 are bottom trawls, mid-water trawls, and nets. The rest of the French vessels that practiced other gears, along with vessels from other countries, were grouped into one fleet. We therefore defined the following four fishing fleets: French bottom trawlers, French mid-water trawlers, French netters, and others.

Since fishing fleets are highly aggregated, the temporal variabilities are simplified. Only annual variabilities were considered, and seasonal variabilities were ignored. Fishing period was defined as one period per year, and $E_{fleet, season}$ was constant throughout the year. For the first three fleets that include exclusively French vessels, the fishing effort time series $E_{fleet, period}$ were derived from the logbook data of the Fisheries Information System of Ifremer (SIH—Système d'Informations Halieutiques) and Directorate general for Maritime affairs, Fisheries and Aquaculture (DGAMPA) over the period 2002–2021. As for the fleet 'others', its fishing effort was estimated during calibration, since fishing effort data is not available for some of the fishing vessels. Target species of each fleet were also identified from the catch data of SIH.

Selectivity parameters (L_{50} and L_{75} in Table 1) and discard rates (supplementary material, Table S7) were estimated using catch-at-length data obtained from the at-sea observation program ObsMer and stored in SIH (including landings and discards).

Catchabilities Q_{fleet} and $Q_{fleet, sp}$ were estimated during the calibration. The catchability matrix of $Q_{fleet, sp}$ can be found in the supplementary material (Table S6).

Initial state

In OSMOSE, the initialization defines the state of ecosystem before the first time step of simulation. The initial state includes properties such as abundance, biomass, size and age structure, and initial trophic level of each fish school. We used data of biomass, catch, and catch-at-length data in 2002 for the initialization. The initialization is separate for each species and is done by the function *initialise_osmose* in the R package *osmose* (version 4.4.0.9004). The algorithm is based on a single species population dynamics model. This initialization replaced the spin-up process in the previous version and therefore greatly reduced the calculation time.

Inter-annual calibration

Parameter calibration was carried out with the R package *calibrar* [version 0.3.0.0012, (Oliveros-Ramos and Shin 2025)] and the model was calibrated with observed data to represent the EEC ecosystem over the period 2002–2021. The optimization algorithm AHR-ES (Adaptive Hierarchical Recombination Evolutionary Strategy, Oliveros-Ramos 2014, Oliveros-Ramos and Shin 2025) was used for the calibration.

During the inter-annual calibration, model outputs are fitted to time series of biomass, catch, and catch-at-length data (referred to as calibration data from here on) to reproduce the temporal dynamics in the ecosystem. Calibration data consisted of model-based biomass estimates, biomass index, landings (ICES 2023e), and catch-at-length (Ifremer 2022). Details on data availability and sources are presented in the supplementary material, Table S5. For stocks entirely located within the ICES Division 27.7d, the estimated biomasses were directly used (sole and plaice) (ICES 2023a). For stocks with a wider distribution than the stock assessment area, the estimated biomass data is taken as proportional to total stock biomass according to the ratio between landings in the EEC and total landings (herring, mackerel, cod, whiting; ICES 2023b, 2023c, 2023d). For unassessed species, data from the bottom-trawl survey, Channel Ground Fish Survey were used (CGFS, Giraldo et al. 1988). All calibration data were unified to yearly data.

In the optimization algorithm AHR-ES, the objective function was created by computing a likelihood based on all the calibration data components and its weights. We consid-

Table 2. Summary of phases in the calibration of OSMOSE-EEC.

Phase	Parameters	Number of parameters	Number of generations
1	Accessibilities of prey field groups to focal species, additional mortalities and base larval mortalities	43	200
2	Parameters in phase 1+ ΔL_{max} (flexibility of realized growth compared with theoretical growth)	59	200
3	Parameters in phase 2 + annual variabilities of larval mortalities of plaice and sole	101	300
4	Parameters in phase 3 + fleet catchability, fleet catchability by species, annual fishing effort of the fishing fleet 'others'	159	400

ered commercial landings data as the most reliable source of information, compared to estimates of species biomass derived from scientific surveys. In consequence, more weight was given to catch data (less uncertainty; coefficient of variance = 0.05) than to the biomass and biomass indices (coefficient of variance = 0.25, except 0.1 for plaice and sole). For plaice and sole, the stock assessment of ICES is done specifically for the EEC and therefore is considered more reliable than other species, for which the stock assessment is done for a larger area. The catch-at-length data were given the same weight as biomass and biomass indices data (coefficient of variance = 0.25).

Parameters with few supporting data have been adjusted during the calibration. The calibration was composed of four phases (Table 2), following the example of Oliveros-Ramos et al. (2017), where each phase consists of a number of generations (i.e. iteration of the optimization process). The first phase included parameters with least supporting information, such as accessibilities between prey field groups and focal species, additional mortalities and base larval mortalities of each species. The second phase added the ΔL_{max} of each species, a parameter that determines the range of realized growth compared to average growth. The third phase added annual variabilities of larval mortalities of plaice and sole. The fourth phase added the fishing parameters, the fleet catchabilities, the catchabilities between each fleet and its target species, as well as the annual fishing effort of the fishing fleet 'others'. Several calibration trials alternating model tuning and using previous calibration results were needed until obtaining a final configuration, where further improvements of the likelihood function were not possible.

Scenarios

OWFs deployment scenarios

To predict the potential impact of OWF implementation by 2050, we used four OWF deployment scenarios proposed by the French Renewable Energy Trade Association (Syndicat des Énergies Renouvelable—SER, 2024). These scenarios respond to key aspects of public debate on offshore wind energy development in France: visibility of OWFs located near the coast; effects on the marine environment; cohabitation of uses, in particular with fishing; cost of offshore wind energy in comparison to other energy sources. SER elaborated four deployment scenarios (Table 3). The first three scenarios prioritize three key aspects respectively: energy cost, environment effects, and seascape modification, namely 'cost minimization', 'exclusion from environmental protection zones', 'long distance from the coast'. Finally, the fourth scenario, 'balance', combines a balanced compromise of the previous three scenarios. The scenario 'balance' is the most probable scenario, according to SER (2024). Complementary information on the OWFs in EEC can be found in the supplementary material (Table S8).

OWF effects during the construction phase

During the construction phase, three effects were considered: acoustic disturbance, sediment resuspension, and fishing access restriction. Acoustic disturbance and sediment resuspension were implemented by modifying the probability of presence in the distribution maps to simulate avoidance of fish schools. Acoustic disturbance influences all fish species. Species with a swim bladder (red mullet, pouting, whiting, cod, poor cod, dragonet, herring, sardine, horse mackerel) are more sensitive to acoustic disturbance than species without a swim bladder (lesser spotted dogfish, thornback ray, plaice, sole, mackerel, squids, cuttlefish). The area of impact for the former group is defined as a 15 km buffer zone around OWFs, following the results of an impact assessment that was done in the North Sea (Popper et al. 2014, Boyle and New 2018). For the latter group, the area of impact is defined as being the same as OWF area, considering their low sensitivity (Popper et al. 2014). Within the impact zone, the presence probability is reduced by 50%, according to the survey results of fish avoidance following acoustic disturbance (Popper et al. 2014). Sediment resuspension was found to only influence herring and sardine (Engell-Sørensen and Skyt 2001), with the impact area and the magnitude of impact being also defined as a 15 km buffer zone around OWFs. Implementation of OWF effects during the construction phase by species can be found in the supplementary material (Table S9). During the construction phase, fishing effort of all fleets is set to 0 in the OWF construction area. Fishing is redistributed uniformly to the rest of the EEC so that the total fishing effort stays the same.

