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► To cite this version:

Quentin Noguès, Yoann Baulaz, Joanne Clavel, Emma Araignous, Pierre Bourdaud, et al.. The usefulness of food web models in the ecosystem services framework: Quantifying, mapping, and linking services supply. *Ecosystem Services*, 2023, 63 (Art. 101550), 14 p. 10.1016/j.ecoser.2023.101550 . hal-04202055

HAL Id: hal-04202055

<https://hal.science/hal-04202055>

Submitted on 11 Sep 2023

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1 **The usefulness of food web models in the Ecosystem Services framework:**
2 **quantifying, mapping, and linking services supply**

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21 Journal: **Ecosystem services**

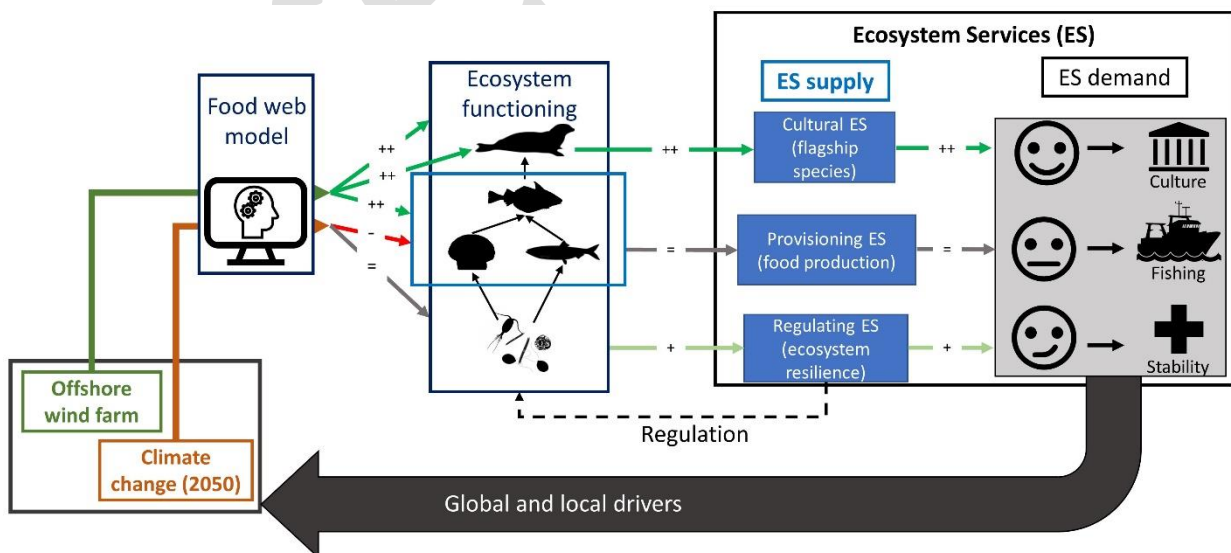
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23

24 Abstract

25 Coastal ecosystems provide a wide range of valuable ecosystem services (ES) for human
26 wellbeing. Such services depend on the functioning and structure of ecosystems.
27 Unfortunately, these ecosystems are threatened by humans, directly impairing their ability to
28 provide these services. In order to predict such changes, we used a food web model to forecast
29 potential spatial changes in ES supply in the Seine Bay (English Channel), due to climate change
30 effects (CC) and the setup of an offshore wind farm (OWF). Three ES were studied, food
31 production from fishing, top predator production for cultural purposes and the potential
32 resistance of the ecosystem inferred from its organization. The ability of the Seine Bay
33 ecosystem to produce food appears to be negatively impacted by the effect of climate change.
34 Because of the important economic role of fishing in Normandy, such changes could percolate
35 on the entire social and economic system of the bay. The Courseulles-sur-Mer offshore wind
36 farm appears to increase the supply of services and limit the impact of climate change at the
37 local spatial scale, which could give stakeholders insights into mitigating the effects of climate
38 change. Such ecosystem approach enables for a more integrative view of ES supply, through
39 the characterization of the entire system functioning.

40 **Key words:** Ecosystem services supply; Ecosystem functioning; Ecological network
41 analysis; Ecosystem change; cumulative effects; mapping



42

43 Graphical abstract

44 1 Introduction

45 Marine and coastal ecosystems are of great importance for societies around the world
46 as they provide many ecosystem services (ES) of high values (Galparsoro et al., 2012; Martínez
47 et al., 2007). Unfortunately, these ecosystems are highly threatened by anthropic activities.
48 Indeed, more than half of all humans live at least 200 kilometers from the coast (Kennish,
49 2002; UNEP et al., 2012), which puts a tremendous pressure on them, through fishing or
50 habitat destruction, among others. Such pressures may threaten the supply of ES and thus
51 change our relationship with nature (MEA et al., 2005; Worm et al., 2006). In order to better
52 manage such changes, we need to adequately quantify the supply of ES (De Groot et al., 2010),
53 as well as their evolution in the face of changes resulting from multiple anthropic drivers like
54 climate change (CC), fishing, and marine renewable energies, among others. We need to
55 develop holistic approaches that can properly model the effects of a wide range of drivers on
56 whole ecosystems, on their structure and organization, and more importantly for ES, their
57 functioning (De Groot, R.S., 1992; Duncan et al., 2015; Hein et al., 2006).

58 Modeling marine ecosystems as interconnected systems is necessary to accurately
59 portray their dynamic and functioning (Shurin et al., 2006), with changes in one part of the
60 system often cascading throughout the whole system. Ecosystem-based management has
61 been described as the solution needed to enable a sustainable exploitation of marine
62 ecosystems (Buhl-Mortensen et al., 2017; Gregory et al., 2013), and in an ecosystem services
63 (ES) framework, to better maintain the supply of a wide range of ES (Beaumont et al., 2007).
64 Indeed, the supply of ES depends on the functioning of the entire ecosystem, and many
65 ecological groups may play a significant role supplying ES, at a wide range of scales (Kremen,
66 2005). Using ecosystem approaches to quantify ES thus responds to the demands of
67 stakeholders in the management and monitoring of the marine environment, to adequately
68 predict potential changes in the functioning of coastal ecosystems.

69 Food web models are ideal Ecosystem-based management tools as they quantify trophic
70 interactions in marine ecosystems (predator prey relationships). They can quantify many
71 aspects of ecosystems, from structural information (biomasses) to, here, more informative
72 functional information like energy flows between ecological groups, providing knowledge
73 about the ecosystem functioning (Thompson et al., 2012). They can thus quantify the

74 secondary production of any ecological group in an ecosystem and the effective activity of
75 such group in providing a said ES (Beaumont et al., 2007; Duncan et al., 2015). Moreover,
76 information other than group production can also be quantified using ecological network
77 analysis (ENA). With network analysis, more complex information relying on the trophic
78 pathways of the entire food web can be computed. This is used to better understand the
79 properties of an ecosystem (Finn, 1976; Libralato, 2013; Ulanowicz and Norden, 1990; Nogues
80 et al., 2022). They can be linked to emerging properties of ecosystems like maturity or
81 ecological resilience which are inherently linked to the ecosystem functioning (Bondavalli et
82 al., 2006; Christensen, 1995; Saint-Béat et al., 2015). Food web models can thus help assess a
83 wide variety of ES, while keeping an integrative view of ecosystems and considering their
84 inherent complexity.

85 Food web models have been widely used to study human impacts on ecosystems. These
86 models were applied to the Bay of Seine to simulate the ecosystem effects of different
87 anthropogenic pressures and enhance our understanding of ecosystem functioning (Halouani
88 et al., 2020; Raoux et al., 2017; Tecchio et al., 2016). However, despite the improved
89 capabilities of food web models in the last years, the effects of anthropogenic pressures were
90 often limited to fishing pressure (Kytinou et al., 2020). The wide range and diversity of outputs
91 they provide could help to better address the diversity of human-nature relationships such as
92 the cultural ES category (looking at specific species or hole ecosystem parameters like
93 diversity), which has often been neglected (Blicharska et al., 2017). Integrating social sciences
94 into ecological research has become a top issue in the ES scientific community (Collins et al.,
95 2011; Redman et al., 2004). Extensive theoretical work has been done on food webs, providing
96 a great deal of knowledge about ecosystems and their regulatory mechanisms (Frederiksen et
97 al., 2006; Menge, 2000). However, the link between complex quantitative approaches and
98 values related to human-nature relationships are rarely mobilized in the ecosystem services
99 literature, and even less so in ES assessment works.

100 In this paper, we show the usefulness of Ecospace, a spatial food web modeling
101 approach, to quantify the supply of several ES in the extended Seine Bay (eBoS) in the English
102 Channel. This work is not intended to extensively quantify each ES supplied by the eBoS
103 ecosystem, but rather to show the potential of food web models to quantify ES supply using
104 functional model outputs. One service from each category of ES of the CICES (*Common*

105 *International Classification of Ecosystem Services*) was chosen (Haines-Young and Potschin,
106 2018), each depending on different biotic component (either species or group of species).
107 After selecting the most suitable indices — from basic production output to a more complex
108 network index — we quantify the actual supply of each of these ES and map the eBoS based
109 on its ability to provide the selected ES. We identify spatially which of the functional regions
110 of the eBoS play a key role in ES supply. We use insights from previous works on the eBoS to
111 model the potential effects of CC and of an offshore wind farm (OWF) on the supply of the
112 selected ES. Furthermore, we combine CC and the OWF to determine their cumulative effects
113 on the selected services. Finally, we discuss the utility of food web models in quantifying ES,
114 their benefits and especially their ability to bring an environmental view to the ES framework.

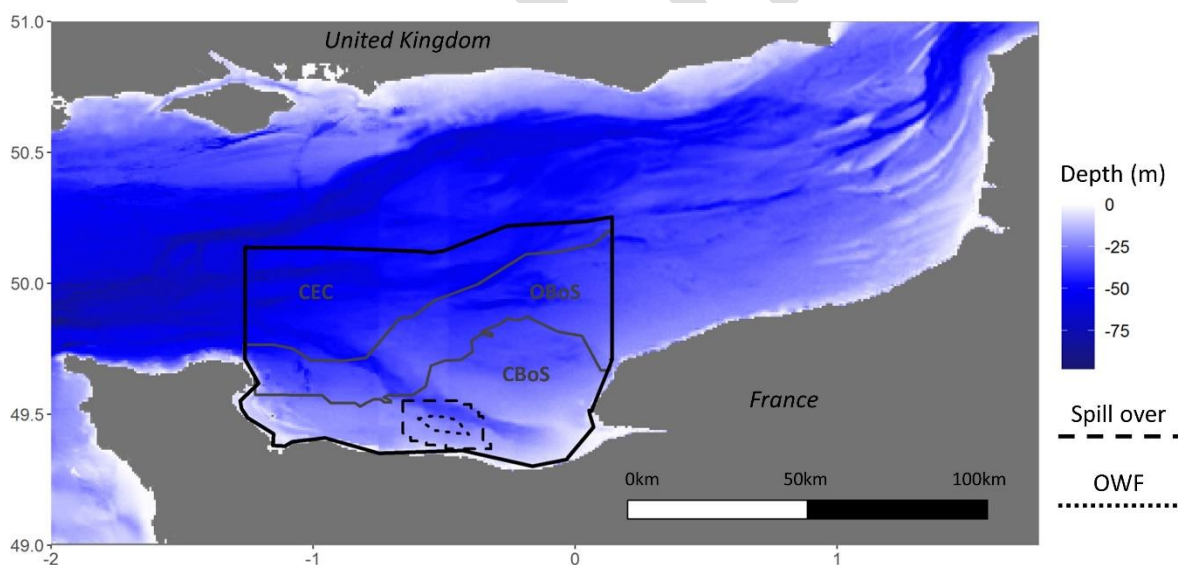
115 2 Materials and methods

116 2.1 Study area

117 The extended Seine Bay (eBoS) is a sea space enclosed between the Cotentin peninsula
118 on the west and the 'Pays de Caux' in Normandy, on the east. South of the eBoS is the Calvados
119 Coastline in France and north is the French-British delimitation of the Exclusive Economic
120 Zones (Figure - 1). It is a shallow coastal system open on the north to the English Channel, with
121 a mean depth of 35 m. Notable geomorphologic features include the Seine estuary south-east
122 of the eBoS and the Seine estuary paleo-valley on the north-west (Dauvin, 2015). The eBoS
123 ecosystem can be divided into three functional regions, from coast to offshore, with the most
124 coastal regions being the most productive and most ecologically diverse (Nogues et al., 2022).
125 This is reflected in the ecosystem functioning of these regions, with the most coastal region
126 being more resilient and complex than the offshore ones. Other structural sub-regions were
127 also defined, inside the OWF (OWF), and around it (spillover zone). These regions were
128 defined to help distinguish the effects of the different drivers on the ecosystem.

