Towards an ecosystem approach of floating wind farm combined to climate change in the Bay of Biscay (France)

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Abstract

The Bay of Biscay includes areas of environmental importance, with a wide variety of benthic habitats and rich biodiversity. However, it experiences strong anthropogenic pressures, and the effects of climate change are already evident. Renewable energy infrastructures are set to be installed with the aim of reducing carbon footprint by 2050. However, their effects on the environment demonstrate the need for holistic studies prior to the project design. The Ecopath with Ecosim model can be used to model the entire food web and explore different scenarios for changes in the Bay of Biscay. In this study, four scenarios are developed: (1) a reference scenario based on the 2007-2016 environmental conditions; (2) a climate change scenario (increased production and consumption rates of fish to reflect rising sea temperature, presence of non-indigenous species and local distributions maps derived from species distribution models); (3) an offshore wind farm scenario (a biofouling group, wind farm area closed to fishing activities and increasing the area suitability for species likely to aggregate under the turbines); (4) a cumulative effects scenario. The results are analyzed in terms of biomass and catches within the wind farm and the surrounding area. The main findings were that (1) the arrival of non-indigenous species could lead to a change in the structure of the local food web, resulting in a general increase in fish biomass; (2) the attractiveness of the wind farm lead to a cascading effects; (3) the combination of the wind farm and climate change could cause contrasting effects on biomass and catches depending on the trophic groups, and a potential reorganization of the current food web. These results reflect potential effects of floating wind farms on the structure of the food web that should be considered in fisheries management scenarios in the context of a changing environment.

Keywords: ecosystem modeling, ecosystem approach, offshore wind farm, climate change, reef effect, reserve effect, Non Indigenous Species

1. Introduction

Given the urgent need to address climate change and the growing world population, which is leading to ever-increasing demand for energy, the development of renewable energies seems to be a strategic choice for many countries. Offshore Renewable Energies (ORE), which include marine renewable energies and offshore wind farms (OWF), are rapidly expanding in countries with sufficient maritime space. The installation of ORE lead to changes in the ecosystem, the most-documented being the reef effect, the aggregation effect, and the reserve effect (Hemery 2020). The reef effect is characterized by the colonization of all submerged surfaces by organisms with at least one fixed life stage (i.e. biofouling). The aggregation effect is due to the tendency of certain fish species, such as

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tuna or mackerel, to gather under floating structures, as well as to the protection offered by the new habitat created by the reef effect, particularly for juvenile fish (Werner et al. 2024; Copping et al. 2021; Reubens et al. 2011). Finally, the reserve effect is induced by the partial or total restriction of fishing activities within the OWF for safety purposes, and can lead to an increase in species richness and biomasses (Coates et al. 2016; Hammar et al. 2016). However, coastal waters are generally under heavy pressure from fishing, leisure activities, shipping and aggregate extraction. Moreover, climate change is a pressure that affects all trophic compartments and environmental parameters, and its effects are already significant in many ecosystems (Kristiansen et al. 2024), such as changes in primary production (Lotze et al. 2019) or shifts in species distribution (Lenoir et al. 2020). Additionally, there are numerous environmental issues to contend with, notably the preservation of fragile habitats and the protection of biodiversity. ORE must integrate into this multi-faceted context.

In light of the conservation opportunities created by ORE, it is essential to develop reliable tools to support sector development for decision-makers by testing various management scenarios. Today, given the high level of exploitation of coastal systems and the changes taking place there, it is necessary to anticipate the cumulative effects before building new projects. The ecosystem approach, a holistic environmental management method recommended by the Convention on Biological Diversity (Borja et al. 2016), integrates all the biotic and abiotic components of the system. This approach contrasts with the traditional management methods, which study pressure-receptor pairs independently. Although more complex to implement and requiring extensive local data, it provides a comprehensive view of the pressures generated by ORE on receptors, both directly and indirectly. The ecosystem approach is particularly well-suited for studying coastal systems in a context of global change and intense human activities, as seen in the Bay of Biscay (Pınarbaşı et al. 2020).

This study examines the cumulative effects (both individually and in combination) of climate change (Le Marchand et al. 2022) and the OWF on the local food web in the Bay of Biscay, where the floating wind farm is proposed to be located in southern Brittany, off the islands of Groix and Belle-Île. For this purpose, we use a method based on the Ecopath with Ecosim trophic model and its Ecospace spatial module (Christensen et al. 2014). The Ecopath suite is frequently used to model issues related to climate change (Corrales et al. 2018; Bentley et al. 2017; Libralato et al. 2015) and to ORE (Püts et al. 2023; Salaün et al. 2023; Alexander et al. 2016). In this study, climate change is represented by the arrival of subtropical non-indigenous species (NIS), the redistribution of local species following the increase in water temperature and the physiological changes associated with this temperature rise. The OWF is investigated by modeling the reef, aggregation and reserve effects. Four scenarios were modeled: a reference scenario, a climate change scenario (CC), an offshore wind farm scenario (OWF) and a cumulative effects scenario (CC+OWF). The modeling results are analyzed through two ecological indicators: the biomasses of trophic groups and catches. We discuss afterwards the reliability of this method by comparing the results obtained with *in situ* observations of wind farms and the results of other models, in order to determine the applicability of the method to other case studies.

2. Material and method

2.1. Study area

The Bay of Biscay is a large continental shelf in the north-east Atlantic, located to the west of France. Covering an area of 80,000 km², it slopes gently down to 200 meters depth, where the

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continental slope begins (Figure 1). The Bay of Biscay is subject to significant anthropogenic pressures: it experiences intense fisheries, maritime transport, aggregate extraction, and military and tourism activities. Additionally, the Bay of Biscay includes areas of environmental importance, featuring a wide variety of benthic habitats and sediment types (mud, sand, rocks, seagrass, laminaria), spawning grounds, nursery areas, as well as a rich biodiversity with a strong presence of top predators such as sharks, cetaceans, and seabirds. Beyond these numerous pressures and marine uses, the effects of climate change (rising sea water temperatures, arrival of non-native subtropical species, etc.) have already been recorded (Chust et al. 2021).