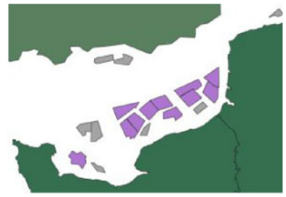
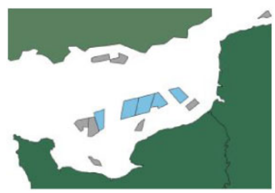
OWF effects during the operational phase

During the operational phase, only fishing restrictions were considered. Three scenarios were defined: no restriction, trawlers closure, complete closure. Under the no restriction scenario, all fleets can fish in OWFs; under the trawlers closure scenario, only netters can fish in OWFs; under the complete closure scenario, no fleet can fish in OWFs. Under all fishing closure scenarios, fishing is redistributed uniformly to the rest of the EEC so that the total fishing effort stays the same.

Simulations and analysis

We conducted the simulations based on a factorial plan of the four deployment scenarios and three fishing regulation scenarios described above (Fig. 2), as well as one reference scenario without any OWFs. To account for the stochasticity of OSMOSE, 30 replicates were conducted for each scenario

Table 3. Information about OWF deployment scenarios proposed by the French Renewable Energy Trade Association (Syndicat des Énergies Renouvelable—SER, 2024).

OWFs deployment scenario	Priorities	Total capacity by 2050	Spatial coverage (%)	Map
Cost minimization	Minimize final electricity cost for the community.	>13.5GW	13.4	
Exclusion from environmental protection zones	Implementation of OWFs outside of any regulatory protection zone under the Code of the Environment.	>9GW	9.7	
Long distance from the coast	Implementation of OWFs at a distance from the coast greater than 20 nautical miles (>37 km) in order to limit the visibility of the park from the coast and interactions with the different uses of the coastal strip.	>6GW	7.5	
Balance (most probable scenario according to SER (2024).	Balanced consideration of technical, seascape, environmental, and economic issues.	>12GW	8.6	

In the maps, grey areas are OWFs that are currently in operation, under construction or in development by March 2024. Coloured areas are potential future OWFs that differ across deployment scenarios.

combination. This number was chosen because the variability of key outputs stabilizes beyond 30 replicates (supplementary material, Fig. S2). The simulation period is from 2002 to 2050, including a calibration period from 2002 to 2021, and a projection period from 2022 to 2050.

Three indicators were used for evaluation of OWF impacts: total fish biomass, total fish yield, and large fish index of catch (LFI catch, threshold at 40 cm). We have chosen LFI catch, an accessible indicator to fishery managers and the public, thanks to its mathematical simplicity and cost effectiveness (Shephard et al. 2011, Halouani et al. 2019). The analysis was done initially in three periods: 2011–2022 (before OWF construction), 2023–2034 (from the beginning of first OWF construction phase to the end of last OWF construction phase), and 2035–2050 (after OWF construction). Each OWF deployment scenario and fishing regulation scenario were compared with the reference scenario. A *t*-test was applied to verify the significance of difference between each scenario and the reference scenario. Analysis of variance (ANOVA) was applied to verify whether each fishing regulations or OWF deployment have different influences and whether these two factors interact to influence the ecosystem. All analyses were performed using R Statistical Software (version 4.2.2; R Core Team 2022).

Then, time series of biomass, yield, and LFI catch were calculated to analyse the potential temporal changes under each combination of scenarios. Last, potential spatial patterns of total biomass and total yield under OWFs impacts were explored.

Results

Results and validation of calibration

The biomass, yield, and catch-at-length by species is compared with calibration data to evaluate the performance of calibration (Fig. 3–5). For the six species with absolute biomass as calibration data, half of them have simulated overall biomass and trend coherent with calibration data (Fig. 3). For sole and plaice, the downward trends of the last years were well reproduced. However, the model overestimates the biomass of plaice at the beginning of the time series. For herring and cod, simulated biomass is consistent with calibration data. For whiting and mackerel, biomass was underestimated.

For species with relative biomass index as calibration data, the ascending trend of thornback ray (entire simulation period) and lesser-spotted dogfish (2011–2021) were well reproduced. The temporal trend of cuttlefish, dragonet, horse mackerel, poor cod, and red mullet were partly reproduced. The model was not replicating the fluctuations of pouting, sardine, and squid biomass.

In terms of yield, most species showed consistent simulated outputs with calibration data (Fig. 4), with exceptions of underestimation for cod (2002–2016), lesser-spotted dog-

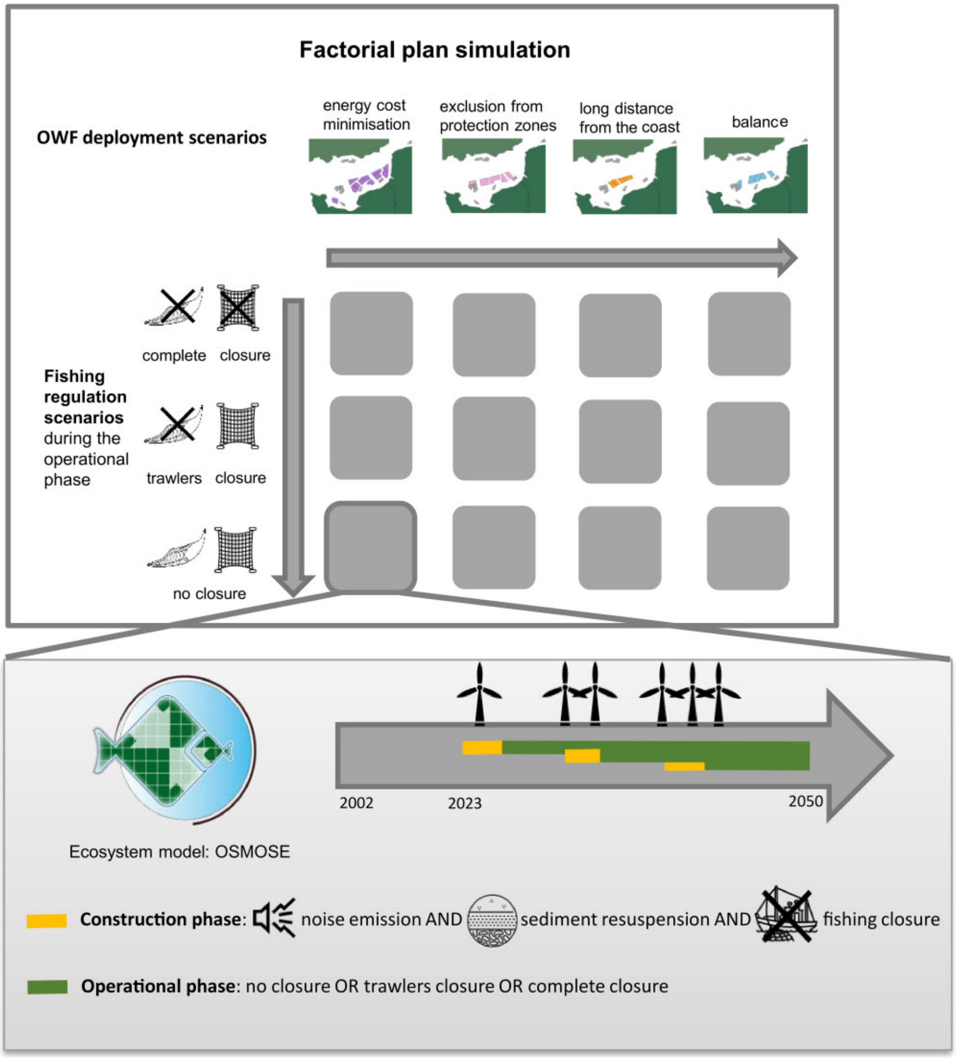


Figure 2. Simulation protocol. The simulation experiments were based on a factorial plan combining four deployment scenarios and three fishing regulation scenarios. The simulation period was 2002–2050, during which three groups of OWFs were set to be constructed in 2023–2024, 2028–2029, and 2033–2034, respectively.

fish (2009–2021) and thornback ray. The model outputs have reproduced yield declines of plaice, sardine, and sole, but the simulated declines were earlier than observed data. Poor cod and dragonet are not shown because they are not exploited.