129 The eBoS ecosystem, inside the English Channel, with a ship entering or leaving it every
130 ~ 10 minutes, is one of the busiest shipping corridors in the world with 20% of the global
131 maritime transport (Buléon and Shurmer-Smith, 2021). Its coastlines are densely populated
132 with densities often reaching 500 inhabitants/km², a significant population living in close
133 proximity of the eBoS and benefiting from its ES, the eBoS is home to a wide variety of
134 anthropic activities (Buléon and Shurmer-Smith, 2021; Dauvin et al., 2020). The Normandy

135 coastline is an important known tourism area: mainly recreational (marinas, seaside resorts,
136 "blue flag" label, sailing, *etc.*), historical and cultural (World War II landing beaches being
137 classified as a UNESCO World Heritage Site, Viking invasions, museums and maritime heritage,
138 *etc.*), and also natural (animal watching, hiking, coastal paths, *etc.*). Fishing plays an essential
139 role in the eBoS, including on-foot fishing. Several big fishing ports are located in direct
140 proximity of the eBoS; Port-en-Bessin is the port in France for king scallops fishing (more than
141 15,000 tons of annual catch in Normandy) and the fourth most earning fish market in France
142 in 2016 (Buléon and Shurmer-Smith, 2021). Aquaculture activities (mussels and oysters) are
143 also important. The eBoS sea space has important marine renewable energy perspectives (one
144 of the largest in Europe) with two OWF under construction, Courseulles-sur-Mer (~ 50 km², 64
145 turbines) and Fécamp (~60 km², 71 turbines) on its east. A third wind farm will be located in
146 Dieppe-Le-Tréport, while a fourth and a fifth OWF are also under discussion and should be
147 located in the northwestern part of the Seine Bay. Thus, the eBoS plays a key role for many
148 people and activities, making crucial the understanding of its ability to provide ES, and how
149 this may evolve in response to human activities.



150

151 **Figure - 1 Map of the extended Seine Bay (eBoS) within the English Channel.**

152 The eBoS model is mapped with a continuous black line and includes
153 the coastal system of the Bay of Seine from 5 meters depth to the France/UK
154 Exclusive Economic Zone delimitation. The offshore wind farm (OWF) sub-
155 region is mapped with a dotted line, and the spillover sub-region around the
156 park in a dashed line. Inside of the eBoS, the functional regions of the
157 ecosystem determined in Nogues et al., 2022 are indicated: the Central

158 English Channel (CEC), the Offshore Bay of Seine (OBoS) and the Coastal Bay
159 of Seine (CBoS).

160 2.2 Spatial food web modeling of the eBoS using Ecospace.

161 Food web models are network models that represent prey/predator interactions to
162 quantify the pathways of energy between the different ecological groups of an ecosystem
163 (Dunne, 2006). They are composed of nodes and edges: nodes represent ecological groups,
164 i.e., one or several species with similar ecology and trophic sources (Gauzens et al., 2015),
165 edges are flows of energy between nodes and represent prey/predator interactions. Food web
166 models have been created for determining ecosystem's unknowns that are hard to quantify
167 *in situ*. Many approaches to model food webs exist in the literature (Kytinou et al., 2020),
168 which may be static (steady-state model) or dynamic, in time and even space. In this study we
169 used a spatio-temporal dynamic model, Ecospace, which is part of a modeling approach called
170 *Ecopath with Ecosim (EwE; Pauly et al., 2000)*. The *EwE* framework is composed of three
171 models: *Ecopath* (steady state approach), *Ecosim* (time dynamic approach) and *Ecospace*
172 (spatial-temporal approach).

173 Food web models of the eBoS were built to perform various studies of the effects of
174 multiple anthropic activities (Supplementary materials Table S – 1, S – 2 & S - 3). A full
175 description of the *EwE* framework used to build food web models of the Bay is available in
176 Pauly et al. (2000). The *EwE* framework is based on *Ecopath*. *Ecopath* is used to define the
177 system topology, which includes the number of trophic groups using biomass, production,
178 consumption and ecotrophic efficiency data, and the links between groups using species diet.
179 *Ecopath* follows two main equations which set its steady state nature:

$$\text{Production} = \text{Predation mortality} + \text{fishing mortality} + \text{biomass accumulation} + \quad (1) \\ \text{net migration} + \text{other mortality.}$$

$$\text{Consumption} = \text{Production} + \text{respiration} + \text{excretion} \quad (2)$$

180 The eBoS *Ecopath*, *Ecosim* and *Ecospace* models are composed of 42 groups, including
181 40 living groups and 2 non-living groups. Living groups include a large spectrum of marine
182 species from planktivorous species to marine mammals and sea birds (Supplementary
183 materials Table S – 4 & S - 5).

184 Ecosim is the time dynamic module of Ecopath (Christensen and Walters,2004). It was
185 implemented based on parameters inherited from the Ecopath model of Bay of Seine
186 (Halouani et al. 2020). The Ecosim model was fitted to times series of catches and biomass to
187 calibrate the relationship dynamics between the different trophic group for the period 2000
188 – 2015 (Supplementary materials Table S – 2 and Halouani *et al.* 2020).

189 Ecospace is the spatio-temporal module of Ecopath that allows the representation of
190 the dynamics of the different components of the ecosystem on a two-dimensional spatial grid
191 with homogeneous cells of equal size (each cell being a dynamic trophic model). Trophic
192 groups and fishing fleets are assigned to the different cells of the Ecospace model using
193 environmental drivers. Trophic groups can move between the cells of the grid according to
194 “Eularian” approach and the distribution of the fishing mortality is based on a gravity model
195 (Walters et al., 1999, Walters et al., 2010). Ecospace can also be used for spatial management,
196 to simulate spatial fishing regulations.

197 The Ecospace spatial model of the eBoS was composed of 4907 cells, each cell modeling
198 a time dynamic Ecosim food web model and having a resolution of 0.015° x 0.015°. The
199 distribution of the 40 trophic groups in each cell of the Ecospace was set using multiple
200 environmental driver maps (Environmental maps and suitability maps, see (Supplementary
201 materials Table S – 2). Environmental maps include depth map from GEBCO (Supplementary
202 materials Table S – 2, Figure S - 1) as well as a primary production map from SeaWifs
203 representing the relative chlorophyll a concentration in the bay in 2000 (Figure S - 2). As for
204 suitability maps, they were added in Nogues et al. (2022) and were built from species
205 distribution model (SDM) suitability index maps (Christensen et al., 2014; Coll et al., 2019;
206 Supplementary Materials Table S- 2, 3 and 4). SDM are correlative approaches, which correlate
207 species occurrences with environmental parameters to determine species habitat suitability.
208 Species distribution models used climatic as well as habitat parameters (Ben Rais Lasram et
209 al., 2020; (Supplementary materials Table S – 3). When ecological groups were composed of
210 only one species, SDM outputs were directly applied to drive the group distribution while
211 groups composed of multiple species were driven according to the weighted suitability index
212 maps of each species, based on their biomass (Bourdaud et al., 2021). More details on the
213 models are available in Halouani et al. (2020) and Nogues et al. (2022).

214 The finalized eBos Ecospace model developed in Nogues et al. (2022) is used as
215 reference scenario and represents the current state of the ecosystem before introducing
216 impacts induced by different anthropogenic drivers.

217 2.3 Anthropogenic drivers modeling

218 Modeling the effects of CC and of the Courseulles-sur-Mer OWF on the food web of the
219 eBoS was made by Nogues et al. (2022) using different data sources introduced in Ecospace
220 using built-in tools. We describe briefly the methods used here.

221 SDM suitability index maps were used to define species distribution and to simulate the
222 effect of CC on species distribution. As described before, the initial distribution of species was
223 driven by suitability index maps computed using current climatic parameters (2012 to 2015).
224 To model the climate change effect, SDM were also run with climatic parameters from forcing
225 scenarios of the IPCC (Intergovernmental Panel on Climate Change) (Ben Rais Lasram et al.,
226 2020). We tested different scenarios and favored the RCP 8.5 scenario at the 2050 horizon
227 because we considered it more realistic (Schwalm et al., 2020). For introducing suitability
228 index maps in the Ecospace model, we used the Spatial-Temporal framework of *EwE 6*
229 (Steenbeek et al., 2013). This allowed us to replace the reference suitability index maps with
230 the CC suitability index maps as environmental drivers, thus changing the habitat suitability
231 for each species according to the expected effect of CC on the species distribution. By changing
232 the habitat suitability and following the foraging arenas theory (Ahrens et al., 2012; Walters
233 et al., 1997), this altered multiple predation parameters for the species and *in fine* the species
234 vulnerability to predation, its consumption and thus its production (Christensen *et al.*, 2014).

235 To model the potential effects of the Courseulles-sur-Mer OWF, data from previous
236 studies on its potential impacts were introduced in Ecospace through built-in tools. Here we
237 have decided to model the long lasting and structuring effects of the OWF on the ecosystem,
238 thus we focused on the impact of the operational phase of the OWF (Bergström et al., 2013;
239 Elmer et al., 2006; Koeller et al., 2006). Many sources state that the most relevant long-lasting
240 effects of the OWF on its environment are the reef effect caused by the arrival of new hard
241 substrate and the partial reserve effect caused by the closing of fishing activities within the
242 OWF area (Degraer et al., 2020; De Mesel et al., 2015; Langhamer, 2012). The reserve effect
243 of the Courseulles-sur-Mer OWF was first modeled by Halouani *et al.* (2020), of which we

244 follow the method. In Ecospace, marine protected areas can be created by blocking fisheries
245 access to certain cells of the grid. In this manner, 6 out of the 37 cells of the OWF area were
246 prohibited to fishing activities as to correctly represent the OWF owners' proposal to
247 "optimize" fishing by closing only fifteen percent of the OWF total surface (Raoux et al., 2018).

248 To model the potential reef effect caused by the OWF, we used results from Raoux et
249 al. (2017), who modeled the Courseulles-sur-Mer OWF reef effect with Ecopath. There, several
250 groups biomasses were forced as they appeared to be benefiting from the reef effect of the
251 OWF in other parks in Europe (Supplementary materials Table S - 8). The same effects on the
252 same ecological groups were model in the eBoS Ecospace model using new environmental
253 driver maps, which mirror the forcing used by Raoux et al. (2017). Thus, the habitat of the
254 OWF was made more suitable for the species considered attracted by the OWF reef effect in
255 Raoux et al. (2017) (the increase in biomass was translated in an increase in habitat suitability,
256 benefiting species consumption, production and thus biomass).

257 Scenarios tested here thus include: the reference scenario, the offshore wind farm
258 operation with the reef and the partial reserve effect, climate change in 2050, and all
259 anthropogenic drivers combined.

260 2.4 Ecosystem services quantification

261 Using the previously published eBoS model, we quantified ES supply following Haines-
262 Young and Potschin (2010 & 2018) framework and considered ES supply to be the result of
263 ecosystem functions which determine the "capacity of ecosystems to provide goods and
264 services that satisfy human needs, directly and indirectly" (De Groot, 1992). We also
265 considered the requirements of Boerema et al. (2017) to coherently define what is quantified:
266 is it the actual supply of ES or the potential supply of ES? The potential supply of ES refers to
267 the capacity of the system to produce such services while the actual supply of ES defines the
268 part used for the well-being of human population (Bastian et al., 2012).

269 Ecospace will produce a wide range of outputs: from structural outputs like groups
270 biomass and trophic levels, to fishing outputs like fishing mortality, and even functional
271 outputs like catches and trophic flows between groups when using the enaR Ecospace plugin
272 (Nogues et al. 2022). Here we used functional outputs, either directly looking at groups
273 production or through Ecological Network analysis (Supplementary materials Table S - 9).

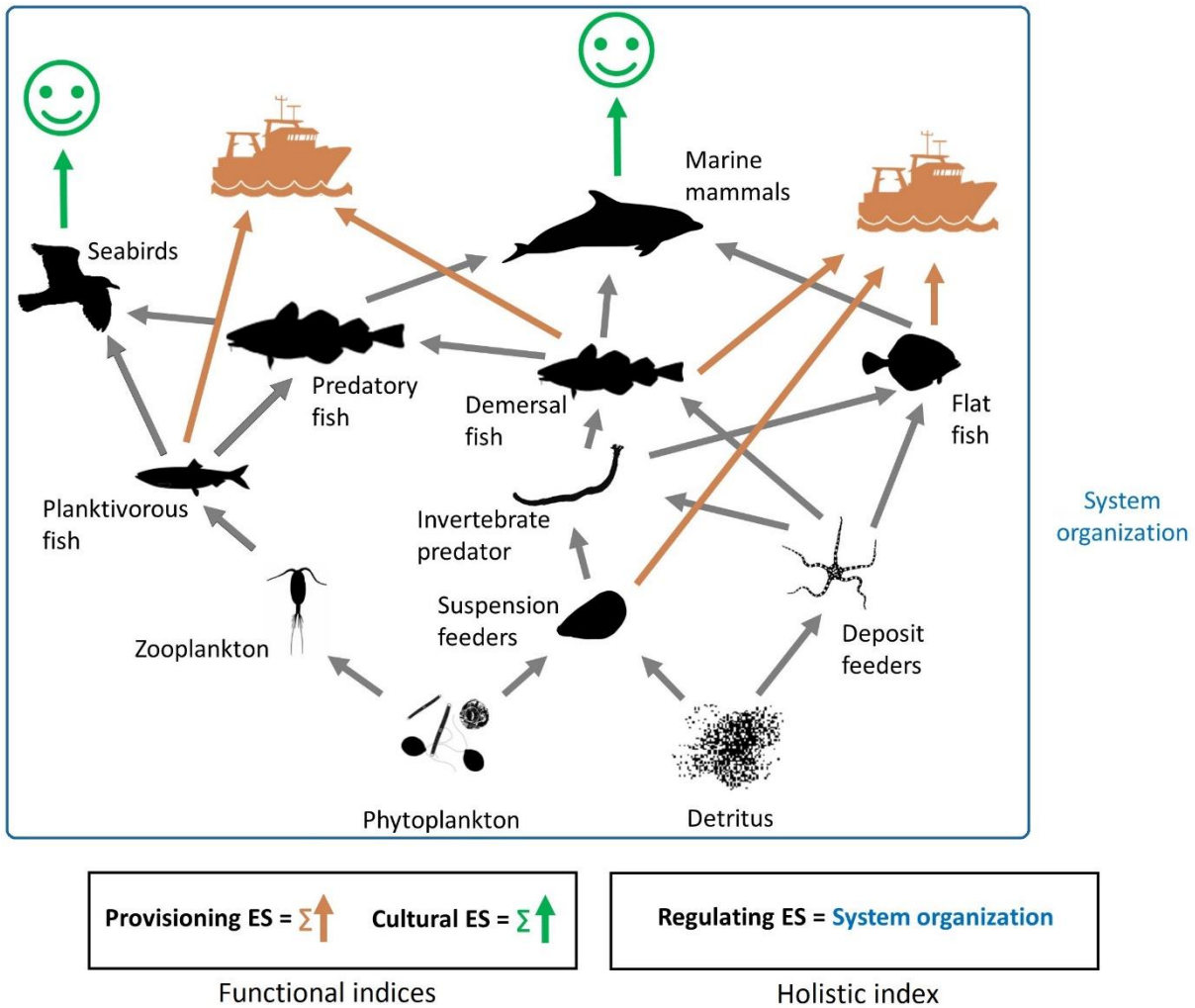
274 Since we do not aim at an exhaustive quantification of ES supply, we decided to quantify a
275 limited number of services, using a wide range of outputs. This was made to give insights on
276 how food web models could be used to quantify ES supply.