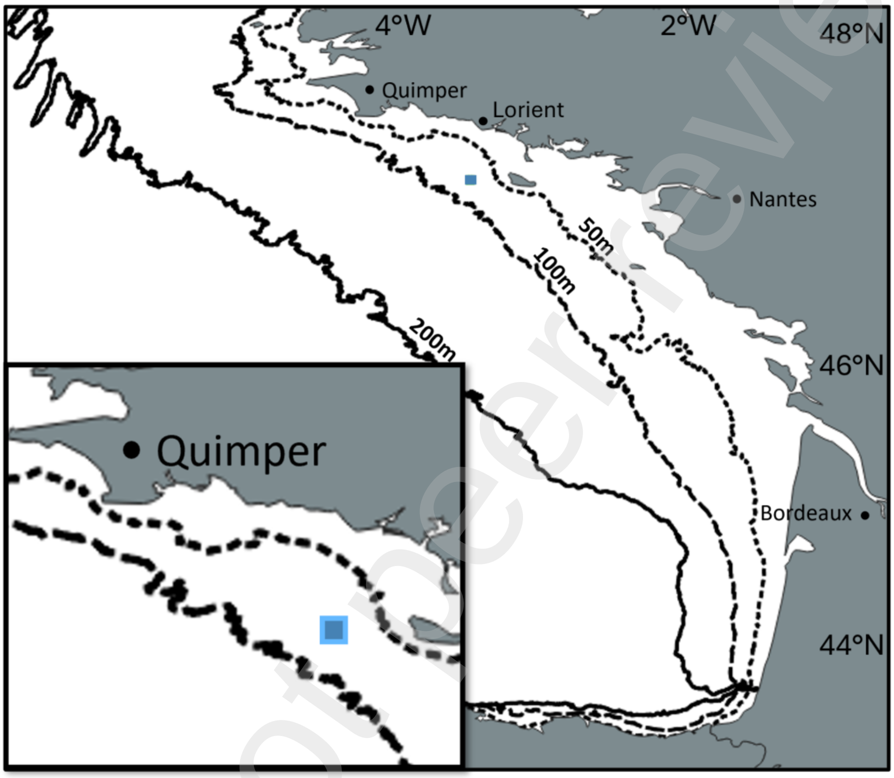

Figure 1: study area in the Bay of Biscay. The blue box corresponds to the location of the South Brittany floating wind farm. The dark blue represents the areas inside the wind farm and the light blue represents the adjacent area outside the wind farm.

The Bay of Biscay is France's leading fishing zone, with 320,000 tons of fish, molluscs and crustaceans caught in 2021 (ICES, 2024). The main fish species targeted by fisheries include anglerfishes (*Lophius budegassa* and *Lophius piscatorius*), hake (*Merluccius merluccius*), sole (*Solea solea*), megrim (*Lepidorhombus whiffiagonis*), sardine (*Sardina pilchardus*), anchovy (*Engraulis encrasicolus*), seabass (*Dicentrarchus labrax*), mackerel (*Scomber scombrus*), horse mackerel (*Trachurus trachurus*), whiting (*Merlangius merlangus*) and blue whiting (*Micromesistius poutassou*). The Bay of Biscay is also home to 6 of France's 10 largest fishing ports by tonnage of fish landed: Lorient, Le Guilvinec, Saint-Jean-de-Luz, Saint-Guénolé, La Turballe and Les Sables d'Olonne. The main fishing technics employed include bottom trawl, pelagic trawl, seine, line and longline.

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2.2. Ecopath

2.2.1. Presentation of the model

Ecopath is a trophic mass-balance model developed for aquatic resource management (Polovina 1984; Christensen et Walters 2004). It is based on two main equations that quantify the flows between the different trophic groups in a food web (Pauly 1980). A trophic group is made up of several species sharing the same prey and predators.

The first equation determines the production rate:

Production = fishery catch + predation mortality + net migration + biomass accumulation + other mortality

Formally, for a trophic group *i* and a predator *j*, this equation is:

$$B_i \text{ x } (P/B)_i = Y_i + \sum_j (B_j \text{ x } (Q/B)_j \text{ x } DC_{ij}) + Ex_i + Bacc_i + B_i(1 - EE_i) \text{ x } (P/B)_I \qquad (1)$$

where B is the biomass density (t.km^{-2}), P/B is the production rate (year^{-1}), Y is the total catch (t.km^{-2}), Q/B is the consumption rate (year^{-1}), DC is the diet composition (DC_{ij} is the proportion of *i* in the diet of *j*), Ex is the net migration rate (year^{-1}), Bacc is the biomass accumulation (year^{-1}), and EE is the ecotrophic efficiency. The EE represents the part of the biomass group that is consumed or fished and cannot be higher than 1. It can be adjusted by modifying the trophic group diet, in order to balance the model.

The second equation determines the consumption rate:

Consumption = production + respiration + unassimilated food

Formally, this equation for a trophic group *i* and a predator *j* is:

$$B_i \text{ x } (Q/B)_i = B_i \text{ x } (P/B)_i + R_i + U_i \qquad (2)$$

where R is the respiration (t.km^{-2}) and U is the unassimilated food rate.

The model presented in this study was derived from a previously published model (Le Marchand et al. 2022), which itself was adapted from two other models on the Bay of Biscay (Lassalle et al. 2011; Moullec et al. 2017) and represented an average situation for the years 2007 to 2016. It compared different hypotheses regarding the arrival of Non-Indigenous Species (NIS) in the Bay of Biscay in the context of increasing sea temperature. For the purpose of this study, the model was modified into four scenarios to incorporate the required parameters for the four hypotheses (reference, CC, OWF and CC+OWF; Table 1).

2.2.2. Scenarios

The reference scenario, without climate change neither offshore wind farms, has 44 trophic groups (Appendix A): 4 homeotherm groups, 13 monospecific fish groups targeted by fishing activities,

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8 multispecific fish groups, 2 cephalopod groups, 8 benthic invertebrate groups, 3 zooplankton groups, 3 phytoplankton groups, 1 bacterial group and 2 non-living groups (discards and detritus). Data on biomass, P/B and Q/B and diets come from the reference hypothesis model of Le Marchand et al (2022) (Appendix B).