In terms of mean length at catch (Fig. 5), simulated outputs were consistent with calibration data, except for herring, sardine, and lesser-spotted dogfish, where the length is underestimated. For most species, the size data from both observations and simulations did not exhibit any clear trend. Except for the thornback ray, whose ascending trend in mean catch at length was reproduced by the model. Poor cod and dragonet are not shown because they are not exploited.

The emergent properties of the model were analysed to ensure its ecological realism. Trophic level was compared with data from stable isotope analysis (Fig. 6). Simulated trophic spectra were in good agreement with trophic level estimated from stable isotope measurements for around half of the species. For cod, dragonet, herring, horse mackerel, mackerel, plaice, sardine, whiting, mean value of empirical data is located in the middle of the model simulation. For lesser-spotted dogfish, poor cod, red mullet, sole, squids, and thornback ray, even if the mean value of empirical data deviates from the simulation, the range of model simulation mostly encompassed the range of empirical data. Other emergent properties, including diet composition and growth curve are provided in the supplementary material (Figs. S3, S4).

OWF impact at the scale of the EEC

In 2023–2034, three groups of OWFs were constructed and then entered the operational phase. During this period, total biomass decreased in 9 out of 12 scenarios combinations (Fig. 7, upper row). The greatest decrease of 1.3% on average was in the scenario combination 'no closure during operational phase' and 'cost minimization' (Fig. 7a, purple box). This combination is also the only one that leads to a yield decrease of 1.7% (Fig. 8a, purple box). LFI catch showed an increase between 2.6% and 3.7% under three scenario combinations (Fig. 9a–c).

In 2035–2050, all OWFs were assumed to be in operation. During this period, all OWF scenarios showed decreases of

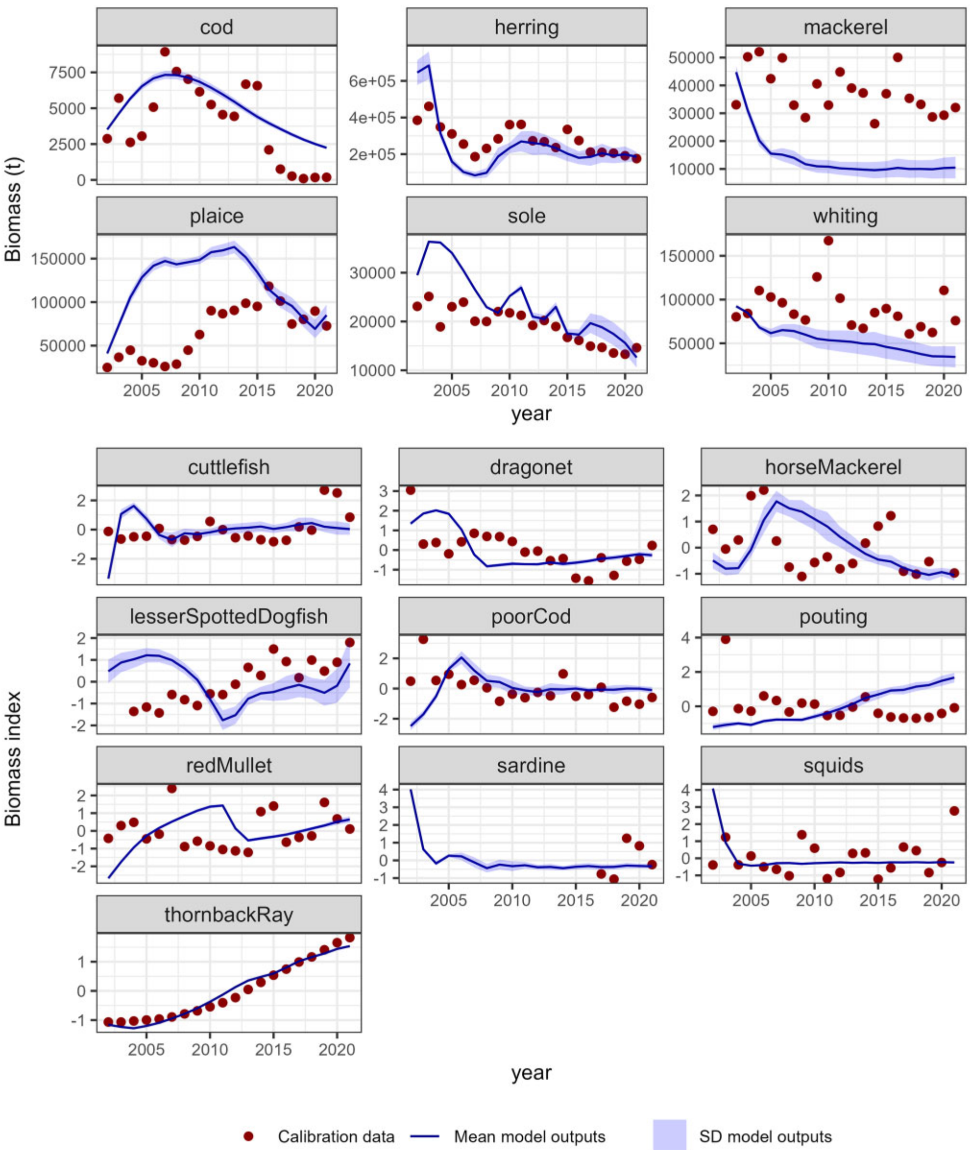


Figure 3. Comparison of model outputs and biomass data in 2002–2021. For cod, herring, mackerel, plaice, sole and whiting, biomass was in tons. For other species, biomass was expressed as standardized indices. Point: calibration data; Line: mean of model outputs; Band: standard deviation (SD) of model outputs.

total biomass (Fig. 7d–f) as well as total yield (Fig. 8d–f). LFI catch did not show significant changes in any OWF scenarios (Fig. 9d–f). Fishing regulation and OWF spatial deployment might interact to influence total biomass. For example, when combined with 'no closure during operational phase', 'cost minimization' led to the highest biomass loss (2.3% on average, Fig. 7d, purple box) among the four deployment scenarios, while 'long distance from the coast' led to the lowest biomass loss (1.6% of on average, Fig. 7d, orange box). On the contrary, when combined with 'trawlers closure during operational phase', 'cost minimization' led to the least biomass loss (1% on average, Fig. 7e, purple box) while 'long distance from the coast' led to the most biomass loss (1.9% on average, Fig. 7e, orange box).

In terms of yield, it decreases under all scenario combinations, with the three fishing regulations showing clear differences (Fig. 8d–f). When closing fishing access (either for trawlers or for all fleets) during the operational phase (Fig. 8e–f), total yield decreases more than when allowing fishing access, despite the reallocation of fishing effort (Fig. 8d). Among the four deployment scenarios, 'cost minimization' is the one that impacted most the total yield, leading to a decrease of 7.6% on average when combined with 'trawlers closure during operational phase' (Fig. 8e, purple box) and 8.2% on average under 'complete closure during operational phase' (Fig. 8f, purple box). Other scenarios combinations showed yield loss <6% (Fig. 8d–f, pink, orange, and blue boxes).

More figures of temporal changes of the indicators can be found in the supplementary material (Tables S6–S8).