277 The ES selected by the authors represent ES of great importance in the eBoS but also in
278 many other ecosystems and include:

- 279 • Provisioning ES -> Food provisioning from fishing (CICES 1.1.6.1). To quantify it, we
280 used capture flows computed from Ecospace for the fish and the invertebrate groups
281 that we combined to quantify the actual supply of the ES (in t/km²/year). Using
282 captures as an indicator of ES supply has been suggested in previous studies (Böhnke-
283 Henrichs et al., 2013; Olander et al., 2018; Weijerman et al., 2018). This indicator
284 quantifies the actual supply of ES and consider fishing capacity: availability of the
285 targeted groups, catchability, price and distance to port for each gear type and
286 depending on fleet activity (Walters et al., 1999). Most captured species in the eBoS
287 include European pilchards (*Sardina pilchardus*), King scallops (*Pecten maximus*),
288 European plaices (*Pleuronectes platessa*), small-spotted catsharks (*Scyliorhinus*
289 *canicula*), mackerels (*Scomber scombrus*). For an exhaustive list of the captured
290 species, please refer to the supplementary materials (Table S - 4).
- 291 • Regulating ES -> Ecological resilience based on food web functioning referred as
292 “Biological control/insurance” (Baumgärtner and Strunz, 2011; Böhnke-Henrichs et al.,
293 2013; Peled et al., 2020). In food webs, some network properties can be stabilizing.
294 These stabilizing effects can be linked to the ‘ecological resilience’ which determines
295 the ability of an ecosystem to maintain its original state in the context of external
296 changes (Holling, 1996; Saint-Béat et al., 2015), and to maintain ES supply (Biggs et al.,
297 2012; Daily et al., 1997). For the ecological resilience ES, the relative redundancy ENA
298 index was used (RDC, no unit). ENA indices provide information on the functioning and
299 organization of trophic networks and are computed with various equations which
300 consider the entire flow matrix between trophic groups (Supplementary materials
301 Table S - 9). The relative redundancy characterizes the redundancy of trophic pathways
302 (functional redundancy). The relative redundancy (RDC or R/DC: overhead of the
303 internal flows: R, on the development capacity: DC) can only vary between 0 and 1. A
304 relative redundancy close to 0 indicates a very constrained and organized system (i.e.,

305 a low uncertainty around the origin of the trophic input, more akin to a food chain),
306 while close to 1 indicates an inorganized and redundant system (i.e., a high uncertainty
307 around the origin of the trophic input indicates redundant trophic pathways and thus
308 a high flow diversity). Following ecological theory studies (Odum, 1953; Ulanowicz,
309 2018) and field experiments (e.g. Baird et al., 2007; Cardinale et al., 2002), the
310 organization of an ecosystem seems to be a good measure of the ecosystem resilience,
311 and thus of the actual ES supply (Biggs et al., 2012).

312 • Cultural ES -> Flagship species (CICES 3.2.2.1): this ES represents the existential cultural
313 role of certain animal species. Species that people think should be conserved and have
314 an important sentimental, imaginary, or relational intrinsic value to them. For the
315 flagship species ES, we used the summed production of multiple top predator
316 compartments (in t/km²/year). Species considered include Bottlenose dolphins
317 (*Tursiops truncatus*), harbour porpoises (*Phocoena phocoena*), grey seals (*Halichoerus*
318 *grypus*), harbor seals (*Phoca vitulina*) and various marine sea birds like gulls (*Larus sp*),
319 northern gannet (*Morus bassanus*), common guillemot (*Uria aalge*) and scoters
320 (*Melanitta nigra / Melanitta fusca*). For an exhaustive list of flagship species, please
321 refer to the supplementary materials (Table S - 4). These species were aggregated in 6
322 trophic groups: three marine mammal groups (dolphins, seals, and harbour porpoises)
323 and three sea bird groups (Surface feeding birds, benthic feeding birds and plunge and
324 pursuit birds). The ES indicator was the sum of both birds and marine mammals'
325 production (components of the cultural index). We selected such species based on
326 preliminary results from current research studying humans and biodiversity
327 relationships through ethnographic inquiry and quantitative survey (Sensitroph, n.d.).
328 Due to the difficulty in quantifying the interactions between the production of flagship
329 species and humans, for the benefit of cultural enhancement (Blicharska et al., 2017),
330 this indicator is thus more akin to the potential supply of ES.



331

332

Figure - 2 Diagram of ecosystem service supply indices in the food web.

333

Schematic of the food web, representing trophic groups (icons) and energy flows (arrows). Indicators can be divided in two main groups: functional index (energy flows or catches in orange and flagship species production in green), and holistic index (entire ecosystem properties: regulating ES). A detailed description of the equations used is provided in supplementary materials (Table S - 9).

337

338

2.5 Evolution and mapping of ES supply in the eBoS.

339

Indicators of ecosystem services supply were computed for the reference scenario, the CC scenario, the OWF scenario and the combined CC and OWF scenario. Each scenario was then compared to the reference one to determine the separate and combined impacts of anthropogenic drivers. This aims to get an overview of the area producing ES, and to determine the effects of either CC and/or of the OWF on the ES supply, as well as their

343

344 potential cumulative effects. Components were also compared to explain potential changes
345 in ES supply.

346 Indicators quantifying the supply of each ES were mapped for each scenario tested in
347 the eBoS. To better analyze the evolution of ES supply, we partitioned the eBoS based on
348 previously determined functional regions and structural sub-regions (Figure - 1).

349 To determine whether the effect of each driver (CC or OWF) on the ES supply was
350 important, a Cliff Delta was calculated to compare the indicators of the reference Ecospace
351 scenario with the scenarios modelling one of the two drivers, for each region of the model.
352 The Cliff delta is a non-parametric effect size metric that quantifies the amount of difference
353 between two groups of observations (Cliff, 1993; Tecchio et al., 2016). It was previously used
354 to compare ENA values inside the eBoS (Nogues et al., 2020) and the same threshold values
355 threshold as Romano et al. (2006) were kept (negligible if the Cliff Delta ($|\partial\text{Cliff}|$) was < 0.147 ,
356 low if $0.147 < |\partial\text{Cliff}| < 0.33$, medium if $0.33 < |\partial\text{Cliff}| < 0.474$, or strong if $|\partial\text{Cliff}| >$
357 0.474).

358 To characterize the cumulative effects resulting from CC and the OWF on the ES supply,
359 the individual effects (ΔI_s^{sep} , eq.3) of each driver were summed to determine the additive
360 effect of both CC and the OWF ($\sum \Delta I_s^{sep}$).

$$\Delta I_s^{sep} = \frac{I_s - I_r}{I_r} \quad (3)$$

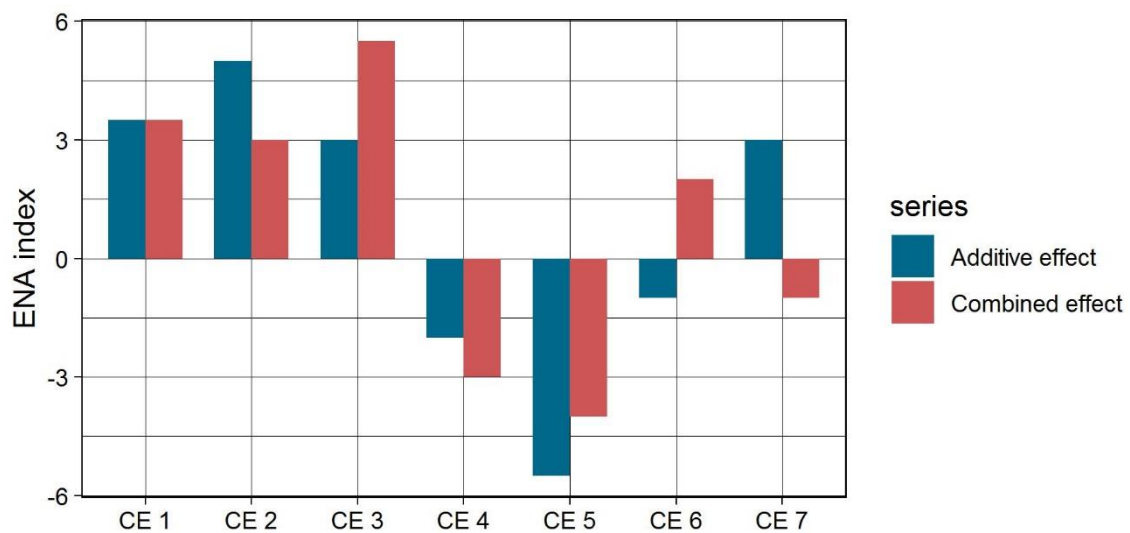
361 where I_r is the index value of the reference model and I_s the index value of a single-effect
362 model (OWF only or CC only).

363 The additive effect ($\sum \Delta I_s^{sep}$) was then compared to the combined effect (ΔI_c^{cum} , eq.4)
364 of both drivers to determine cumulative effects resulting from the interaction of CC and of the
365 OWF on the ES supply (Figure - 33, Fu et al., 2018; Nogues et al., 2020; Travers-Trolet et al.,
366 2014). This comparison was made for each functional and structural region of the eBoS. To
367 determine if the cumulative effect was relevant on the said supply of ES, the Cliff delta was
368 used to compare the additive effect to the combined one, for each region and ES supply
369 indicator.

$$\Delta I_c^{cum} = \frac{I_c - I_r}{I_r} \quad (4)$$

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371 where I_r is the index value of the reference model and I_s the index value of a single-effect
 372 model (OWF only or CC only).



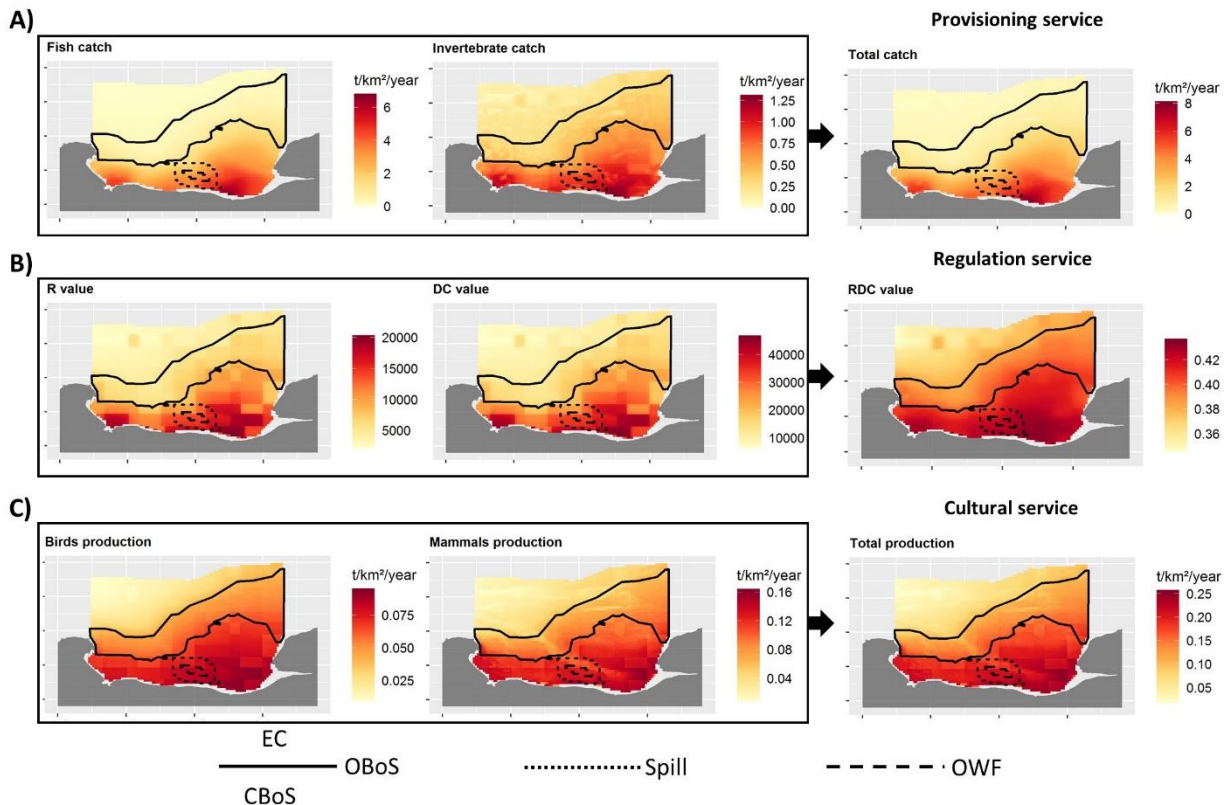
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374 **Figure - 3 A typology of potential cumulative effects (CE) resulting from the**
 375 **interactions of multiple drivers** (Travers-Trolet et al., 2014).