The OWF scenario (Table 1) uses the values from the reference scenario, with the addition of a "biofouling" trophic group, composed mainly of filter-feeding species, such as mussels. Its P/B, Q/B and diet are identical to those of the "Surface suspension & deposit feeders" group (Appendix B). Its initial biomass in Ecopath is 0.01 $t.km^{-2}$ and is forced to increase in Ecosim (see next section).

The CC scenario (Table 1) is built upon the reference scenario by adding eight trophic groups of NIS fish (3 monospecific groups (*Sardinella aurita*, *Trachurus tracae* and *Merluccius senegalensis*) and 5 multispecific groups(flatfishes, demersal benthos feeders, demersal piscivorous, pelagic piscivorous and pelagic planktivorous) whose biomasses were estimated by Ecopath (EE = 0.95). Data on P/B and Q/B and diets for NIS are sourced from Le Marchand et al (2022), which studied different hypotheses for the arrival of NIS in the Bay of Biscay food web. Additionally, the CC scenario includes increased P/B and Q/B values for local fish to simulate the effect of increased sea temperature on fish metabolisms under the RCP8.5 scenario (Hoegh-Guldberg et al. 2018; Appendix B).

The CC+OWF scenario (Table 1) incorporates parameters from both the CC and OWF scenarios. It includes 53 trophic groups (44 from the reference scenario, 1 biofouling group and 8 NIS groups), along with increased P/B and Q/B of local fish (Appendix B).

The model also includes 11 fishing fleets, with landings and discards data sourced from Le Marchand et al (2022). Since our hypotheses do not account for temporal changes in fishing pressure, these values remain consistent across all scenarios, and NIS are fished in the same manner as local species (Appendix C).

Finally, once balanced, the four scenarios were evaluated using a prebal diagnostic. This procedure ensures that the model's main parameters adhere to the guidelines established by Link (2010), thereby confirming the model's robustness (Appendix D).

2.3. Ecosim

2.3.1. Presentation of the model

Ecosim is a dynamic module of Ecopath that models the temporal evolution of biomasses and catches. It is based on a main equation that defines the growth rate for a trophic group *i* and a predator *j*:

$$dB_i/dt = G_i \sum_j Q_{ji} - \sum_j Q_{ij} + I_i - (M_i + F_i + E_i)\, B_i \qquad (3)$$

where G is the net growth efficiency ($year^{-1}$), I and E are the immigration and emigration rates ($year^{-1}$), M is the natural mortality ($year^{-1}$), and F is the fishing mortality ($t.year^{-1}$) (Walters et al. 1997; Christensen et Walters 2004). The consumption rates Q is modeled following the concept of foraging arena (Ahrens et al. 2012). In this theory, the biomass of the trophic group *i* is divided between the vulnerable fraction V*i*, meaning the prey is available for predators, and the non-vulnerable fraction B*i* – V*i*, meaning the prey is not available. When the vulnerability index is low, the interaction is

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considered bottom-up controlled. When the vulnerability index is high, the interaction is considered top-down controlled.

The model was calibrated for the period from 2007 to 2016 and then projected to 2050. To reproduce historical values, several times series of biomass, catches and primary production were used to fit the model. The biomass and catch data were calculated similarly to the Ecopath input data (Le Marchand et al. 2022): the biomass data was derived from stock estimates provided by the ICES (ICES, 2020) for the main commercial species in the Bay of Biscay, while catch data were obtained from ICES, which provides total biomass caught for each species annually in areas 8a and 8b. Monthly primary production was also incorporated as a forcing function on phytoplankton groups. Satellite data were extracted for the years 2007 to 2016 (http://orca.science.oregonstate.edu/1080.by.2160.monthly.hdf.cafe.m.php), and daily values were aggregated across the Bay of Biscay to obtain mean monthly values.

2.3.2. Reef effect

Ecosim was also employed to simulate the reef effect in the OWF and CC+OWF scenarios (Table 1), through the increased biomass of the "biofouling" trophic group. The theoretical biomass used in this model was calculated based on the dimensions of the wind turbines initially planned for the Groix-Belle-Ile pilot farm (Appendix E), that has since been canceled: semi-submersible floats consisting made up of three 9 meters in diameter columns immersed over 18 meters and each anchored by two 0.475-metre wide chains, as well as a central column supporting the wind turbine, 10 meters in diameter and immersed over 18 meters. The columns are connected to the central column by 3 rectangular bases measuring 10*8*21 meters. The surface area theoretically colonizable by biofouling per floating wind turbine was calculated to be 7216 m² (float + cables). The biomass of fixed species was estimated at 10 $kg.m^{-2}$ in the euphotic zone (the floats and the first twenty meters of cables) (Castric & Chasse 1991), as artificial reefs are typically colonized similarly to natural rocks (Coolen et al. 2020). In the case of complete colonization of submerged surfaces by fixed organisms, this estimation gives 72 tons of biofouling per wind turbine. With a spatial coverage of 1.5 km² per wind turbine, these estimates represent a biomass of 48 $t.km^{-2}$ at the offshore wind farm site. This high biomass is made possible by the large vertical surface area that can be colonized.

A forcing function was applied to increase the biomass of biofouling from 0.01 t.km² to 48 t.km² between 2025 and 2028 to simulate the installation of a floating wind farm in 2025, maintaining this biomass level until 2050. The model was calibrated using the "fit to time series" of Ecosim, which calculates the vulnerabilities of each species so that the values estimated by Ecosim are as close as possible to the integrated time series.

2.4. Ecospace

2.4.1. Presentation of the model

The Ecospace module inherits data from Ecosim and projects it onto a two-dimensional map representing the entire study area. This map consists of a grid of cells, each assigned specific environmental values. Using this information, Ecopath calculates a new food web for each cell, with biomass values estimated based on the environmental data. Each trophic group is assigned a dispersal rate, allowing biomass to move between cells according to the mobility of the organisms (Appendix G).