Spatial extent of OWF impact

Heat maps showed spatialized total biomass (Fig. 10) and total yield (Fig. 11), under combination of each fishing regulation scenario, and balance deployment scenario (the most probable deployment scenario), relative to the reference simulations. Before OWF construction (2011–2022), the model stochasticity caused small variabilities in outputs.

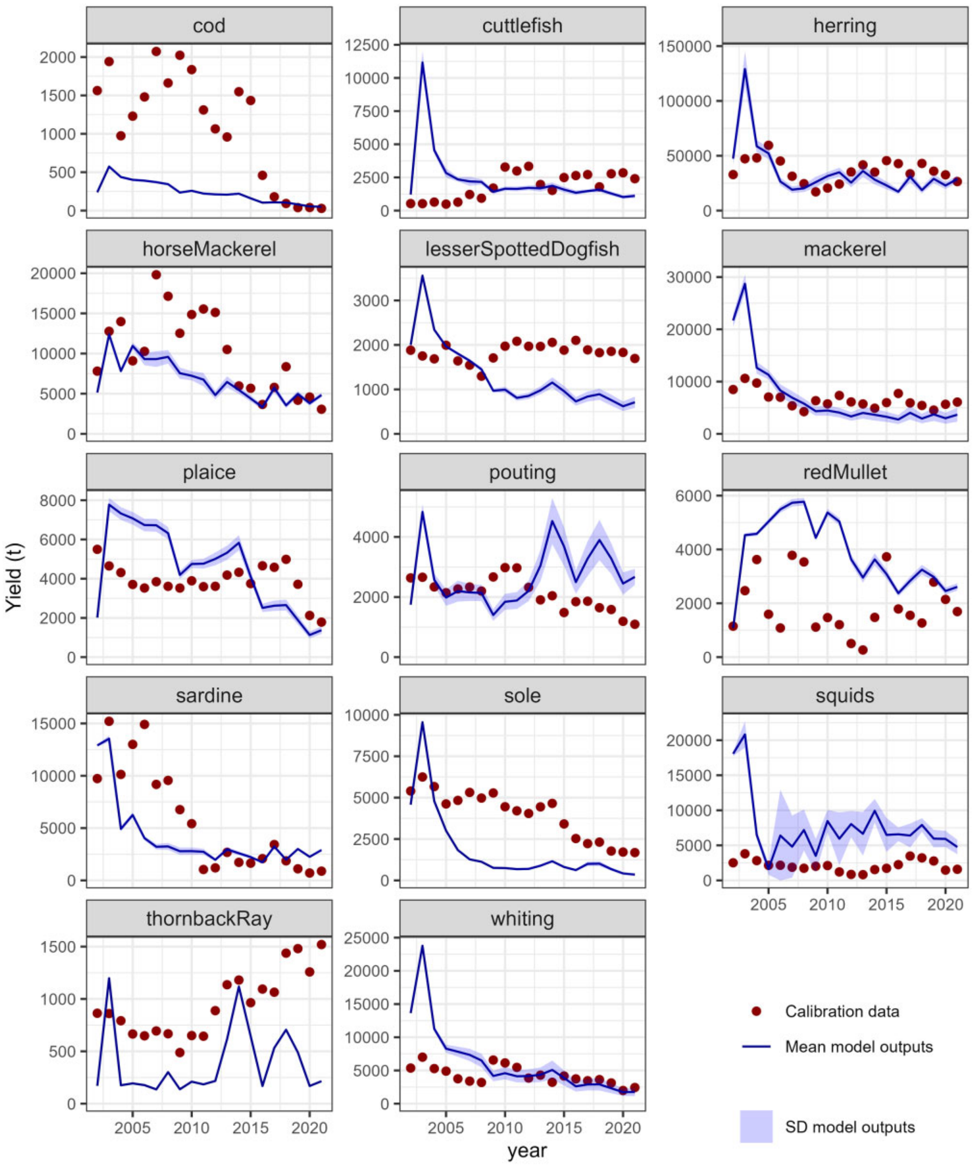


Figure 4. Comparison of model outputs and yield data in 2002–2021. Point: calibration data; Line: mean model of outputs; Band: standard deviation (SD) of model outputs.

In 2023–2034, three groups of OWFs were constructed consequently. During this period, there were more cells with biomass loss than in the previous period, mostly at the edge of the map (Fig. 10d–f). Fishing closure caused yield decrease under all scenarios (Fig. 11d–f). Under the 'no closure during operational phase' scenario, the yield decrease in OWFs was homogenous across OWFs and less than other scenarios. That is because the fishing access restriction was only put forward during the 2 years of construction. Under the other two scenarios, since the fishing restriction continues throughout the operational phase, the yield decrease was greater and differed among OWFs, depending on the construction time.

In 2035–2049, all OWFs were in operation. Under the three scenarios, biomass loss became dominant and biomass gain was rarely observed (Fig. 10g–i). Under the 'trawlers closure' and 'complete closure' scenarios, yield decreased further within OWFs and increased in areas outside OWFs (Fig. 11h–i). Under the 'complete closure' scenario, no fishing activity was allowed in OWFs. The yield gains outside OWFs were relatively homogenous. On the contrary, the under no closure scenario (Fig. 11g), yield both within and outside OWFs returned to the reference level.

Discussion

Updates and inter-annual calibration of OSMOSE-EEC

We have made several changes in the previously developed OSMOSE-EEC model to accommodate an impact assessment of OWFs, including the first application of fishing fleet and inter-annual calibration in OSMOSE. Due to model complexity, we had to reduce the number of fleets to simplify inter-annual calibration. The aggregation of fishing vessels constrained the level of detail in fishing seasonality, size selectivity, catchability, and effort spatial distribution. Part of which could explain the difficulty we had to reproduce the dynamics of catch and biomass of certain species in our model (Girardin et al. 2018). A more precise representation of fishing activities