376 Cumulative effects are determined by comparing the additive effect
 377 (sum of the individual effects of each driver; in blue) to the combined effect
 378 of both driver (in red). CE 1 is additive with no driver interactions; CE 2 is
 379 positive dampened; CE 3 is positive synergistic; CE 4 is negative synergistic;
 380 CE 5 is negative dampened; CE 6 is positive antagonistic; CE 7 is negative
 381 antagonistic.

382 3 Results

383 The ES supply indicators were mapped for the eBoS and show a higher supply for all
 384 indicators in the most coastal part of the study area, i.e. the Coastal Seine Bay (CBoS). We
 385 observe a decreasing intensity of the supply of all three ES, following a gradient from the coast
 386 to the open sea (Figure - 44). Indices either reflect the primary production map (regulation
 387 service, see Supplementary materials Figure S - 2), the depth map (cultural service, see
 388 Supplementary materials Figure S - 1), or follow a close coast to shore gradient (provisioning
 389 service). This demonstrates the relationship between the ecosystem and the environment
 390 defined in Ecospace using environmental drivers.



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Figure - 4 Indicators of Ecosystem services supply in the extended Bay of Seine model.

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The first two columns of maps present the components used to build the ES indices (third column). The regions and sub-regions of the model are also mapped with the dotted line mapping the OWF, the dotted one the spillover region and the continuous line each functional region of the eBoS (CBoS, OBoS, CEC).

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For the effect of CC on the ES supply, the provisioning ES (total catch) seems to be the most impacted with around 30 % loss in the CEC region to approximately 9 % in the Coastal Bay of Seine region (Figure - 5). This appeared to be mainly linked to the loss of invertebrate catches while fish catches did not display any major evolution due to CC. The eBoS, invertebrate catches are mainly represented by King scallop catches (79% in the reference and 85% in the CC scenario). The other ES supplies are less impacted, but we notice an increase in the regulating ES for the most coastal region, with high local increase in resilience (RDC) as visible in the OWF sub-region. Finally, the cultural ES present limited changes due to CC, with very localized increase spotted in the OWF sub-region (Figure - 5).

Region	Provisioning service			Cultural service			Regulation service		
	Fish catches	Invertebrate catches	Total catches	Birds production	Mammals production	Total production	DC	R	Redundancy (RDC)
CEC	-0,89	-52,64 ***	-28,93***	7,28	0,92	3,56	1,67	2,12	0,41
OBoS	-0,42	-53,12 ***	-20,61**	2,26	0,39	1,15	1,97	2,41	0,42
CBoS	1,75	-45,55 ***	-8,52	0,19	0,45	0,35	2,17	2,91	0,69 *
Spill	-1,17	-48,28 ***	-10,99*	-0,21	1,75	0,97	2,02	2,75	0,69 *
OWF	-1,81	-48,64 ***	-11,75**	-0,20	1,78 **	1,00 **	2,11 *	2,88 **	0,75 ***

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Figure - 5 Climate change effects in 2050 on the ecosystem services supply indicators compare to the reference scenario (in percent), per region.

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Effects of CC were computed per functional and structural regions of the eBoS. To determine if the effect is important or not, Cliff's deltas were realized with variation considered: *** strong ($|\partial\text{Cliff}| > 0.474$); ** medium ($0.33 < |\partial\text{Cliff}| < 0.474$); * small ($0.147 < |\partial\text{Cliff}| < 0.33$); nothing, negligible ($|\partial\text{Cliff}| < 0.147$), (Romano et al., 2006). Colors were plotted only on the indicators with a $|\partial\text{Cliff}| > 0.147$ and show the decreasing (blue) and increasing intensity (red) of the indices. Regions include: the Central English Channel (CEC), the Offshore Bay of Seine (OBoS) and the Coastal Bay of Seine (CBoS).

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The potential reserve and reef effects of the future OWF of Courseulles-sur-Mer have strong impacts on the ES supply inside the park (Figure - 6). All the ES are affected, with large variations compared to the reference scenario: both the reserve and reef effects of the OWF appear to increase ES supply.

Region	Provisioning service			Cultural service			Regulation service		
	Fish catches	Invertebrate catches	Total catches	Birds production	Mammals production	Total production	DC	R	Redundancy (RDC)
CBoS	-0,21	0,04	-0,16	-0,35	-0,21	-0,26	0,03	0,03	0,00
Spill	-6,96	-0,76	-5,67	-1,07	-2,60	-2,00	-0,35	-0,49	-0,15
OWF	65,63 ***	2,04 ***	52,12 ***	66,45 ***	4,02 ***	28,65 ***	2,38 *	3,39 **	0,98 ***

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Figure - 6 Offshore wind farm effects on the ecosystem services supply indicators compare to the reference scenario (in percent), per region.

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Effects of the OWF were computed per functional and structural regions of the eBoS. To determine if the effect is important or not, Cliff's deltas were realized with variation considered: *** strong ($|\partial\text{Cliff}| > 0.474$); ** medium ($0.33 < |\partial\text{Cliff}| < 0.474$); * small ($0.147 < |\partial\text{Cliff}| < 0.33$); nothing, negligible ($|\partial\text{Cliff}| < 0.147$), (Romano et al., 2006). Colors were plotted only on the indicators with a $|\partial\text{Cliff}| > 0.147$ and show the decreasing (blue) and increasing intensity (red) of the indices. Regions include: the Central English Channel (CEC), the Offshore Bay of Seine (OBoS) and the Coastal Bay of Seine (CBoS).

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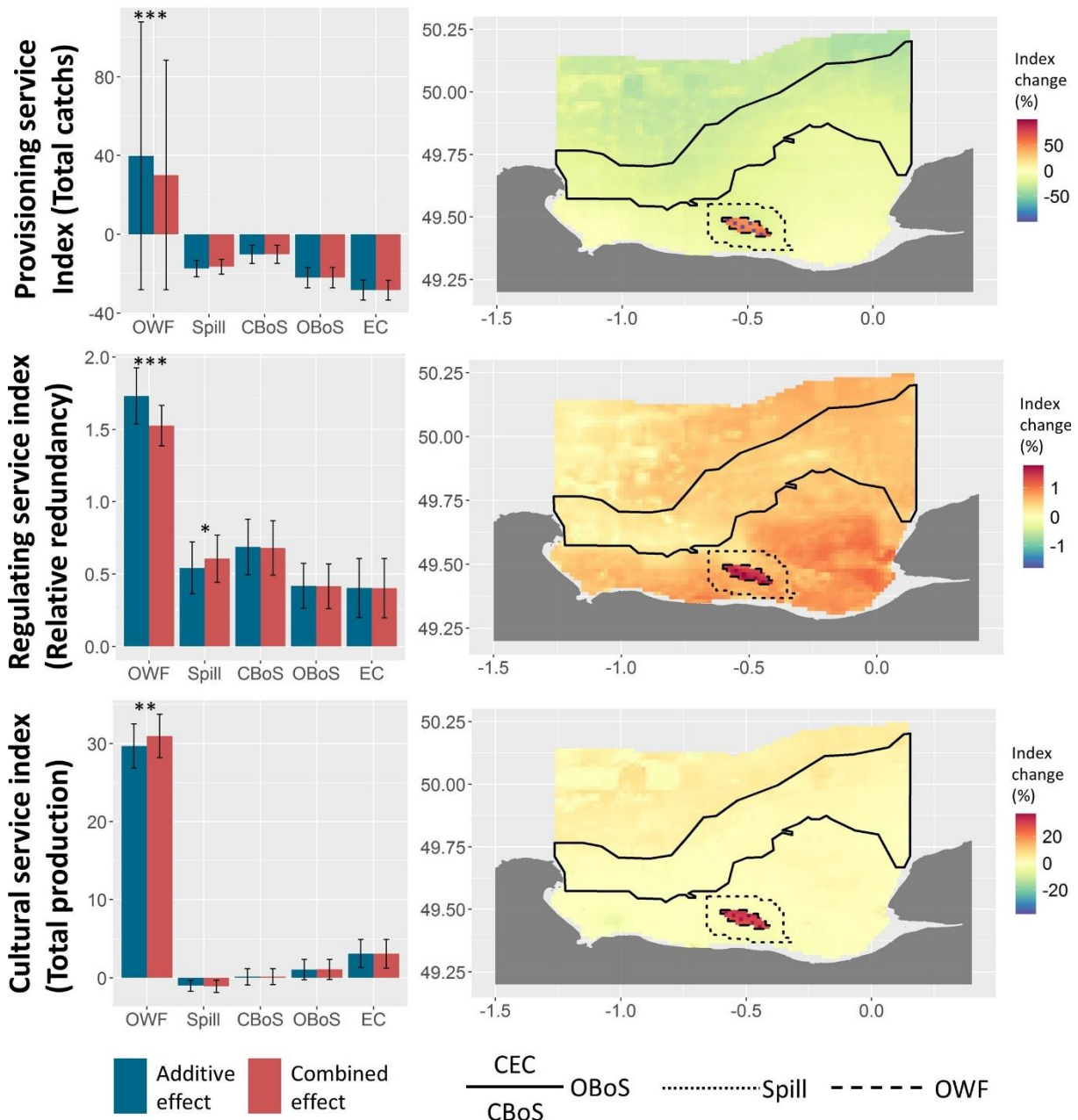
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When both anthropogenic drivers are combined, cumulative effects appear near the OWF (Figure – 77). Despite the high variability of catches inside the OWF sub-region due to

439 the partial reserve effect being applied for 6 of the 37 Ecospace cells of the park, visible on
440 error bars (the same in both the separated and combined effects scenarios), a positive
441 dampened effect can be seen on the provisioning ES supply in the OWF. The regulating ES had
442 cumulative effects, but unlike the provisioning one, it is not only limited to the OWF since a
443 small cumulative effect is also visible in the spillover region of the OWF, resulting in a positive
444 synergistic effect. Inside the OWF, the regulating ES also experienced a positive dampened
445 effect, like the provisioning ES. Finally, the cultural ES showed a positive synergistic effect of
446 the combined CC and reef and partial reserve effects inside the OWF (Figure – 77).

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Figure – 7 Cumulative effects of climate change and of the offshore wind farm on the ecosystem services supply indices.

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Bar charts compare the additive effects to the combined effects of both CC and of the OWF while the map plot combine the effects of both drivers on each ES supply indicators. Error bars display the standard deviation. To determine if cumulative effects were considered important or not, Cliff’s deltas were realized with variation considered: *** strong ($|\partial\text{Cliff}| > 0.474$); ** medium ($0.33 < |\partial\text{Cliff}| < 0.474$); * small ($0.147 < |\partial\text{Cliff}| < 0.33$); nothing, negligible ($|\partial\text{Cliff}| < 0.147$).

458 4 Discussion

459 To our knowledge, this study constitutes the first attempt to quantify the supply of ES
460 using ecological network analysis, through both holistic and functional indices. It aims to
461 display the potential and usefulness of food web models in the ES framework. However, this
462 comes with limitations that are worth to be kept in mind. They come from the wide range of
463 CC effects or OWF effects. One can hardly model the full extent of these effects, especially
464 since they are still under debate amongst the scientific community (Dannheim et al., 2020).
465 One way to tackle this issue is to better consider the uncertainty around the input of the
466 model, either through the biological constraints (Meersche et al., 2009; Steenbeek et al.,
467 2018), or through the forcing inputs like the suitability index maps computed by the niche
468 models (Bourdaud et al., 2021). However, this was not done due to computation time but
469 should be encouraged in future works. This does not prevent this study from identifying trends
470 related to expected changes in the environment. Further, this paper is based on the previous
471 studies of the eBoS that did not attempt to model the full extent of the effects of CC and the
472 OWF but rather, to model their main and most structuring effects on the food web and then
473 to gradually improve on them. We thus benefit from the improvements on the OWF
474 simulation from Halouani et al. (2020) and on CC simulation from Bourdaud et al. (2021), while
475 giving new insights compared to Nogues et al. 2022 on impacts for humans.

476 4.1 Climate change effect on the ecosystem services supply of the eBoS

477 Climate change appears to have a significant effect on ES supply. With losses reaching
478 up to 30% for the supply of the provisioning ES, CC seems to have a major impact on the food
479 production of the eBoS. This appears to be mainly due to losses in invertebrate catches,
480 attributed to the important decrease of King Scallops (*Pectens maximus*) suitability, which play
481 a major part in invertebrate catches. This potentially high impact of CC on this species of
482 shellfish was already pointed out in (Lavaud, 2014; Rombouts et al., 2012). This would result
483 from the expected Northward drift of many cold-water species due to the expected increase
484 in water temperature (Kleisner et al., 2017, 2016; Nye et al., 2009). While a similar decrease
485 in king scallop catches was also observed in Bourdaud et al. (2020), here it is the result of a
486 decrease in environmental suitability rather than a shift within the bay (different methodology
487 to model climate change). In Bourdaud et al. (2020), catches of other species like Atlantic cod

488 were also negatively impacted by CC in 2100, while in this case, in 2050, only king scallop
489 catches were significantly affected.