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For this study, the base map is a grid of 232×255 cells (59,160 cells), of which 40,764 correspond to the continental shelf. Each cell has a surface area of 5.06 km² (2.25 km size). Depth, primary production and sediment maps (rocks, coarse sediment, sand, fine sand, sandy mud, mud and muddy sand) were added as environmental data. The area chosen for the offshore wind farm's location was placed within the zone defined for the future South Brittany floating wind farm, situated 36 km from Lorient. The wind farm modeled in this study covers an area of 45 km², corresponding to 9 cells of the Ecospace grid.

2.4.2. Climate change simulation

To simulate the CC and CC+OWF scenarios, Ecospace was forced by the results of niche models for local species and NIS (Le Marchand et al. 2020), following the method established by Coll et al. (2019) and Bourdaud et al. (2021). This method consists of creating an environment suitability map for each trophic group, where the value of each cell corresponds to the probability of species presence or the average probabilities of presence for species in the trophic group predicted for 2050 under the RCP8.5 scenario, estimated by modeling its potential ecological niche (Le Marchand et al. 2022). Each created map is then indicated as the preferred habitat for the corresponding group in the "Habitat foraging usage" section. This input allows the model to define the spatial abundance of each trophic group for each grid cell (Christensen et al. 2014). The values vary from 0 to 1, depending on the degree of affinity of the trophic group for the environmental variables presented in the cell, 1 means that the cell is very favorable to the organism, resulting in high biomass.

2.4.3. Wind farm simulation

The OWF and CC+OWF scenarios were simulated based on two parameters: the reserve effect and the aggregation effect. The reserve effect was modeled by simulating no fishing activities inside the wind farm. In addition, species with a tendency to aggregate around wind turbines or under floats (horse mackerel, mackerel, pouts, pelagic piscivorous, pelagic planktivorous (Dempster, 2005; Reubens et al. 2013; Moreno et al. 2016)) were given a favorability of 1 in the wind farm zone. An environment suitability map specific to the "biofouling" trophic group, restricted to the wind farm area, was also created and indicated as preferential habitat in the "Habitat foraging usage" section.

Table 1: parameters modeled for each scenario: reference, climate change (CC), wind farms (OWF) and cumulative effects (CC+OWF).

Scenario	**Ecopath**			**Ecosim**	**Ecospace**			
	Biofouling ($0.01\ t.km^{-2}$)	**NIS**	**P/B and Q/B increased**	**Biofouling forced ($48\ t.km^{-2}$)**	**Locale species maps**	**NIS maps**	**Favorability (fish and biofouling)**	**Fisheries restriction**
Reference					X			
CC		X	X		X	X		
OWF	X			X	X		X	X
CC+OWF	X	X	X	X	X	X	X	X

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2.5. Achieving results

2.5.1. Biomasses and catches

Once parameterized, the model was projected over 34 years, with biomass and catches data recorded annually in the Bay of Biscay cells for all trophic groups. Only the last ten years were retained to ensure a stabilized system. These years were averaged to limit interannual variations. The results obtained are thus averages of biomass and catches for all trophic groups across all model cells, for each of the four scenarios.

Projected decadal biomasses and catches for each trophic group were extracted for the nine cells affected by the wind farm, as well as for the 16 neighboring cells around the wind farm. The data were then summed for each of these areas (within and outside the wind farm).

To study the changes induced within the wind farm and its surrounding area, an anomaly (in percentage) was calculated between the reference scenario and each of the three scenarios studied. The results presented in this study correspond to decadal biomass and catches anomalies in the areas studied (within and around the wind farm), compared with the reference scenario. For greater clarity, the trophic groups have been grouped into six assemblages (i.e. demersal fish, pelagic fish, piscivorous fish, benthos feeder fish, marine mammals & birds and benthic invertebrates - Appendix F). The biofouling trophic group was not integrated in the results. The results for each trophic group are presented in appendix H and I.

2.5.2. Cumulative effects assessment

To understand the effects of the CC+OWF scenario, the biomass and catches anomalies of the CC and OWF scenarios were summed and compared with the anomalies obtained with the CC+OWF scenario (Figure 2). If the addition of the two scenarios gives a higher result, either positive or negative, the cumulative effects scenario is said to be "dampened"; if the addition of the two scenarios gives a lower result, the cumulative effects scenario is said to be "synergistic"; if the addition of the two scenarios gives an opposite result, the cumulative effects scenario is said to be "antagonistic".

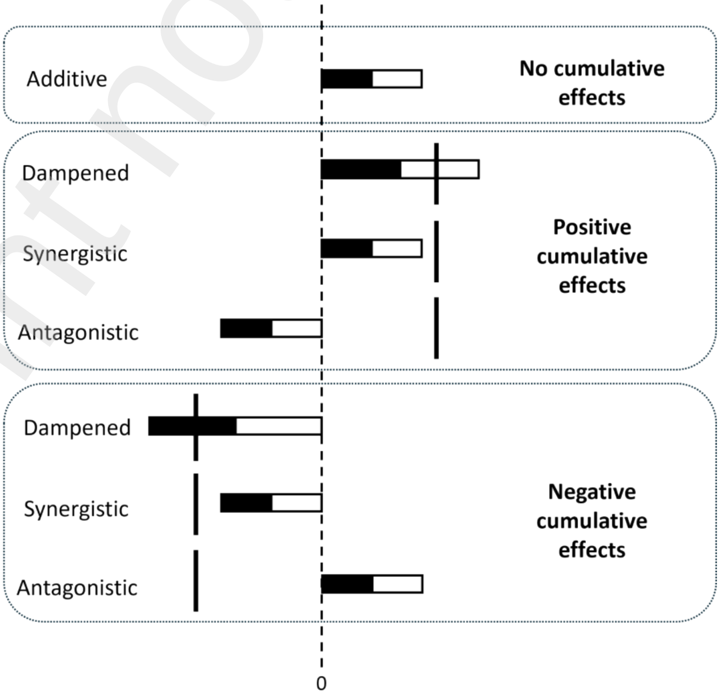

Figure 2: Conceptual diagram representing the results of the addition of two effects (black and white bars), compared with the results of a scenario of cumulative effects (black vertical lines) on a biological indicator, and the term associated with each

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case, used in figures 4 and 5. This graphic representation follows the broad lines of diagrams from the literature on cumulative effects (Halpern et al. 2008), applied to the specific characteristics of offshore wind farms and climate change (Nogues et al. 2023).