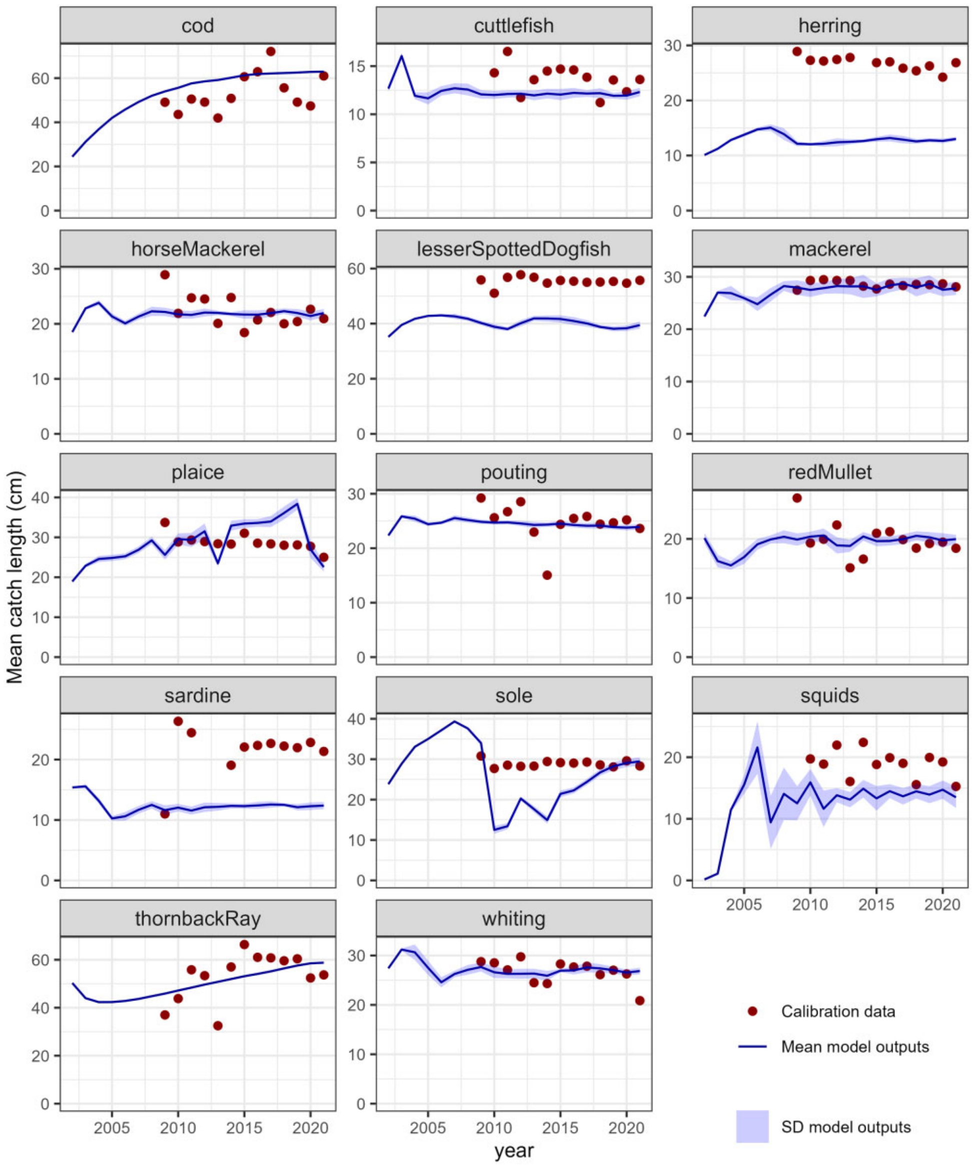


Figure 5. Comparison of model outputs and mean length in catch data in 2009–2021. Point: calibration data; Line: mean of model outputs; Band: standard deviation (SD) of model outputs.

and temporal variation of larval mortality (Oliveros-Ramos et al. 2017) could improve the calibration. However, it will be much more computationally expensive. On the other hand, potential bias might exist in the calibration data. One example is the biomass data of mackerel, for which the stock assessment is done on the entire North-East Atlantic Ocean (ICES 2023d). We had to estimate its biomass in the EEC based on the proportion of catch in EEC compared with the entire stock assessment zone.

Other improvements could focus on implementing a bioenergetic sub-model to better account for climate-induced changes (Morell et al. 2023), the representation of benthic habitat changes (Raoux et al. 2017, 2019) or adding marine birds and mammals (Serpetti et al. 2021).

Selections of OWF effects in cumulative impact scenarios

To our knowledge, our study is a first attempt at using an individual-based and size-based ecosystem model to investigate the ecosystem effect of OWFs, and a first attempt to take into account both the construction and operational phase of OWFs. In our study, we chose to implement pile driving acoustic emission and sediment resuspension during the construction phase of OWFs. Estimates on the disturbance level are based on a few in-situ observations (Popper et al. 2014) and modelling data (Boyle and New 2018). However, such parameters are highly spatially and temporally variable and could be changed with technical improvement and precaution measures. Currently, empirical data at large scale is still missing. With several observation projects ongoing in the study area, the upcoming data will consolidate the quantitative effects. In this case, we would be able to define the functional response of organisms to habitat change related to OWFs, rather than forcing impacts or effects of OWFs.

Characteristics of the OSMOSE model have limited some potential OWF effects, such as the artificial reef effect. Previous studies using the EwE model have modelled this effect by adding benthos biomass, or adding hard substrate habitat (Table 4). In the OSMOSE-EEC configuration, benthos is divided in 5 groups according to size, including three groups for which

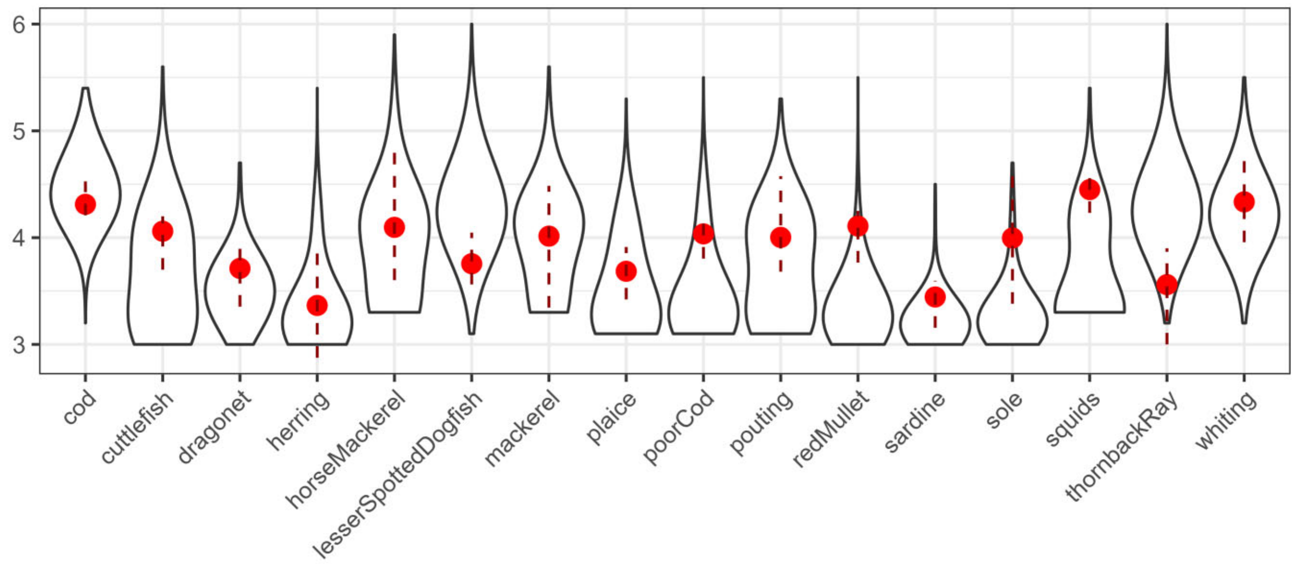


Figure 6. Simulated biomass distribution structured by trophic level in 2015 (violins), with trophic level data in 2015 based on stable isotopes analysis (Cresson et al. 2023). Point: mean of trophic level data; Dotted line: range of trophic level data.