490 Fishing, in particular King scallop fishing, plays a key economic role in Normandy. King
491 scallop represents ~40% of the seafood sales at the Port-en-Bessin fish market (Buléon and
492 Shurmer-Smith, 2021), making it one of the most valuable species in the eBoS. The evolving
493 supply of the food provisioning ES, linked to the changing rate between fish and invertebrate
494 capture due to CC will thus have a major impact on fishing fleets which will necessarily have
495 to evolve. In a political context (Brexit) where the areas and quotas dedicated to fishing are
496 already restricted and with the recent effects of the Covid-19, one can only assume that CC
497 will have a major effect on Normandy economy and socio-cultural fabric. The whole fishing
498 sector (fishmongers, shipyards, fish processing industries) may not be able to resist to such an
499 evolution. Fishing (in particular king scallop fishing) also plays an essential part in tourism
500 industry, including local gastronomy and restaurants, reflecting a strong synergy between the
501 food provisioning ES and the cultural ES. Potential changes in the stocks of king scallops
502 could then have economic and socio-cultural repercussions far beyond the frame of the Seine
503 Bay fishery and affecting many beneficiaries. The indicator of the supply of the food
504 provisioning ES could then reflect change in several ES and components of the social system
505 (Haraldsson et al., 2020; Niquil et al., 2021), caused by CC. Here, the provisioning indicator is
506 thus more akin to a link between two different systems, the ecological system and the social
507 system that depends on fishing and king scallops the social and the ecological system, where
508 one perturbation in the ecosystem can cascade throughout the social system (Haraldsson et
509 al., 2020; Niquil et al., 2021). CC could also impact fish quality and availability, but we didn't
510 consider such aspects in this study (Bourdaud et al., 2021; Pauly et al., 1998).

511 The effects of climate change on ES supply are not all negative. One potentially light
512 positive effect of CC on the eBoS is the possible increase in the ecological resilience of the food
513 web. This is visible as the supply of the regulating ES increases in the coastal zone of the eBoS.
514 While small, the increase remains significant and can indicate important changes in the
515 ecosystem organization and functioning (e.g. Tomczak et al. 2013). This effect is however very
516 specific to this system and cannot be generalized for other systems as it depends on the
517 organization and functioning of the initial system. Climate change modeling is subject to many
518 uncertainties, and many more effects might arise from it (Harley et al., 2006; Wernberg et al.,

519 2012). However, this shows potential tradeoff in the effects of anthropogenic drivers on ES
520 supply. With CC having potentially important negative effects on part of the ecosystem,
521 resulting in the hypothetical decrease of the supply of one service (food provision), but not on
522 the whole system and thus on other services supply. Food web models thus show their ability
523 in describing the functional mechanisms at the root of tradeoff, required for spatial planning
524 in ecosystem management (Aryal et al., 2022).

525 4.2 Offshore wind farm effect on ecosystem services supply in the eBoS

526 The OWF of Courseulles-sur-Mer reef and partial reserve effects seem to have a positive
527 effect on the ES supply in the eBoS, for all the studied ES supply indicators. This finding
528 confirms the results obtained in several previous studies that showed that not only fishermen
529 could benefit of the OWF despite losses in fishing areas (Halouani et al., 2020) but the OWF
530 also has a positive effect on the food web resilience (Raoux et al., 2019).

531 One of these positive effects is the increased production of flagship species due to the
532 reef and partial reserve effects of OWF. This impacts species like marine mammals such as
533 bottlenose dolphins (*Tursiops truncatus*) and harbour porpoises (*Phocoena phocoena*), and
534 surface feeding sea birds like gulls (*Larus sp*). Studies have already shown positive effects of
535 the OWF on these species, with some displaying an attractive effect of wind turbines on some
536 marine seabird like gulls (Blew et al., 2008; Vanermen et al., 2015), while other have described
537 a similar attraction of marine mammals like harbour porpoises (Scheidat et al., 2011) or no
538 effects at all on grey and harbor seals (Edrén et al., 2010; Tougaard et al., 2006). This must
539 however be taken carefully. Indeed, one of the limitations of our approach is that the OWF
540 effect on the ecosystem was limited to the expected main effects of the OWF on the
541 ecosystem i.e. the underwater reef and partial reserve effects. However, the OWF can have
542 other important effects that may not be as structuring. On one hand, several studies have
543 pointed out the potential negative effects of OWFs on such species like the dislocation or
544 collision effects of OWF on seabird species like northern gannets (Blew et al., 2008; Furness
545 et al., 2013; Vanermen et al., 2019) or on migratory species (Masden et al., 2009), as well as
546 the potential effects of underwater noise of wind turbines on marine mammals like harbour
547 porpoises feeding behavior (Carstensen et al., 2006). However, some pointed out the
548 potential adaptive power of marine mammals to environmental changes, which may limit the
549 negative effects of the OWF (Tyack, 2008). Here, we can say that the modelled effects of the

550 OWF of Courseulles-sur-Mer may benefit flagship species by increasing their prey densities in
551 the OWF (Lindeboom et al., 2011), as visible in the strong increase of fish capture inside the
552 OWF. The increase in marine mammals' preys like whiting (*Merlangius merlangus*) and
553 pouting (*Trisopterus luscus*) is straight forward as they are directly benefiting from the reef
554 effect on smaller benthic invertebrates like invertebrate filter feeders. For sea birds on the
555 other, this is explained by the increase in the production of prey species not directly benefiting
556 from the reef effect of the OWF like European sprat (*Sprattus sprattus*) and European pilchard
557 (*Sardina pilchardus*, see supplementary materials Figure S – 3 & 4 and Table S - 8 & S2 - 2).
558 Rather, these species benefited from the indirect effect of the OWF on the hole ecosystem,
559 only observable when considering the entire food web.

560 4.3 The combined effects of both drivers

561 Combining the effects of the OWF and of CC resulted in significant cumulative effects
562 (CE) on each indicator of ES supply. The OWF seems able to limit the losses of the provisioning
563 ES caused by CC, while improving the supply of the cultural and the regulating ones. This is
564 mainly visible inside the OWF, where driver interactions were the strongest. The interactions
565 between the drivers resulted in CE (difference between the additive and the cumulative
566 effects), but with different ranges between the indicators. As such the ENA index showed small
567 CE around the OWF, in the spillover region, while the community-based indicators (catches,
568 and flagship species productions), mainly display CE within the farm. These observations go
569 alongside previous works indicating that CE happen often when two or more drivers interact
570 with each other (Darling and Côté, 2008); and that the spatial extent of cumulative effects can
571 vary depending on the studied ecosystem property, with some CE able to happen outside of
572 the expected zone of anthropogenic driver's interaction (Nogues et al., submitted). Marine
573 protected areas and artificial reefs have already demonstrated their ability to increase ES
574 supply (Leenhardt et al., 2015; Qin et al., 2011; Ramos et al., 2019). We demonstrate that, in
575 Courseulles-sur-Mer, the reef and partial reserve effects seem to be able to keep this ability
576 to increase ES supply, despite the effect of climate change. This is in spite of the dampening
577 CE resulting from both drivers' interaction, visible with the lower increase in ES supply in the
578 combined effect compared to the additive one (see Figure - 7). As the positive reef and partial
579 reserve effects remain limited in space, this could emphasize the need for ecological

580 management plans at a larger spatial scale (Charles, 2012), as to prevent the impact of CC on
581 ES supply and thus on human wellbeing.

582 4.4 Spatial planning using food web models

583 Ecosystem approaches like food web models can also inform marine planification by
584 identifying key areas for ES supply. The link between ES supply indicators being strongly
585 associated to ecological and trophic mechanism, as species interact with other species within
586 their vicinity (depending on their ability to move), specific ecological areas are going to stand
587 out. In the Bay, the coastal region is the most productive and the most diverse ecologically.
588 This increase the odds that this area of the ecosystem is going to play a key role in ES supply
589 (Sieber et al., 2018). This is evident from the higher value of the ES supply indices in the coastal
590 area of the bay. This could thus justify management action to maintain ES supply, like a three-
591 mile coastal zone of restricted fishing activities like trawling (Engel and Kvitek, 1998; Pranovi
592 et al., 2015). Another possible path could be to benefit ES supply in more offshore areas of
593 the bay, where the supply of ES is lesser. With the reef and reserve effect of the OWF
594 increasing ES supply, these offshore areas could be selected for future OWF installations,
595 which could not only benefit the studied ES supply, but could also limit the aesthetical impact
596 on the landscape (Sullivan et al., 2013), despite the increased cost of more offshore farms
597 (Virtanen et al., 2022).

598 Coastal regions are sensitive environments, subject to a high concentration of human
599 activities (He and Silliman, 2019) highly vulnerable to environmental change (eutrophication
600 or global warming). This makes the mapping of ES supply crucial for management as it gives
601 insight about the importance of these areas for humans (Maes et al., 2012), as seen here.
602 Using ecosystem approaches to support management could allow for a better forecasting of
603 these impacts on the ecosystem and the ability to explore new solutions, making food web
604 model invaluable for managing coastal ecosystem.

605 4.5 Food web model: toward a more ecosystem-based approach of ecosystem 606 services

607 Integrative and connected approaches are lacking in ES studies (García-Onetti et al.,
608 2018). The proxies most often used to map the supply of marine ES are bathymetric maps,
609 habitat distribution maps, sediment maps, tidal maps and water temperature maps (Lavorel

610 et al., 2017). However, these parameters do not consider the interconnectivity of marine
611 systems and are not sufficient to characterize the supply of marine ES (Dee et al., 2017; Guerry
612 et al., 2012). Moreover, ES relations in space and time are in general defined using correlative
613 approaches (Agudelo et al., 2020; Lee and Lautenbach, 2016; Li et al., 2018), without any
614 information on causal mechanisms responsible for these relationships.

615 To identify tradeoff between ES, methodological advances need to be made to quantify
616 how relationships between species / ecological functions shape the supply of ES. Ecological
617 functions such as primary production or secondary production, play a key role in supplying ES
618 (Armoškaitė et al., 2020; Martinetto et al., 2020). However, through the increasing subdivision
619 of ES and of the ecological functions they are relying on (Hummel et al., 2019), one may
620 consider processes as disconnected. In nature, these functions are all interconnected, forming
621 a continuum between species/groups - functions and ES. The quantification of ES needs to
622 take this connectivity into account (De Groot et al., 2010), as it enables:

- 623 - The detection of causal relationship between ES. Such relationship can be linked to
624 a species playing a role in the supply of multiple services (Duncan et al., 2015). This
625 shown here with the effects of the OWF on demersal and benthic fish like poutings
626 (*Trisopterus luscus*), dragonets (*Callionymidae sp*), cods (*Gadus morhua*) and
627 various flat fishes (Supplementary materials Table S - 10) in the bay. With the
628 increase of fish production and biomass due to the OWF, captures increase within
629 the OWF, which benefits the provisioning ES. However, this will also benefit
630 flagship species like marine mammals which will have more available food,
631 increasing the supply of the cultural ES (Busch et al., 2010). Relationships can also
632 be based on other vectors like fishing discards. Indeed, the increase in catches
633 inside the OWF resulted in a higher amount of discards, benefiting surface feeding
634 seabirds like gulls, which are known to feed from it (Montevecchi, 2001; Garthe
635 and Scherp, 2003; Karris et al., 2018). With the increase of catches and the increase
636 in flagship species production within the OWF like Gulls, there is therefore no
637 tradeoff between the cultural and provisioning ES despite both potentially
638 competing for the same resources.
- 639 - The Quantification of new types of ES, such as services depending on the
640 organisation of the food web (e.g. ecosystem resilience - Contanza, R and Mageau,

641 1999; Saint-Béat et al., 2015) and thus on the overall functioning of the ecosystem
642 (Kremen 2005). For example, the increase in the production of some fish groups
643 like pouting due to the OWF will not only benefit the provisioning service since it is
644 fished or the cultural service since it is a prey to marine mammals like dolphins, but
645 it will also, in part, increase the redundancy of trophic pathways, improving the
646 ecosystem resilience.

647 These benefits open ways to study a wider range of ES, with better forecasting power
648 (De Groot et al., 2010; Müller et al., 2010). For example, the cultural ES category has often
649 been back sided (Blicharska et al., 2017). Such an omission may be explained by the
650 oversimplification of the attachment of humans to the natural world and the fracture in
651 sciences between nature and culture. Like ecosystems and their role in ES supply, the cultural
652 construct is directly related to the ecosystem functioning and organization, intertwined
653 through multiple species, functions and ES, rather than compartmentalized (Mongruel et al.,
654 2019). For example, food production has fostered development of rich fishing cultures, that
655 vary by location, in terms of fished species but also of local communities, boats and other
656 technologies, physical port characteristics, fish markets, and, obviously, culinary practices. The
657 present study has shown a potential collapse of scallop populations under CC effects. If the
658 consequences on the provisioning ES are clear, it will also have repercussions on the whole
659 social system since scallop fishing in a way shapes the coastal Normandy's identity. Strong link
660 between cultural and other categories of ES are revealed here, which are often
661 underestimated (Blicharska et al., 2017). These inter-woven relationships have been described
662 and studied in Humanities and Social sciences and should be further integrated in ES studies.

663 Conclusion

664 This study demonstrates that food web models are useful for mapping, quantifying, and
665 understanding the mechanism of ES supply and its evolution in the face of environmental
666 changes. It determined that the coastal part of the bay of seine played a key role in ES supply,
667 making this area a priority for conservation. Our model revealed that OWF could increase the
668 studied ES supply, it also described the multi-species mechanisms responsible for such
669 increase. It showed that CC was going to have significant effect on some ES, with potentially

670 strong repercussion for the social system. Despite this, and the potential cumulative effects
671 with CC, the OWF was still able to limit locally some of the effects of CC.

672 The food web model utilized here was also able to detect links between ES, based on a
673 posteriori observations and analysis, determining specific tradeoff between ES supply. This
674 was possible since food web model look at what makes ecosystems unique: species living in it
675 and the relationships between them, instead of making correlations based on previously
676 observed relationships in other unrelated systems. Food web models also allow the
677 mobilization of ecological theories rarely employed within the ES framework. Indeed, ES
678 supply is often quantified using observations and non-mechanistic approaches (coverage
679 areas, fishing values... Dade et al. (2019)). However, such structural information can hardly
680 characterize the functioning of ecosystems and the complex mechanisms at work within them.
681 Food web models and ecological network analysis thus gives new insights on previously poorly
682 mobilized information. Finally, food web models such as Ecospace enable the mapping of ES
683 supply while accounting for complex ecological mechanisms such as species movement,
684 habitat suitability and species interactions, providing a better mapping of ES and a higher
685 predictive potential.