3. Results

The PREBAL analysis indicated that 13 out of 16 conditions are met for the reference scenario, OWF and CC+OWF, and 12 out of 16 conditions are met for the CC scenario (Appendix D).

3.1. Effects on biomasses

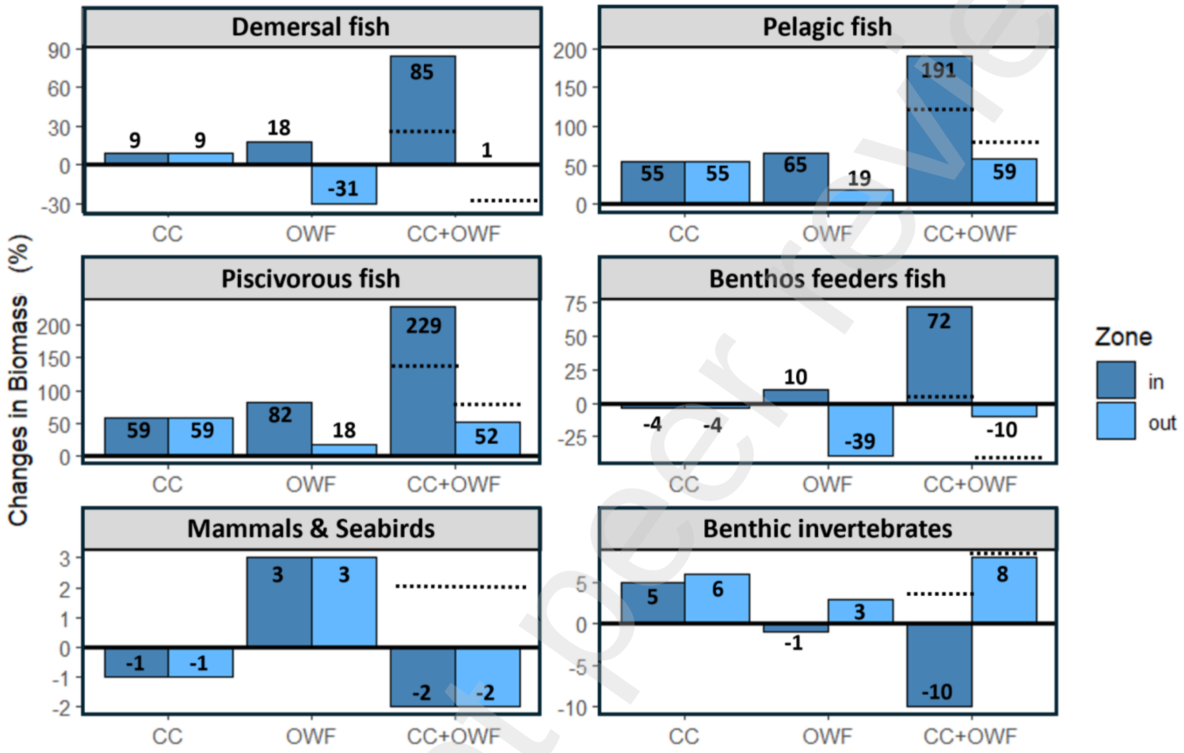

Figure 3: Relative biomasses change (in %) of the six assemblages (Appendix F) compared with the reference scenario for each scenario (CC, OWF and CC+OWF). The dark blue bars represent the areas inside the wind farm and the light blue bars represent the adjacent area outside the wind farm. Detailed information by species are given in the appendix H. The dotted lines correspond to the sum of results of CC and OWF scenarios, to compare the additive effects to the cumulative effects scenario CC+OWF.

The CC scenario positively influenced the biomass of demersal (+9% compared to the reference scenario), pelagic (+55%) and piscivorous fish (+59%). It also resulted in a 5% increase in the biomass of benthic invertebrates (Figure 3). Conversely, it lead to a decline in the biomass of benthos feeders fish (-4%), especially sole (-64%), plaice (-64%), and pouts (-75%) (Appendix H) as well as marine mammals and seabirds (-1%), notably toothed whales (-7%, Appendix H).

Under the OWF scenario, relative biomass differences are estimated between the inside of the wind farm ("in" zone - dark blue in Figure 3) and the outside the wind farm ("out" zone - light blue in Figure 3). Both inside and outside the wind farm, the relative biomass of pelagic fish (+65% and +19% respectively), piscivorous fish (+82% and +18%), and marine mammals and birds (+3%) increased. Demersal fish and benthos feeders increased in biomass inside the wind farm and decreased outside the wind farm (respectively +18% and -31% for demersal fish, and +10% and -39% for benthos feeders).

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In contrast, benthic invertebrates exhibited a decrease inside (-1%) and an increase outside the wind farm (+3%).

The CC+OWF scenario (Figure 3) demonstrated a positive synergy in the biomasses of fish groups within the wind farm: demersal (+85% compared to the reference scenario), pelagic (+191%), piscivorous (+229%), and benthos feeders (+72%). However, it showed a negative antagonism in the biomass of marine mammals and birds (-2%) and benthic invertebrates (-10%). Outside the wind farm, no synergy was observed. The cumulative effects on pelagic fish (+59%), piscivorous fish (+52%), and benthic invertebrates (+8%) resulted in a positively dampened effect on their biomasses while demersal fish experienced a positive antagonistic effect (+1%). Conversely, this scenario caused a negatively dampened effect on the biomass of benthos feeder fish (-10%) and a negative antagonistic effect on the biomass of marine mammals and birds (-2%).