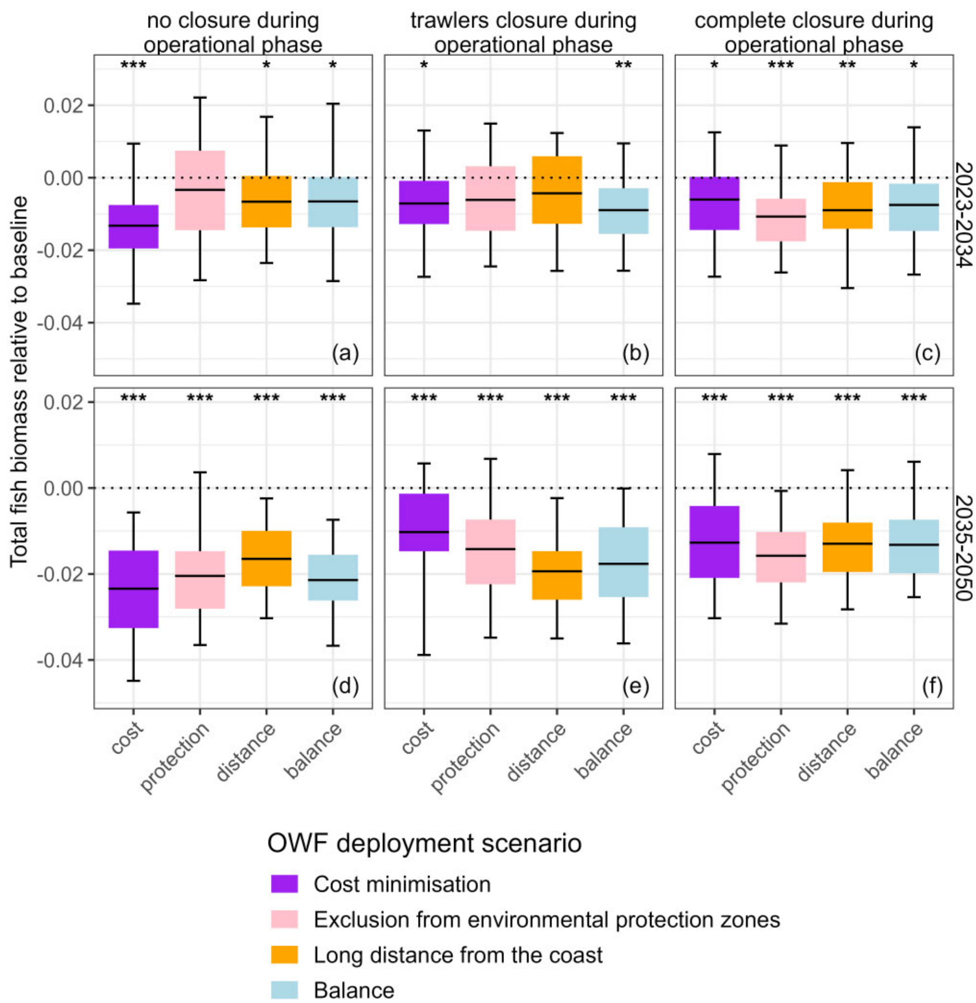


Figure 7. Total fish biomass across OWF deployment scenarios and periods, relative to the baseline (dashed lines). Stars: significant level (∗: P-value < 0.05, ∗∗: P-value < 0.01, ∗∗∗: P-value < 0.001); Bar: mean; box: 25th–75th percentile (IQR); Whiskers: max./min. 1.5 × IQR above/below box.

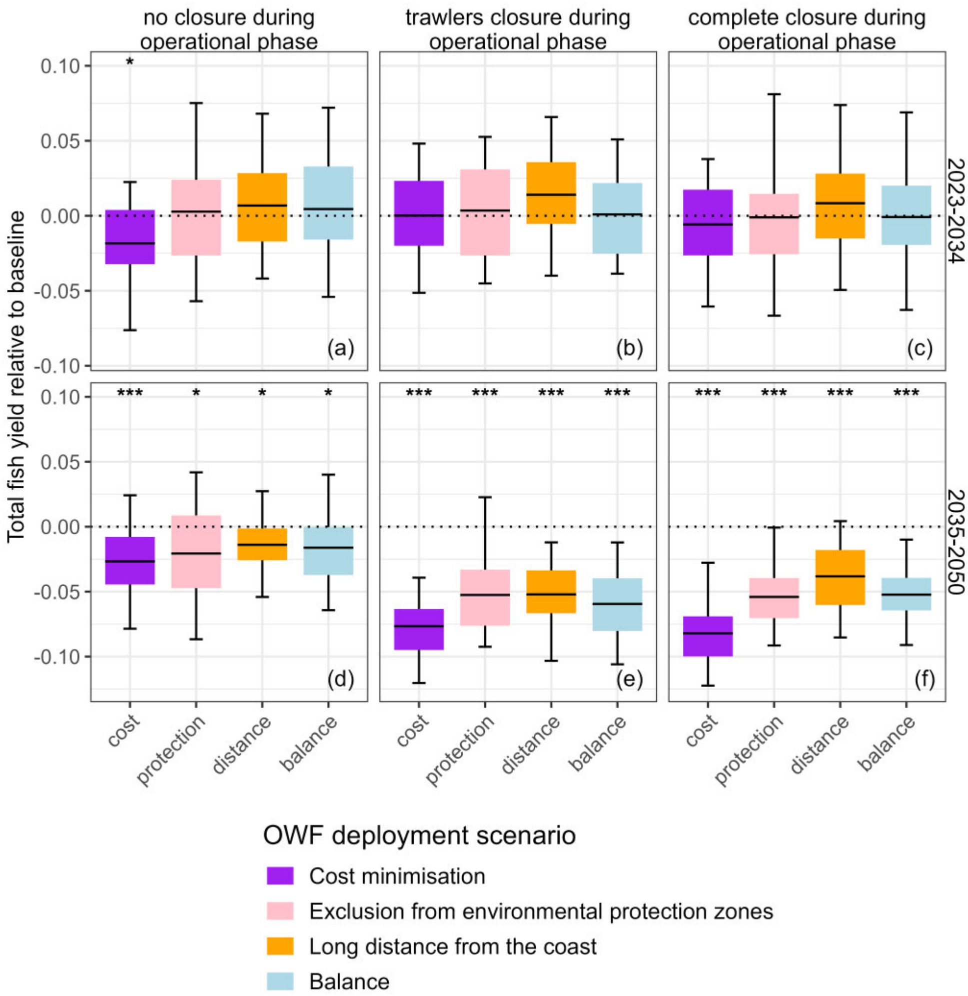


Figure 8. Total fish yield across OWF deployment scenarios and periods, relative to the baseline (dashed lines). Stars: significant level (∗: P-value < 0.05, ∗∗: P-value < 0.01, ∗∗∗: P-value < 0.001); Bar: mean; box: 25th–75th percentile (IQR); Whiskers: max./min. 1.5 × IQR above/below box.

the biomass is provided by the ERSEM biogeochemical model and two groups for which the biomass is set as high values to not limit predation. This representation of benthic groups complicates the integration of an artificial reef effect into the tested scenarios. Attraction of fish around wind turbines has been observed in in-situ studies (Degraer et al. 2020, Mavraki et al. 2021). However, this phenomenon does not necessarily lead to a biomass increase at a larger scale. The perimeter of a cell is around 8 km in OSMOSE-EEC, which is almost half the size of an OWFs. Considering the incoherence between the spatial scale of observed aggregation effects and OSMOSE-EEC grid, we decided not to include this effect in our scenario design explicitly.

Some other effects have been highlighted by other studies but were excluded due to specificities of the EEC. We neglected effects of electromagnetism because all wind turbines in the EEC will have fixed foundations and buried cables, in which the level of electromagnetic field is too low to influence fish behaviour and physiology (Taormina et al. 2018). We also excluded the effect of hydrodynamics modifications on primary production, because it is found to be important in stratified water but not in well-mixed waters (Daewel et al. 2022), such as the EEC.

OWF implementation and fishing regulation scenarios

The OWF implementation was simplified in order to reduce the complexity of simulations. For example, OWFs have different construction periods. We aggregated OWFs in three groups so that all OWFs within the same group have the same construction phase. The Rampion I wind farm was already in operation within the period of calibration, and therefore its implementation was not considered in the tested scenarios.

Assessing the trade-offs between fishing activities and the ascending demand of ocean space for OWFs is becoming increasingly important (Austrheim et al. 2022). In reality, the implemented fishing regulation could be more complex and varies among OWFs. During the construction phase, fishing could be allowed in a delimited area of the OWFs depending on the construction progress. During the operational phase, seasonal regulation might apply, in which a type of gear is only allowed within a certain period of the year.