686

687 Acknowledgements

688 This work was funded by the Normandy Region (RIN Trophi-Services project) and the
689 SENSITROPH project which benefited from a “Fondation de France” investments. We also
690 thank the partners and collaborators of the APPEAL and WINDSERV projects for their help in
691 compiling the datasets and for giving expert advice.

692 **Competing interest statement**

693 The authors have no conflict of interest to declare.

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1214 Supplementary materials

1215 **Table S - 1: Previous modeling works on the extended Seine Bay.**

Sources	Models	Objectives	Description and additions
Raoux et al. 2017	EwE: Ecopath steady state model	<ul style="list-style-type: none"> - Study of the Courseulles-sur-Mer offshore wind farm (OWF) effects on the local food web. - Trophic network analysis of the consequences of the OWF for the ecosystem structure and functioning. 	<ul style="list-style-type: none"> - Ecopath modeling of the Courseulles-sur-Mer food web before and after the construction of the offshore wind farm. - Model the impact of additional hard substrates (reef effect), and fishing closure (reserve effect) on the local food web.
Halouani et al. 2018	EwE: Ecopath, Ecosim and Ecospace steady state and dynamic models	<ul style="list-style-type: none"> - Spatial study of the extended Seine Bay (eBoS). - Sensitivity analysis of fishing closure inside the Courseulles-sur-Mer OWF for fisheries in the Seine Bay. 	<ul style="list-style-type: none"> - Ecopath update over Raoux et al. 2017. - Ecosim and Ecospace dynamic model setup. - Ecospace set up using habitat parameters based on depth and sediment types.
Ben Rais Lasram et al. 2019	Species distribution models (not EwE)	Development of a multi-algorithms and hierarchical species distribution modeling method used on species endemic to the Seine Bay.	<ul style="list-style-type: none"> - Hierarchical method using both climatic and habitat parameters to model a wide range of species distribution and their evolution due to climate change.
Bourdaud et al. 2020	EwE: Ecosim and Ecospace dynamic models	<ul style="list-style-type: none"> - Study the potential effects of climate change on species distribution on the Seine Bay food web. - Consequences of CC for fisheries. 	<ul style="list-style-type: none"> - Integrates species displacement linked to CC in Ecospace using SDMs outputs, to consider the effect of predators-preys relationships.
Nogues et al. 2022	EwE: Ecospace dynamic models	<ul style="list-style-type: none"> - Study of the effects of multiple anthropogenic drivers on the Seine Bay ecosystem functioning. - Modeling of climate change, the OWF reef and full reserve effects, and potential effects of Brexit on fishing. - Spatial assessment of the ecosystem functioning using spatial ecological network analysis. 	<ul style="list-style-type: none"> - Uses SDMs outputs to characterize habitat suitability modifications due to climate change on multiple species. - Adds the partial reserve effect and the reef effect of the OWF of Courseulles-sur-Mer in Ecospace. - Models various fishing efforts scenarios. - Uses spatial ecological network analysis to map ecosystem properties and functioning.

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Table S - 2: Input data used in each modelling approach.

Models	Origins	Input types	Targets	Sources
Ecopath	Raoux et al. 2017; Halouani et al. 2018	Groups biomass, production, consumption, ecotrophic efficiency and diet.	All groups	See Raoux et al. 2017 and Halouani et al. 2018 for details
Ecosim	Halouani et al. 2018	Primary production forcing time series	Phytoplankton	- Satellite ocean data (SeaWifs): (NASA Goddard Space Flight Center and Ocean Biology Processing Group, 2014 - Satellite ocean data (MODIS): Hu et al., 2012
Ecosim	Halouani et al. 2018	Catches, biomass, and fishing mortality time series (for calibration, 29 total)	Fished groups, for the complete list see Halouani et al. 2018.	- SACROIS data (Système d'Information Halieutique, 2017) - Stock assessment data from COMOR campaign report (Foucher, 2013) - Estimated from a surplus-production model (SPiCT) (Pedersen and Berg, 2017) see Halouani et al 2018
Ecosim	Halouani et al. 2018	Fishing efforts time series (1 per fleet)	Fishing fleets	SACROIS data (Système d'Information Halieutique, 2017)
Ecospace	Halouani et al. 2018	Primary production forcing map	Phytoplankton	SeaWifs Chlorophyll a map (https://podaac.jpl.nasa.gov/)
Ecospace	Halouani et al. 2018	Depth forcing map	Depth driven species (see table s - 5)	GEBCO (General Bathymetric Chart of the Oceans: https://www.gebco.net/)
Ecospace	Halouani et al. 2018	Depth forcing functions	Depth driven species (see table s - 5)	See Halouani et al. 2018
Ecospace	Bourdaud et al. 2021; Nogues et al. 2022	Environmental suitability maps (27 total)	Environmental driven species (see table s - 5)	Maps built from Lasram Ben Rais et al. (2019) SDM approach using World Ocean Atlas 2013 V2 historical climatic parameters (https://www.ncei.noaa.gov/products/ocean-climate-laboratory), EMODnet habitat parameters (https://emodnet.ec.europa.eu/en) and various species occurrences data (see Table S - 3)
Ecospace	Nogues et al. 2022	Environmental suitability forcing function	Environmental driven species (see table s - 5)	See Nogues et al. 2022

Ecospace	Nogues et al. 2022	Offshore wind farm suitability maps	Species impacted by the reef effect (see table s - 5)	Maps built from Raoux et al. 2017, see Nogues et al. 2022
Ecospace	Nogues et al. 2022	Offshore wind farm partial reserve map	Fished species	Maps built from Raoux et al. 2017 and Halouani et al. 2018, see Nogues et al. 2022

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Table S - 3: Species distribution model inputs

Model type	Group	Data type	Sources
Climatic (global)	All	Sea surface temperature and salinity (first 50 meters), intermediate sea temperature and salinity (50-200 meters), bottom sea temperature and salinity (last 50 meters)	World Ocean Atlas 2013 V2 historical climatic parameters (https://www.ncei.noaa.gov/products/ocean-climate-laboratory)
Habitat (local)	Benthic and demersal groups	Type of substrate, bathymetry, slope and the orientation of the slope towards the north.	EMODnet-bathymetry (http://www.emodnet-bathymetry.eu/) and EMODnet- seabedhabitats (http://www.emodnet-seabedhabitats.eu/).
All	All	Species occurrences	- Global: OBIS (Ocean Biogeographic Information System); GBIF (Global Biodiversity Information Facility); iNaturalist (A Community for Naturalists); VertNet (vertebrate biodiversity networks); Ecoengine (UC Berkeley's Natural History Data) - Local: IBTS (International Bottom Trawl Survey), CGFS (Channel Ground Fish Survey), EVHOE (Evaluation Halieutique Ouest de l'Europe), CAMANOC and various M2C missions.

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Table S - 4 Ecological groups of the extended bay of Seine Ecospace model with their species composition Fished groups are in grey (light grey: invertebrates, dark grey: fish). Flagship species are in green (light green: marine mammals, dark green: Seabirds).

Ecopath functional group	Species composition
Fish Limande	<i>Limanda limanda</i>
Fish Flounder	<i>Platichthys flesus</i>
Fish european plaice	<i>Pleuronectes platessa</i>
Fish sole	<i>Solea solea</i>
Fish sea bream	<i>Spondyliosoma cantharus</i>
Fish benthos feeders	<i>Callionymus</i>
	<i>Mullus surmuletus</i>
	<i>Labrus bergylta</i>
	<i>Zeus faber</i>
Fish planctivorous	<i>Clupea harengus</i>
	<i>Engraulis encrasicolus</i>
Fish piscivorous	<i>Pollachius pollachius</i>
Fish european sprat	<i>Sprattus sprattus</i>
Fish european pilchard	<i>Sardina pilchardus</i>
Fish poor cod	<i>Trisopterus minutus</i>
Fish pouting	<i>Trisopterus luscus</i>
Fish gurnard	<i>Chelidonichthys lucerna</i>
	<i>Chelidonichthys lastoviza</i>
Fish atlantic horse mackerel	<i>Trachurus trachurus</i>
Fish whiting	<i>Merlangius merlangus</i>
Fish atlantic cod	<i>Gadus morhua</i>
Fish sharks	<i>Mustelus mustelus</i>
	<i>Scyliorhinus canicula</i>
	<i>Scyliorhinus stellaris</i>
Fish rays	<i>Raja clavata</i>
	<i>Raja montagui</i>
Fish european seabass	<i>Dicentrarchus labrax</i>
Fish mackerel	<i>Scomber scombrus</i>
Benthic cephalopods	<i>Sepia officinalis</i>
Benthopelagic cephalopods	<i>Alloteuthis spp</i>
	<i>Loligo vulgaris</i>
Surface feeders seabirds	<i>Larus argentatus / Larus michahellis / Larus marinus / Larus fuscus</i>
	<i>Larus sp</i>
	<i>Larus ridibundus/ Larus melanocephalus</i>
	<i>Rissa tridactyla</i>
	<i>Sterna paradisaea/ Sterna hirundo/ Sterna albifrons/ Thalasseus sandvicensis</i>
Plunge and pursuit divers' seabirds	<i>Fratercula arctica / Uria aalge / Alca torda</i>
	<i>Morus bassanus</i>
	<i>Gavia stellata/ Gavia arctica/ Gavia immer</i>
	<i>Phalacrocorax carbo / Phalacrocorax aristotelis</i>
	<i>Fulmarus glacialis</i>
Benthic feeders seabirds	<i>Melanitta nigra / Melanitta fusca</i>
Phocidae	<i>Halichoerus grypus</i>
	<i>Phoca vitulina</i>
Harbour porpoises	<i>Phocoena phocoena</i>

Ecopath functional group	Species composition
Bottlenose dolphins	<i>Tursiops truncatus</i>
King scallops	<i>Pecten maximus</i>
Benthic inv bivalves filter feeders	<i>Acanthocardia echinata</i>
	<i>Angulus fabula</i>
	<i>Angulus pygmaeus</i>
	<i>Corbula gibba</i>
	<i>Ensis</i>
	<i>Ensis directus</i>
	<i>Ensis magnus</i>
	<i>Kurtiella bidentata</i>
	<i>Lanice conchilega</i>
	<i>Lutraria lutraria</i>
	<i>Mactra stultorum</i>
	<i>Moerella donacina</i>
	<i>Parvicardium scabrum</i>
	<i>Phaxas pellucidus</i>
	<i>Spisula elliptica</i>
	<i>Spisula subtruncata</i>
<i>Tellimya ferruginosa</i>	
<i>Thracia phaseolina</i>	
Benthic inv deposit feeders (Subsurface)	<i>Amphilocheus neapolitanus</i>
	<i>Aphelocheata marioni</i>
	<i>Bathyporeia</i>
	<i>Bathyporeia elegans</i>
	<i>Bathyporeia guilliamsoniana</i>
	<i>Bathyporeia tenuipes</i>
	<i>Capitella capitata</i>
	<i>Capitella minima</i>
	<i>Capitellidae</i>
	<i>Caulleriella alata</i>
	<i>Caulleriella viridis</i>
	<i>Caulleriella zetlandica</i>
	<i>Chaetozone christiei</i>
	<i>Chaetozone gibber</i>
	<i>Chaetozone setosa</i>
	<i>Echinocardium cordatum</i>
	<i>Notomastus latericeus</i>
	<i>Nucula hanleyi</i>
	<i>Nucula nitidosa</i>
	<i>Phascolion (Phascolion) strombus strombus</i>
	<i>Scalibregma inflatum</i>
	<i>Scoloplos (Scoloplos) armiger</i>
	<i>Spio decoratus</i>
<i>Spiophanes bombyx</i>	
<i>Abludomelita obtusata</i>	

Ecopath functional group	Species composition
Benthic inv deposit feeders (Surface)	<i>Abra alba</i>
	<i>Acrocnida brachiata</i>
	<i>Ampharete baltica</i>
	<i>Amphicteis gunneri</i>
	<i>Amphipholis squamata</i>
	<i>Aonides oxycephala</i>
	<i>Aonides paucibranchiata</i>
	<i>Aora gracilis</i>
	<i>Apseudopsis latreillii</i>
	<i>Atylus vedlomensis</i>
	<i>Bodotria arenosa</i>
	<i>Bodotria pulchella</i>
	<i>Bodotria scorpioides</i>
	<i>Cheirocratus</i>
	<i>Cheirocratus intermedius</i>
	<i>Corophium</i>
	<i>Crassikorophium bonellii</i>
	<i>Diastylis bradyi</i>
	<i>Diastylis laevis</i>
	<i>Gastrosaccus sanctus</i>
	<i>Gastrosaccus spinifer</i>
	<i>Lagis koreni</i>
	<i>Magelona filiformis</i>
	<i>Magelona johnstoni</i>
	<i>Megaluropus agilis</i>
	<i>Megamphopus cornutus</i>
	<i>Melinna palmata</i>
	<i>Nebalia bipes</i>
	<i>Owenia fusiformis</i>
	<i>Pariambus typicus</i>
	<i>Periculodes longimanus</i>
	<i>Phtisica marina</i>
	<i>Pinnotheres pisum</i>
	<i>Poecilochaetus serpens</i>
<i>Polycirrus medusa</i>	
<i>Pontocrates arenarius</i>	
<i>Pseudocuma (Pseudocuma) longicorne</i>	
<i>Scolelepis (Scolelepis) squamata</i>	
<i>Scolelepis bonnieri</i>	
<i>Siphonoecetes (Centraloecetes) kroyeranus</i>	
<i>Synchelidium maculatum</i>	
<i>Urothoe elegans</i>	
<i>Urothoe poseidonis</i>	
Benthic inv filter feeders	<i>Ampelisca</i>
	<i>Ampelisca brevicornis</i>