3.2. Effects on catches

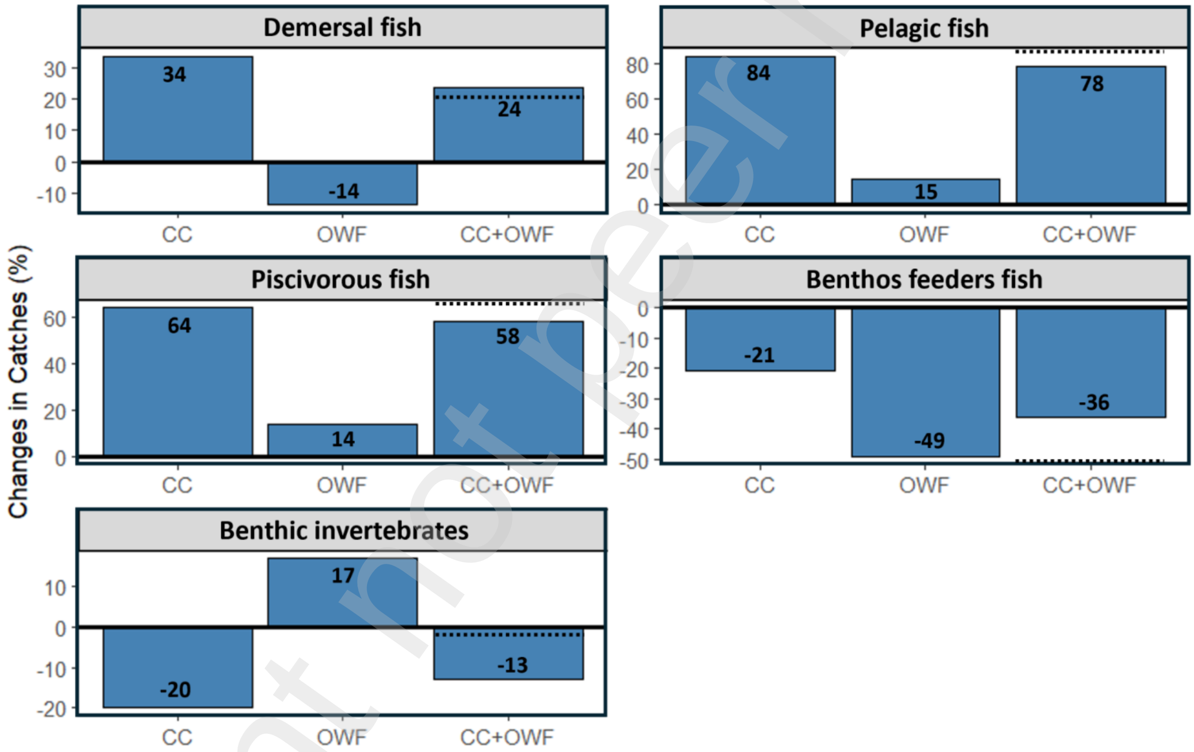

Figure 4: relative catches change (in %) of the six assemblages (Appendix F) compared to the reference scenario for each tested scenario (CC, OWF and CC+OWF). Only the area outside, adjacent to the wind farm, is shown, based on the assumption that the wind farm would be completely closed to fishing. Details by species are provided in appendix I. The dotted lines correspond to the sum of results of CC and OWF scenarios, to compare the additive effects to the cumulative effects scenario CC+OWF.

The CC scenario has positive impacts on the relative catches (Figure 4) of demersal fish (+34% compared to the reference scenario), pelagic fish (+84%), and piscivorous fish (+64%). However, it negatively affects the relative catches of benthos feeder fish (-21%), particularly sole (-60%), plaice (-58%), megrim (-13%), and pouts (-73%) (Appendix I), as well as benthic invertebrates (-20%), mainly due to the decline in catches of benthic cephalopods (-30%).

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The OWF scenario had a positive effect on the relative caches of pelagic fish (+15%), piscivorous fish (+14%), and benthic invertebrates (+17%), while it negatively impacts demersal fish (-14%) and benthic feeder fish (-49%).

For the CC+OWF scenario, the cumulative effects on relative catches follow a similar trend as those on relative biomasses for pelagic fish (+78% - positively dampened), piscivorous fish (+58% - positively dampened) and benthos feeder fish (-36% - negatively dampened). The cumulative effects on the relative catches of demersal fish resulted in a positive synergy (+24%) and a negative synergy on the catches of benthic invertebrates (-13%).

3.3. Effects of NIS arrivals

The biomass and catches estimated by the model for NIS over the period and the area studied were high (Table 2). For the CC scenario, the NIS biomass corresponded to 27% of the total fish biomass in the area and the catches corresponded to 36% of the total catches around the wind farm. For the CC+OWF scenario, the NIS biomass corresponded to 36% of the total biomass, and the catches corresponded to 37% of the total catches around the wind farm. These values revealed that NIS accounted for a significant proportion of the increases in biomass and catches estimated above.

Table 2: average biomasses ($t.km^{-2}$) and catches ($t.km^{-2}$) of the 8 NIS groups estimated by the model over the period 2040-2049, for the two scenarios incorporating these groups: CC and CC+ OWF.

	Biomasses		**Catches**	
NIS	**CC**	**CC+OWF**	**CC**	**CC+OWF**
Merluccius senegalensis	4.48	4.35	3.75	3.57
Trachurus tracae	8.08	61.91	0.61	0.57
Sardinella aurita	12.51	12.31	5.21	5.07
Flatfishes	5.82	2.64	0.20	0.10
Demersal benthos feeders	23.21	46.32	0.74	0.83
Demersal piscivorous	10.33	20.45	1.33	1.39
Pelagic piscivorous	0.78	1.74	0.32	0.34
Pelagic planktivorous	2.9	8.85	0.17	0.21

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4. Discussion

4.1. Limits of the study

In this study, we examine two pressures: climate change and the installation of a floating wind farm, using the Ecopath with Ecosim suite and its Ecospace spatial module. To model these pressures, we test four scenarios: a reference scenario, a climate change scenario (including the arrival of NIS, redistribution of local species, and increase in fish production and consumption parameters), a wind farm scenario (incorporating a biofouling trophic group for the reef effect, enhanced area favorability for certain fish species exhibiting aggregation behavior, and the closure of the wind farm area to fishing activities for the reserve effect), and a scenario combining the cumulative effects of climate change and the wind farm.