We made the assumption that fishing effort does not change after the OWF implementation. In the case of fishing exclusion inside OWFs, fishing effort is redistributed homogeneously outside OWFs. In reality, fishers' response to the presence of OWFs could modify the fishing effort distribution. Potential

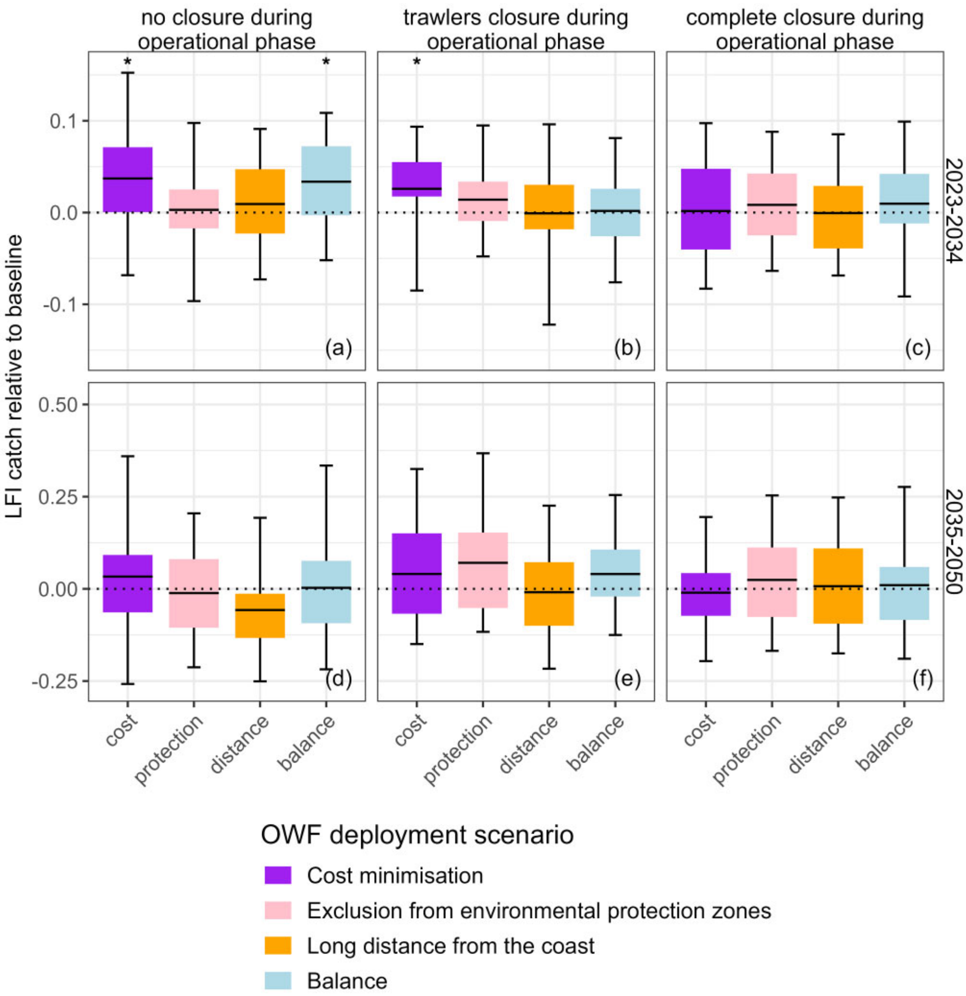


Figure 9. LFI catch across OWF deployment scenarios and periods, relative to the baseline (dashed lines). Stars: significant level (∗: *P*-value < 0.05); Bar: mean; box: 25th–75th percentile (IQR); Whiskers: max./min. 1.5 × IQR above/below box.

responses include avoiding the OWFs to reduce navigation risk (Groenendijk 2018), fishing close to the border of OWFs to benefit from the potential spill-over effect (Kellner et al. 2007), or fishing ground changes in response to changes of target species (Warlick et al. 2025). Future studies on fishers' response will help improve the fishing regulation scenarios in ecosystem models.

OWFs impacts revealed by OSMOSE-EEC and comparison with studies on EwE models

Our results show that slight decreases in total fish biomass and total fish yield could be expected at the scale of entire EEC. Mechanistically, we infer that the avoidance behaviour of fish during OWF construction reduces the effective spatial distribution of fish populations result in spatial contraction of fish distributions and locally intensified predator–prey interactions (Orio et al. 2019). According to the OSMOSE assumption of opportunistic predation—where predation occurs based on size adequacy and spatial co-occurrence, lower-trophic-level species, such as cuttlefish and herring, are particularly vulnerable to this effect, as they experience predation from a broader range of predators. Furthermore, this spatial contraction and the resulting trophic stress are not immediately reversible once construction ends, indicating a potential for long-lasting changes in ecosystem structure (Atlas et al. 2015, 2015; Han et al. 2020).

The level of biomass and yield loss depends on both fishing regulation and OWF deployment. A trade-off may exist among conservation, fisheries, and energy production in decision-making (Kadin et al. 2019). For example, the combination of 'cost minimization' with 'trawlers closure during operational phase' favours offshore wind energy production and helps prevent biomass loss, but leads to greater yield loss compared to other scenario combinations, according to the results of the present analyses. Among the four deployment scenarios, the 'balance' scenario never fell at either extreme. This suggests that, in addition to regulatory and socio-economic considerations, this scenario also represents a balance of ecological factors.

We have selected the most probable deployment scenario 'balance' to explore the spatial extent of OWF impact. The results did not show clear spatial patterns, such as reserve effect or spill-over effect observed in previous OWFs impact assessment studies (Table 7). A major reason could be that our spatial resolution is a lot larger than previous studies that focused

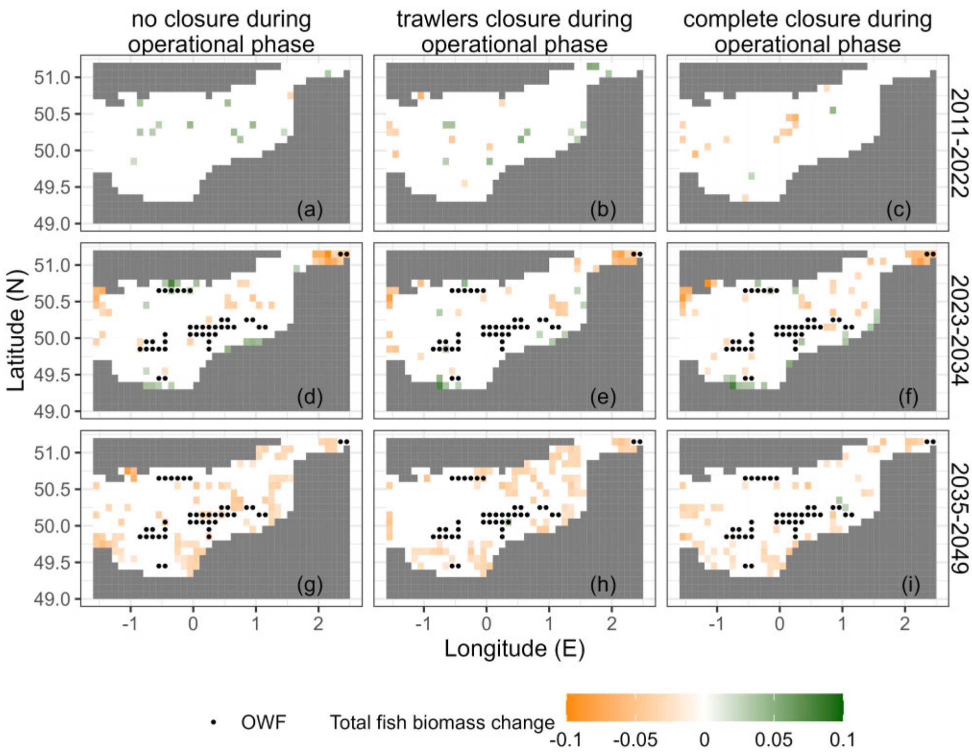


Figure 10. Heat map of total fish biomass under the balance deployment scenario and three fishing regulation scenarios, relative to the baseline. Only significant changes were shown. Dots: cells of OWFs.