Ecopath functional group	Species composition
	<i>Ampelisca diadema</i>
	<i>Ampelisca spinipes</i>
	<i>Ampelisca tenuicornis</i>
	<i>Ampelisca typica</i>
	<i>Phoronis psammophila</i>
	<i>Pisidia longicornis</i>
	<i>Spirobranchus</i>
	<i>Thyone fusus</i>
Benthic inv predators	<i>Antalis vulgaris</i>
	<i>Asterias rubens</i>
	<i>Eteone longa</i>
	<i>Eualus cranchii</i>
	<i>Eulalia mustela</i>
	<i>Eumida</i>
	<i>Eumida bahusiensis</i>
	<i>Eumida sanguinea</i>
	<i>Eunereis longissima</i>
	<i>Eurydice pulchra</i>
	<i>Euspira pulchella</i>
	<i>Exogone (Parexogone) hebes</i>
	<i>Glycera gigantea</i>
	<i>Glycera lapidum</i>
	<i>Glycera tridactyla</i>
	<i>Glycinde nordmanni</i>
	<i>Haplostylus normani</i>
	<i>Harmothoe</i>
	<i>Harmothoe glabra</i>
	<i>Harmothoe pagenstecheri</i>
	<i>Malmgreniella arenicolae</i>
	<i>Myrianida</i>
	<i>Mysta picta</i>
	<i>Nemertea</i>
	<i>Nephtys assimilis</i>
	<i>Nephtys cirrosa</i>
	<i>Nephtys hombergii</i>
	<i>Nephtys kersivalensis</i>
	<i>Nymphon brevirostre</i>
	<i>Paranaitis kosteriensis</i>
	<i>Philocheras bispinosus bispinosus</i>
	<i>Pholoe baltica</i>
	<i>Phyllodoce</i>
	<i>Phyllodoce lineata</i>
	<i>Phyllodoce longipes</i>
	<i>Phyllodoce maculata</i>
	<i>Phyllodoce mucosa</i>

Ecopath functional group	Species composition
	<i>Phyllodoce rosea</i>
	<i>Processa edulis edulis</i>
	<i>Processa modica modica</i>
	<i>Protodorvillea kefersteini</i>
	<i>Sigalion mathildae</i>
	<i>Sthenelais boa</i>
	<i>Tubulanus polymorphus</i>

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Table S - 5 Trophic groups of the eBoS Ecopath with Ecosim model.

Number of groups	Trophic groups	Environmental drivers
1	Phytoplankton	Primary production map
2	Bacteria	Everywhere
3	Microzooplankton	Everywhere
4	Mesozooplankton and macrozooplankton	Everywhere
5	Meiofauna	Everywhere
6	Suprabenthos	Everywhere
7	Benthic inv. deposit feeders (surface)	Suitability index map
8	Benthic inv. deposit feeders (subsurface)	Suitability index map
9	King scallop	Suitability index map
10	Benthic inv. bivalves filter feeders	Suitability index map
11	Benthic inv. filter feeders	Suitability index map
12	Benthic inv. predators	Suitability index map
13	Fish limande	Suitability index map
14	Fish flounder	Suitability index map
15	Fish European plaice	Suitability index map
16	Fish sole	Suitability index map
17	Fish sea bream	Suitability index map
18	Fish benthos feeders	Suitability index map
19	Fish planktivorous	Suitability index map
20	Fish piscivorous	Suitability index map
21	Fish European sprat	Suitability index map
22	Fish European pilchard	Suitability index map
23	Fish poor cod	Suitability index map
24	Fish pouting	Suitability index map
25	Fish gurnard	Suitability index map
26	Fish Atlantic horse mackerel	Suitability index map
27	Fish whiting	Suitability index map
28	Fish Atlantic cod	Suitability index map
29	Fish sharks	Suitability index map
30	Fish rays	Suitability index map
31	Fish European seabass	Suitability index map
32	Fish mackerel	Suitability index map
33	Benthic cephalopods	Suitability index map
34	Benthopelagic cephalopods	Suitability index map
35	Surface feeders sea birds	Everywhere

Number of groups	Trophic groups	Environmental drivers
36	Plunge and pursuit diverse sea birds	Everywhere
37	Benthic feeders sea birds	Depth dependent
38	Phocidae	Depth dependent
39	Harbor porpoises	Depth dependent
40	Bottlenose dolphins	Depth dependent
41	Discards	Everywhere
42	Detritus	Everywhere

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Table S - 6 Fitted climatic species distribution models used to compute environmental driver maps for each trophic group of the eBoS Ecospace model. Models include: multiple regressions (Generalized Linear Model, Generalized Additive Model, Multiple Adaptive Regression Splines), regression trees (Boosted Regression Tree from GBM, Random Forest, Classification Tree Analysis), discriminant analysis (Flexible Discriminant Analysis) and learning techniques (Artificial Neural Network).

Ecopath trophic group	Latin name	Proportion in the group	climatic							
			MARS	ANN	CTA	FDA	GAM	GBM	GLM	RF
Benthic cephalopods	<i>Sepia officinalis</i>	1.00	1		1		1	1	1	1
Benthic inv. deposit feeders (Subsurface)	<i>Echinocardium cordatum</i>	0.66	1		1	1	1	1	1	1
Benthic inv. deposit feeders (Surface)	<i>Ophiothrix fragilis</i>	0.45	1		1	1		1	1	1
Benthic inv. deposit feeders (Surface)	<i>Pectinaria koreni</i>	0.15	1			1				1
Benthic inv. filter feeders	<i>Psammechinus miliaris</i>	0.15	1		1				1	1
Benthic inv. predators	<i>Asterias rubens</i>	0.03	1	1		1	1		1	1
Benthic inv. predators	<i>Buccinum undatum</i>	0.11								1
Benthic inv. predators	<i>Owenia fusiformis</i>	0.66								
Benthic inv. predators	<i>Sagartia troglodytes</i>	0.09					1			
Benthopelagic cephalopods	<i>Alloteuthis subulata</i>	0.09			1	1				1
Benthopelagic cephalopods	<i>Loligo vulgaris</i>	0.91	1				1	1	1	1
Benthic inv. bivalvia filter feeders	<i>Aequipecten opercularis</i>	0.02	1			1	1	1	1	1
Benthic inv. bivalvia filter feeders	<i>Ensis directus</i>	0.00	1		1	1	1	1	1	1
Benthic inv. bivalvia filter feeders	<i>Glycymeris glycymeris</i>	0.61			1	1			1	1
Benthic inv. bivalvia filter feeders	<i>Lanice conchilega</i>	0.01	1	1	1	1	1	1	1	1

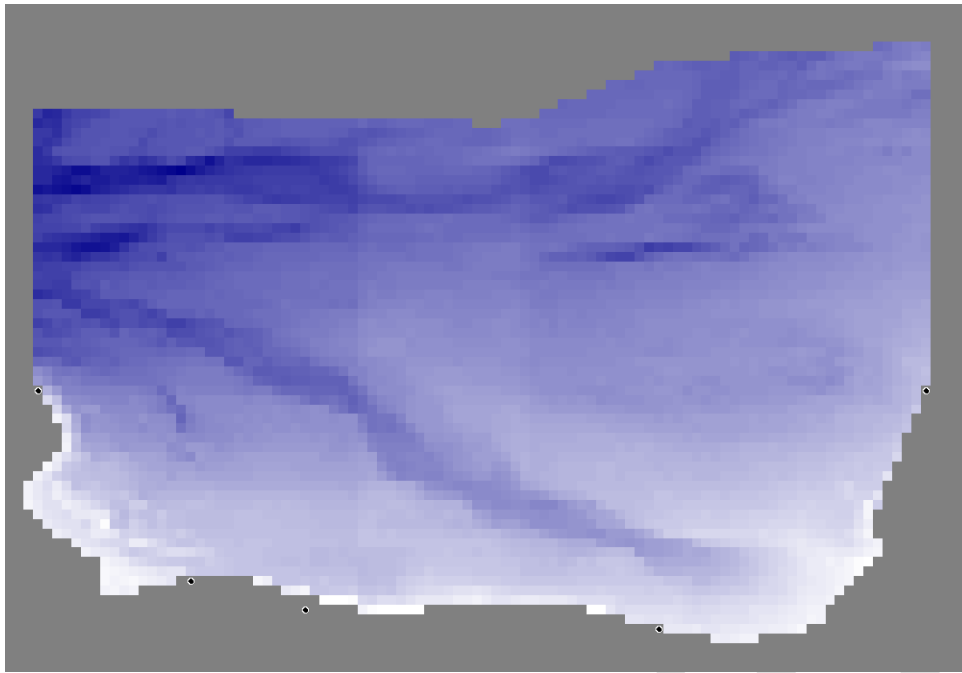
Fish Atlantic cod	<i>Gadus morhua</i>	1.00	1	1	1	1	1	1	1
Fish dab	<i>Limanda limanda</i>	1.00	1		1	1	1	1	1
Fish benthos feeders	<i>Callionymus lyra</i>	0.48	1		1	1	1	1	1
Fish benthos feeders	<i>Labrus bergylta</i>	0.07	1	1	1	1	1	1	1
Fish benthos feeders	<i>Mullus surmuletus</i>	0.27			1		1	1	1
Fish benthos feeders	<i>Zeus faber</i>	0.18	1	1	1	1	1	1	
Fish piscivorous	<i>Pollachius pollachius</i>	1.00	1	1	1	1	1	1	1
Fish planktivorous	<i>Clupea harengus</i>	0.91	1	1	1	1	1	1	1
Fish planktivorous	<i>Engraulis encrasicolus</i>	0.09	1	1	1	1	1	1	1
Fish flounder	<i>Platichthys flesus</i>	1.00	1	1	1	1		1	1
Fish gurnard	<i>Chelidonichthys lastoviza</i>	0.30	1	1	1	1	1	1	1
Fish gurnard	<i>Chelidonichthys lucerna</i>	0.70	1		1	1		1	1
Fish Atlantic horse mackerel	<i>Trachurus trachurus</i>	1.00	1	1	1	1	1	1	1
King scallop	<i>Pecten maximus</i>	1.00	1		1			1	
Fish mackerel	<i>Scomber scombrus</i>	1.00	1			1		1	1
Fish pilchard	<i>Sardina pilchardus</i>	1.00	1	1		1		1	1
Fish plaice	<i>Pleuronectes platessa</i>	1.00	1		1	1		1	1
Fish poor cod	<i>Trisopterus minutus</i>	1.00	1		1	1		1	
Fish pouting	<i>Trisopterus luscus</i>	1.00	1	1	1	1	1	1	1
Fish rays	<i>Raja clavata</i>	0.86	1			1	1	1	1
Fish rays	<i>Raja montagui</i>	0.14	1	1	1	1	1	1	1
Fish sea bream	<i>Spondyliosoma cantharus</i>	1.00			1	1	1	1	1
Fish seabass	<i>Dicentrarchus labrax</i>	1.00							
Fish sharks	<i>Mustelus mustelus</i>	0.37	1	1	1	1	1	1	1
Fish sharks	<i>Scyliorhinus canicula</i>	0.46	1	1	1		1		1
Fish sharks	<i>Scyliorhinus stellaris</i>	0.17	1		1	1	1		1
Fish sole	<i>Solea solea</i>	1.00	1		1	1		1	1
Fish sprat	<i>Sprattus sprattus</i>	1.00	1	1	1		1		1
Fish whiting	<i>Merlangius merlangus</i>	1.00	1		1	1	1		1

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Table S - 7 Fitted habitat species distribution models used to compute environmental driver maps for each trophic group of the eBoS Ecospace model. Models include: multiple regressions (Generalized Linear Model, Generalized Additive Model, Multiple Adaptive Regression Splines), regression trees (Boosted Regression Tree from GBM, Random Forest, Classification Tree Analysis), discriminant analysis (Flexible Discriminant Analysis) and learning techniques (Artificial Neural Network).