First, we must point out several limitations that should be considered when interpreting the results. Beyond the usual limitations of ecosystem models (Steenbeek et al. 2021), from which Ecopath is no exception, such as gaps in knowledge, input precision, and the need to account for uncertainty, the methodology we developed here has its own specific limitations. To begin with, accounting for the reef effect is an essential parameter. This issue, common to offshore wind farms, has been extensively studied (Werner et al. 2024; Nall et al. 2017; Coates et al. 2014). In our model, biofouling has been integrated through a specific group composed of fixed filter-feeding organisms, whose biomass has been drastically increased in Ecosim, and confined to the wind farm area in Ecospace. However, the literature indicates that the colonization of submerged structures is more complex, featuring rich specific diversity that varies greatly depending on the location of the sites, depth, and seasonality (Zupan et al. 2023; De Mesel et al. 2015). Consequently, biofouling biomasses and species compositions might vary significantly (Degraer et al. 2020). Given the structuring role of these organisms, we need to refine our knowledge and integrate these biomass variations into trophic models. To this end, the spatial-temporal framework implemented in the ecospace module (Steenbeek et al. 2013) could greatly improve the modeling of biofouling development via the implementation of local biomass maps at different time steps, which would integrate fine-scale temporal variations. This module could also be used to better incorporate the effects of climate change on the distribution of local species. This method takes into account the probability of presence of the species and projects a redistribution of the initial biomass and habitat preferences over the study area (Bourdaud et al. 2021), while the spatial-temporal framework could permit introducing this sequentially. Next, we included NIS in our study because it is undeniable that climate change is causing species to move towards the poles, leading to a tropicalization of communities in the Bay of Biscay (Montero-Serra et al. 2015; Vergés et al. 2014). However, these species are difficult to integrate into Ecopath for two main reasons: their future biomass remains unknown, which conditions their impact on the food web. Moreover, diets in Ecopath are fixed and don't take into account the opportunistic predation in. To overcome these constraints, we allowed Ecopath to estimate the NIS biomasses and manually set up the diets (Le Marchand et al. 2022). By doing this, we have directly modified the structure of the model for each of the results.

Finally, the trophic model we developed was designed on the scale of the Bay of Biscay continental shelf. While this scale is ideal for studying the effects of species displacement on food webs, it is debatable whether it is perfectly suited to smaller-scale issues, such as wind farms. Here, we have zoomed into the study area. However, the model resolution (5.06 km² - 2.25 km size) is quite large. A smaller spatial grid would allow better characterization of the flows at the scale of the wind

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farm, in particular to get a better spatial definition of any spillover generated by the reserve effect. The limitations related to the scale and resolution of Ecospace have also been pointed out in other ORE studies (Alexander et al. 2016).

4.2. Changes in communities as a result of climate change

The trophic assemblages we modeled were projected to differently react to the CC scenario. As already discussed in the previous study presenting the niche model maps integrated here (Le Marchand et al. 2020), the redistribution of local species following the increase in water temperature is mainly observed in benthos feeders demersal fish. Indeed, bottom-dwelling species were projected to shift westward to find more suitable temperatures at depth (Lenoir and Svenning 2015; Dulvy et al. 2008). This results in a drop in the biomass of flatfish species, particularly sole, plaice and megrim (Appendix H). The strong impact of climate change on flatfish populations has already been noticed in the Bay of Biscay (Hermant et al. 2010). The direct consequence is an increase in the biomass of carnivorous and necrophagous species (Appendix H), for which flatfish are the main predators. On the other hand, while a general increase in the biomass of benthic invertebrates has been demonstrated with the CC scenario, the trends vary from one trophic group to another, reflecting the changes in trophic flows caused by this shift in communities (Pecl et al. 2017).

At the same time, the arrival of pelagic (i.e. *Sardinella aurita*) and piscivorous (i.e. *Trachurus tracae*) NIS also leads to modification in the local food web (Libralato et al. 2015). The NIS biomasses estimated by the model in this study are very high and seem to play a major role in the increased biomass and catches that result from the CC and CC+OWF scenarios. A decrease in the biomass of toothed whales is assessed under the CC scenario, probably due to increased trophic competition from the arrival of new piscivores. The arrival of these new piscivore fishes directly impacts the catches of benthic and pelagic cephalopods.

4.3. Complex changes in the food web caused by the wind farm.

In this study, we were able to integrate both reef and aggregation effects. The aggregation effect was directly modeled using the habitat foraging tool, which increases the favorability of the site for species that tend to congregate under floating structures. The species are mainly pelagic, and therefore highly mobile, allowing them to gravitate around the wind farm in areas open to fishing. The reef effect was estimated by the sharp increase in biofouling biomass in the wind farm (Wilhelmsson and Malm 2008). This had the indirect effect of modifying the food web flows within the site, demonstrating the attractiveness of the wind turbines for benthos feeder species not subject to the aggregation effect (Werner et al. 2024; Bergström et al. 2013). Indeed, the attractiveness of mobile species due to the reef effect has already been recorded and modeled in offshore wind farms (Zupan et al. 2023; Salaün et al. 2023; van Hal et al. 2017). A study in the North Sea has demonstrated that offshore wind farms built on soft sediment have a positive influence on plaice populations, due to the abundance of food and the restriction of fishing activities (Buyse et al. 2023). In the same way, a relatively small biomass increase of demersal benthos feeders within the wind farm has been already recorded in the Baltic Sea (De Troch et al. 2013; Wilhelmsson et al. 2006). In our study, this attractiveness induces a trophic cascade resulting in a decrease in the biomass of benthic invertebrates inside the wind farm. Another indirect effect of this attractiveness due the reef effect is an increase in

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the biomass of benthic invertebrates outside the wind farm, leading to larger catches of benthic cephalopods, Norway lobsters, and large crustaceans in these areas. On the other hand, the result on pouts is unexpected (Appendix H) as a sharp decrease in their biomass is assessed inside the wind farm, despite the fact that this species is subject to the aggregation effect and is a major predator of biofouling (Reubens et al. 2013; Reubens et al. 2011). This result could be explained by significant predation pressure exerted on this species by piscivorous demersal fish, whose biomass increased in the wind farm.