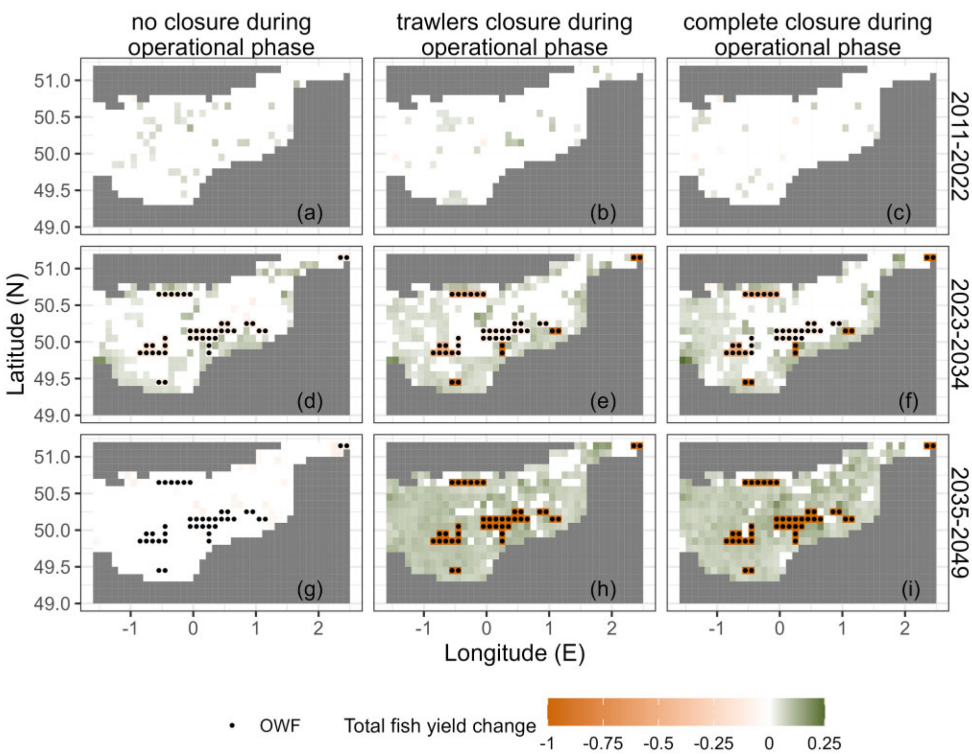


Figure 11. Heat map of total fish yield under the balance deployment scenario and three fishing regulation scenarios, relative to the baseline. Only significant changes were shown. Dots: cells of OWFs.

Table 4. Previous studies of OWF impact assessment using the Ecopath with Ecosim (EwE) model.

Reference	Spatial extent	Effects studied	Implementation	Key findings
Adgé et al. 2024	Local (OWFs and surroundings, implicit)	Fishing exclusion and artificial reef effect	Increase of benthos biomass and fishing effort diminution	Increase of pelagic fish biomass
Püts et al. 2023	Regional (North Sea)	Fishing exclusion and artificial reef effect	Fishing access restriction and habitat modification	Marginal decrease of fish biomass
Serpetti et al. 2021	Local (wind turbine and surroundings)	Artificial reef effect and acoustic disturbance	Attraction of birds and avoidance of whales by habitat modification	Weak effect on fish
Halouani et al. 2020	Regional (extended Bay of Seine)	Fishing exclusion	Fishing access restriction	Increase of fish biomass and catch around OWFs
Raoux et al. 2019, 2017	Regional (extended Bay of Seine, implicit)	Artificial reef effect and fishing exclusion	Increase of benthos and demersal fish biomass	Increase of fish biomass

on one particular OWF. The random movement enables fish schools to exit the area of the OWF and be exposed to higher fishing pressure in adjacent waters. Both the implementation of OWF-related pressures in the scenarios and the resulting outcomes differ between our study and previous ones that used EwE models. The ecological effects of OWFs also vary across EwE model applications (Table 4). These outcomes are likely due to differences in spatial scale, types of pressures considered, effect implementation and the specific characteristics of each ecosystem. In our scenario design, the fishing access restrictions are similar to the studies of Püts et al. (2023) and Halouani et al. (2020). The avoidance of fish due to acoustic disturbance is similar to the scenario of Serpetti et al. (2021), though in the latter study the avoidance is applied to birds and not to fish. The avoidance to sediment resuspension is the effect that has not been considered in previous studies, to our knowledge. And last, the artificial reef effect, studied by Adgé et al. (2024) and Raoux et al. (2019, 2017) was not implemented in this study (see the section 'Selections of OWF effects in cumulative impact scenarios'). Despite these differences in scenario design, the general magnitude of impacts remains consistent across our study and previous studies. Once scenario assumptions are harmonized between the EEC application of the OSMOSE and EwE models, their outputs can be compared to investigate structural uncertainties in the assessment of OWFs impacts.

Conclusion

This study proposes a new tool, the individual-based ecosystem model OSMOSE, to assess the impact of OWFs during the construction phase and the operational phase. Our results indicate that OWF implementation may lead to losses in fish biomass and yield. However, fishing closure within OWFs during the operational phase could partially compensate the biomass loss. We also showed that a balanced OWF spatial deployment is consistent both ecologically and socioeconomically. Further improvements could involve extending OWF impact representation to other biological groups (e.g. benthic habitat modification, behavioural impacts on birds and mammals), refining fish distribution, and movement processes in the model. This work opened new opportunities for inter-model comparisons within the cumulative impact assessment of OWF, given that other ecosystem models, such as Ecospace and Atlantis, have already been applied in the EEC. Conducting inter-model comparisons will provide valuable insights on the robustness of model projections by explicitly addressing uncertainties related to model assumptions. Such approach could enhance the reliability of OWF impact assessments and supports more informed decision-making for EBM.

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Author contributions

Yansong Huang (Formal Analysis [lead], Investigation [lead], Methodology [equal], Visualization [lead], Writing – original draft [lead], Writing – review & editing [lead]), Raphaël Girardin (Conceptualization [equal], Formal Analysis [equal], Funding acquisition [equal], Investigation [equal], Methodology [equal], Project administration [equal], Supervision [lead], Writing – review & editing [equal]), Ricardo Oliveros Ramos (Methodology [equal], Software [lead], Writing – review & editing [equal]), Morgane Travers-Trolet (Methodology [equal], Writing – review & editing [equal]), Antoine Quennevat (Methodology [equal], Writing – review & editing [equal]), Georges Safi (Conceptualization [equal], Funding acquisition [equal], Investigation [equal], Project administration [equal], Supervision [equal], Writing – review & editing [equal]), Frida Ben Rais Lasram (Conceptualization [equal], Funding acquisition [equal], Investigation [equal], Project administration [equal], Supervision [lead], Writing – review & editing[equal]), Ghassen Halouani (Conceptualization [equal], Formal Analysis [equal], Funding acquisition [equal], Investigation [equal], Methodology [equal], Project administration [equal], Supervision [lead], Writing – review & editing [equal])

Supplementary data

Supplementary data is available at *ICES Journal of Marine Science* online.

Conflict of interest: The authors have no conflicts of interest to declare.

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Data availability

Fishery data is available on the Fishery Information System of Ifremer (SIH—Système d'Informations Halieutiques) on request. Configuration files for OSMOSE-EEC and analysis scripts used in this study are available on Zenodo (https://doi.org/10.5281/zenodo.15740531).

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