Ecopath trophic group	Latin name	Proportion in the group	habitat							
			MARS	ANN	CTA	FDA	GAM	GBM	GLM	RF
Benthic cephalopods	<i>Sepia officinalis</i>	1.00	1	1	1	1	1	1	1	1
Benthic inv. deposit feeders (Subsurface)	<i>Echinocardium cordatum</i>	0.66			1				1	1
Benthic inv. deposit feeders (Surface)	<i>Ophiothrix fragilis</i>	0.45	1	1	1	1	1	1	1	1
Benthic inv. deposit feeders (Surface)	<i>Pectinaria koreni</i>	0.15	1		1					1
Benthic inv. filter feeders	<i>Psammechinus miliaris</i>	0.15	1	1	1		1	1	1	1
Benthic inv. predators	<i>Asterias rubens</i>	0.03	1	1	1		1	1	1	
Benthic inv. predators	<i>Buccinum undatum</i>	0.11	1	1	1		1	1	1	1
Benthic inv. predators	<i>Owenia fusiformis</i>	0.66	1		1			1	1	1
Benthic inv. predators	<i>Sagartia troglodytes</i>	0.09								1
Benthopelagic cephalopods	<i>Alloteuthis subulata</i>	0.09								
Benthopelagic cephalopods	<i>Loligo vulgaris</i>	0.91								
Bivalvia inv. filter feeders	<i>Aequipecten opercularis</i>	0.02	1			1	1			
Bivalvia inv. filter feeders	<i>Ensis directus</i>	0.00			1	1		1	1	1
Bivalvia inv. filter feeders	<i>Glycymeris glycymeris</i>	0.61			1					
Bivalvia inv. filter feeders	<i>Lanice conchilega</i>	0.01	1		1	1		1	1	1
Fish Atlantic cod	<i>Gadus morhua</i>	1.00								
Fish dab	<i>Limanda limanda</i>	1.00	1	1	1	1	1	1	1	1
Fish benthos feeders	<i>Callionymus lyra</i>	0.48			1					

Fish benthos feeders	<i>Labrus bergylta</i>	0.07	1	1	1	1	1	1	1
Fish benthos feeders	<i>Mullus surmuletus</i>	0.27							
Fish benthos feeders	<i>Zeus faber</i>	0.18							
Fish piscivorous	<i>Pollachius pollachius</i>	1.00							
Fish planktivorous	<i>Clupea harengus</i>	0.91							
Fish planktivorous	<i>Engraulis encrasicolus</i>	0.09							
Fish flounder	<i>Platichthys flesus</i>	1.00	1	1	1	1	1	1	1
Fish gurnard	<i>Chelidonichthys lastoviza</i>	0.30	1	1	1	1	1	1	1
Fish gurnard	<i>Chelidonichthys lucerna</i>	0.70			1				
Fish Atlantic horse mackerel	<i>Trachurus trachurus</i>	1.00							
King scallop	<i>Pecten maximus</i>	1.00	1	1	1	1	1	1	1
Fish mackerel	<i>Scomber scombrus</i>	1.00							
Fish pilchard	<i>Sardina pilchardus</i>	1.00							
Fish plaice	<i>Pleuronectes platessa</i>	1.00	1	1	1	1	1	1	1
Fish poor cod	<i>Trisopterus minutus</i>	1.00							
Fish pouting	<i>Trisopterus luscus</i>	1.00							
Fish rays	<i>Raja clavata</i>	0.86			1				
Fish rays	<i>Raja montagui</i>	0.14	1	1	1	1	1	1	1
Fish sea bream	<i>Spondyliosoma cantharus</i>	1.00							
Fish seabass	<i>Dicentrarchus labrax</i>	1.00			1				
Fish sharks	<i>Mustelus mustelus</i>	0.37	1	1	1	1	1	1	1
Fish sharks	<i>Scyliorhinus canicula</i>	0.46			1				
Fish sharks	<i>Scyliorhinus stellaris</i>	0.17	1	1	1	1	1	1	1
Fish sole	<i>Solea solea</i>	1.00							
Fish sprat	<i>Sprattus sprattus</i>	1.00							
Fish whiting	<i>Merlangius merlangus</i>	1.00							



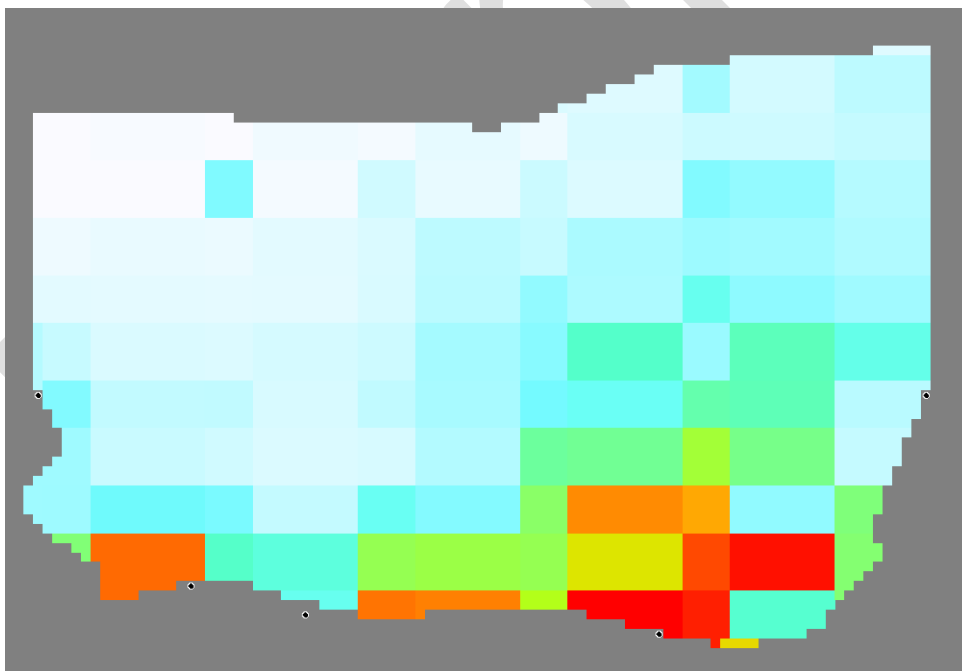
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Figure S - 1 Base depth map from the General Bathymetric Chart of the Oceans.



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Figure S - 2 Primary production map from SeaWiFS representing the relative chlorophyll a concentration in the bay in 2000

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Table S - 8 Environmental driver used to model the reef effect for each trophic group benefiting from it in the eBoS Ecospace model, derived from Raoux et al. (2017).

Area	eBoS groups	Ecospace environmental driver inside the OWF
Outside the OWF	All	0
Inside the OWF	Surface feeders sea birds	6.11
	Fish Atlantic cod	3.49
	Fish whiting	4.18
	Fish pouting	2.32
	Fish benthos feeders	2.07
	Fish sole	1.93
	Fish flounder	4.37
	Fish dab	4.37
	Benthic inv. predators	1.02
	Benthic inv. filter feeders	1.53
	Benthic inv. bivalves	2.2

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Table S - 9 ES supply indicators description.

Ecosystem services	Description	Explanation
Provisioning service	Catch of commercial species by fishermen.	$\sum(C_{fish}) + \sum(C_{invertebrates})$ Where C are catches aggregated by group types.
Regulating service	Trophic pathways redundancy (Ulanowicz and Norden, 1990)	$R = - \sum_{i,j=1}^n T_{ij} \log \left[\frac{T_{ij}^2}{T_i T_j'} \right]$ <p>Where R is the internal relative redundancy, T_{ij} the flow between i and j, T_i the sum of all the flows leaving i, T_j' the sum of all the flows leaving j.</p> $RDC = \frac{R}{DC}$ <p>Where DC is the development capacity of the system.</p>
Cultural service	Production of species of cultural importance	$\sum(P_{marine\ mammals}) + \sum(P_{sea\ birds})$

		<p>Where P are production values of trophic groups.</p> $P_{\text{marine mammals}} = P_{\text{dolphins}} + P_{\text{seals}} + P_{\text{Harbour porpoises}}$ $P_{\text{sea birds}} = P_{\text{surface feeding birds}} + P_{\text{benthic feeding birds}} + P_{\text{plunge pursuit birds}}$
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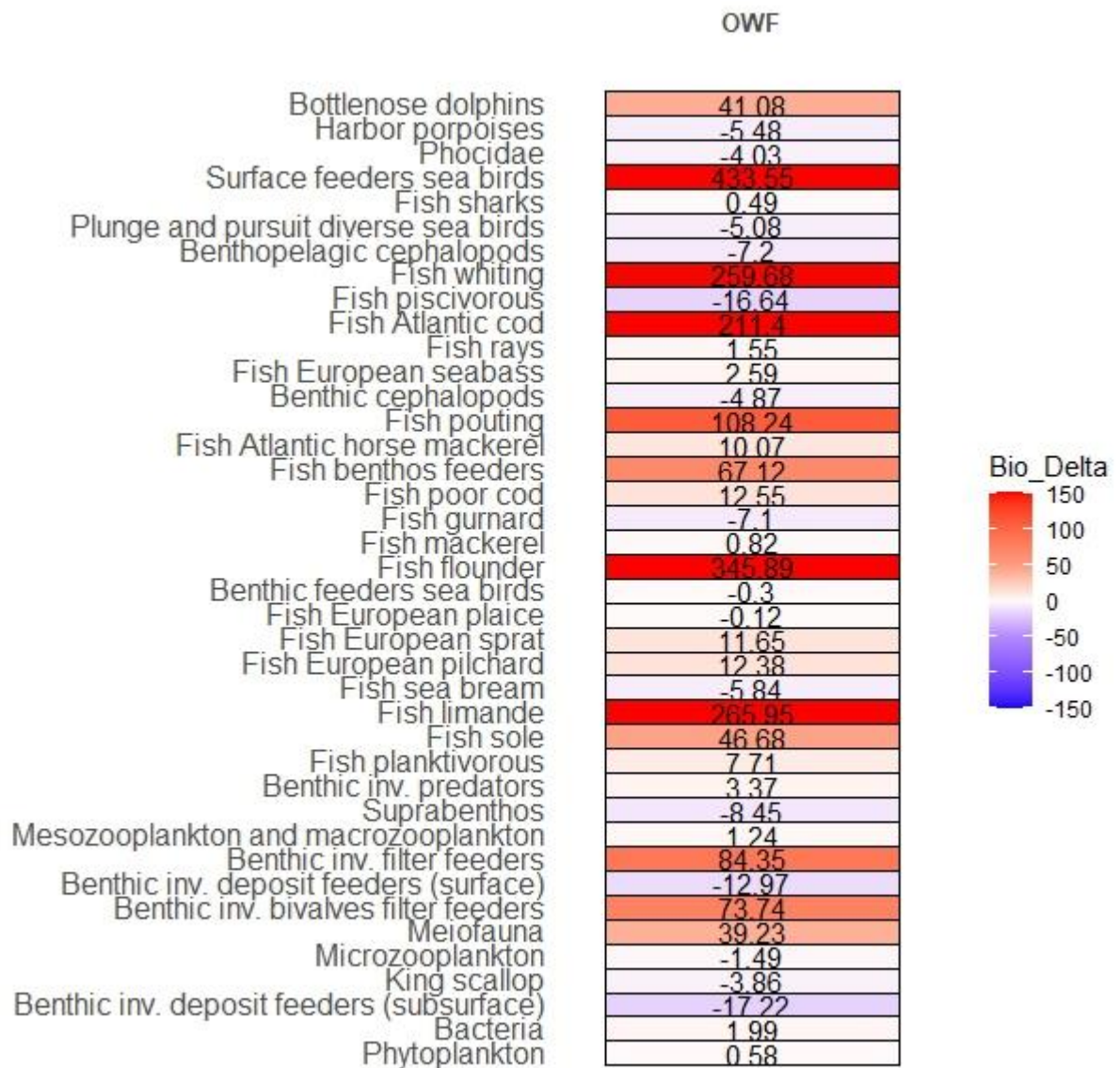
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Table S - 10 Changes in production of mid-trophic level groups due to the OWF

Groups	Delta production (%)
Benthic invertebrates predators	3,35
Fish limande	265,35
Fish flounder	345,79
Fish european plaice	-0,2
Fish sole	46,64
Fish sea bream	-6,25
Fish benthos feeders	67,22
Fish planctivorous	7,73
Fish piscivorous	-16,55
Fish european sprat	11,66
Fish european pilchard	12,24
Fish poor cod	12,65
Fish pouting	108,1
Fish gurnard	-6,93
Fish atlantic horse mackerel	9,8
Fish whiting	259,28
Fish atlantic cod	211,33
Fish sharks	0,41
Fish rays	1,57
Fish european seabass	2,59
Fish mackerel	0,81
Benthic cephalopods	-4,78
Benthopelagic cephalopods	-7,15

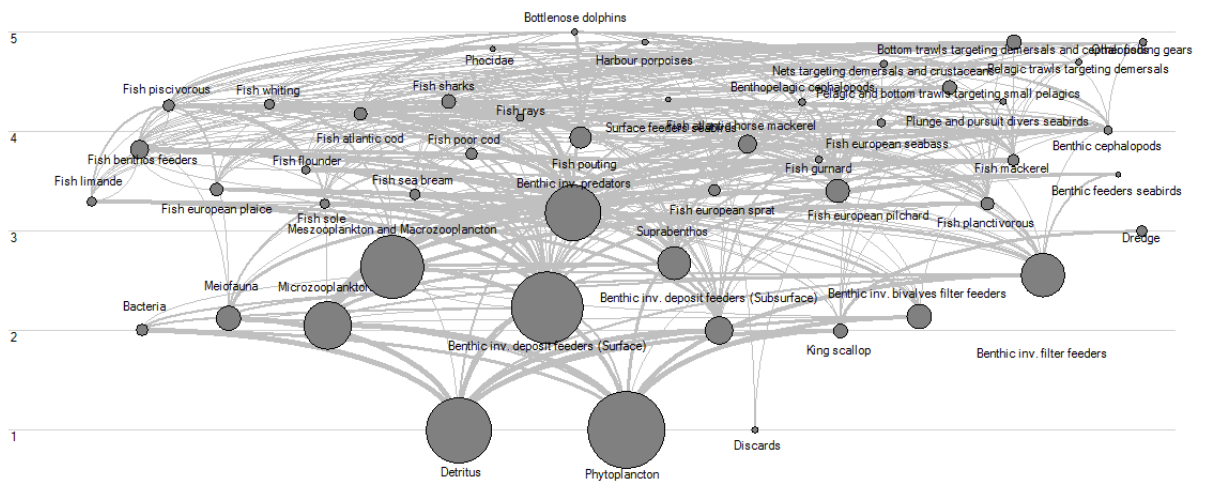
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1266 **Figure S – 3 Effect of the OWF on trophic groups production inside the OWF (in**
 1267 **percent compare to the reference model without the OWF).**

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Figure S – 4 Food web model of the Bay of Seine developed by Halouani et al. (2020). Trophic groups are arranged using trophic level as y-axis. The size of each trophic group is proportional to the biomass it represents.