The reef and aggregation effects make the wind farm attractive to mammals and seabirds, whose biomass was projected to increase in the OWF scenario. It is therefore difficult to distinguish the part due to the reef effect and the part due to the aggregation effect, nevertheless the installation of the wind farm leads to a strong reorganization of the local food web (Raoux et al. 2017). Additionally, the increase in biomass and catches of species that are not subject to the aggregation effect and do not consume biofouling, such as sardines and anchovies, could reflect a reserve effect (Lester et al. 2009). In the same way, Alexander et al. (2016) used species percentage biomass to estimate changes after a 25-year projection period following the installation of ORE devices closed to fisheries. They assessed an increase in monkfish (*Lophius piscatorius* and *L. budegassa*), edible crabs (*Cancer pagurus*) and lobster (*Homarus gammarus*) biomasses, due to a strong reserve effect.

4.5. Local mitigation of climate change through wind farm stronger effects.

To evaluate the combined impacts of the wind farm and climate change on food webs, we conducted an analysis of the cumulative effects between the CC and OWF scenarios compared to the relative differences obtained under the CC+OWF scenario. This approach aligned with the methodology of Nogues et al. (2023). Our results revealed significant variability in cumulative effects, with indications that the wind farm exerted more pronounced overall effects—both beneficial and detrimental. Although Ecopath is regularly employed to model pressures on marine ecosystems, particularly in combination with climate change, the cumulative effects of renewable energies with other pressures remain little studied to date (Stock et al. 2023).

Within the wind farm, the aggregation of species and the reef effect significantly outweighed the localized impacts of climate change. The arrival of NIS further boosted fish biomass in groups already benefiting from increased prey availability and shelter provided by the wind farm, particularly enhancing benthic feeder fish populations at local scale. While benthos feeder fish experienced negative impacts from climate change alone, the cumulative effect was positive, suggesting a local compensation for biomass losses due to climate impacts through the wind farm's habitat attractiveness on some species. In contrast, the cumulative impacts on benthic invertebrate biomass within the wind farm had a negative antagonistic trend, implying that the predation pressure induced by the wind farm mitigated the positive effects of climate change at local scale. Outside the wind farm, the cumulative effects are positive for demersal, pelagic, and piscivorous fish. The arrival of NIS and the redistribution of local species would compensate for the decrease in demersal biomass outside the wind farm indirectly caused by its attractiveness (reef and aggregation effects). Moreover, the high dispersal rate of pelagic species, which are highly mobile, would explain the increase in their biomass around the wind farm. This displacement could be explained by the large amount of prey within the wind farm. Regarding the biomass of benthic invertebrates outside the wind farm, cumulative effects

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are positively moderated due to a reduced predation pressure facilitated by the redistribution of benthos feeder species and the attractiveness of the wind farm.

On the contrary, for mammals and seabirds, climate change appears to exert a more significant influence on biomasses both within and outside the wind farm, leading to antagonistic cumulative effects. This suggests that the attraction of the wind farm does not offset the biomass declines caused by climate change. This outcome underscores a recurring issue addressed in previous studies concerning the effectiveness of marine protected areas in benefiting highly mobile marine species (Wilson, 2016). In addition, the study does not take account of all the effects of the wind farm, as for example the potential avoidance of the area due to noise emissions, particularly by top predators such as cetaceans and seabirds (Cook et al. 2018; Serpetti et al. 2021). Wind farms could also lead to changes in biogeochemistry (Daewel et al. 2022), with knock-on effects throughout the food web, particularly in bottom-up systems. By modeling these effects in addition, the wind farm's failure to compensate for climate change could be even more pronounced. In order to properly understand the changes brought about by a wind farm in the ecosystem, it is necessary to study these little-known effects, and to quantify them so that they can be included in future studies on the cumulative effects of wind farms.

Finally, the cumulative effects on catches for demersal, pelagic and piscivorous fish are positive, reflecting increased biomasses outside the wind farm. Conversely, cumulative effects on benthos feeder fish were modeled as negatively dampened, consistent with their decreased biomass outside the wind farm. These changes could have consequences for traditional fisheries, by reducing fishing pressure on benthos feeders, particularly flatfish. Besides, a study in the North Sea suggests that the installation of wind farms could alter the population dynamics of flatfish by affecting recruitment (Barbut et al. 2020). The fishing pressure could be shifted to pelagic fish, which seem to gravitate around wind farms, and whose biomass could increase with the arrival of NIS. This change in fishing strategies could compensate for the losses modeled in this study. Thus, cumulative effects on catches of benthic invertebrates exhibit negative synergistic trends. Finally, it should be noted that we have considered here that NIS would be of the same commercial interest as local species, but it is possible that this will not be the case, which would de facto modify local catches. Also in this study, only the hypothesis of a ban of fishing activities inside the wind farm was modeled. However, different hypotheses could be tested, such as the partial opening of the wind farm or the authorisation of certain static fisheries, such as lines or traps, whose great potential has been demonstrated in the North Sea, but whose feasibility needs to be explored in terms of both benefits and safety (Bonsu et al. 2024).

5. Conclusion

The ecosystem approach is an environmental management method that enables the modeling of management scenarios integrating all ecosystem components. In this study, we used the Ecopath with Ecosim trophic model, to assess two current pressures on the Atlantic coast: climate change and the exploitation of an offshore wind farm, both individually and in combination. This approach has demonstrated efficacy, yielding results consistent with findings from analogous studies or empirical observations. Particularly notable are the impacts on communities triggered by climate change, including the introduction of NIS and shifts in the distribution of local species. The study also identifies significant alterations in species composition and biomasses inside and outside the wind farm area, attributable to reef effect, aggregation dynamics, and reserve effect. It should be noted, however, that

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the two pressures do not act on the same spatial scale: the effects of offshore wind farms remain localized, whereas climate change acts on a global scale. While ORE are a solution, it is still necessary to reduce consumption.

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