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### ► **To cite this version:**

Yoann Baulaz, Maud Mouchet, Nathalie Niquil, Frida Ben Rais Lasram. An integrated conceptual model to characterize the effects of offshore wind farms on ecosystem services. *Ecosystem Services*, 2023, 60, pp.101513. 10.1016/j.ecoser.2023.101513 . hal-04054370

**HAL Id: hal-04054370**

**<https://hal.science/hal-04054370>**

Submitted on 31 Mar 2023

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# AN INTEGRATED CONCEPTUAL MODEL TO CHARACTERIZE THE EFFECTS OF OFFSHORE WIND FARMS ON ECOSYSTEM SERVICES

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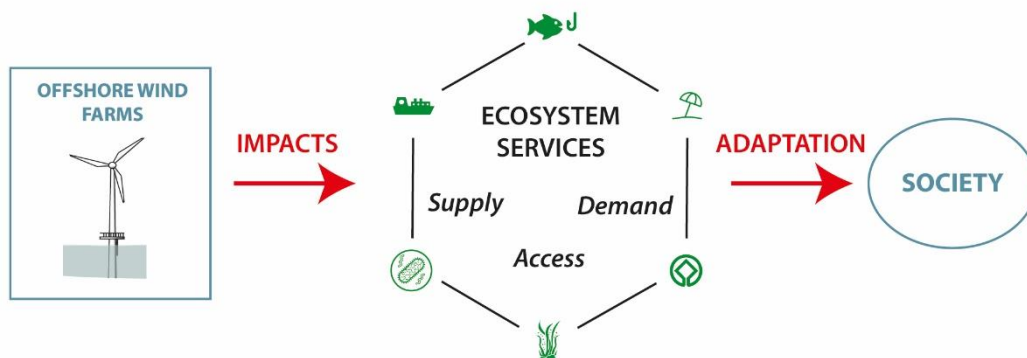
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## Abstract

Offshore wind farm development has become a key measure of energy transition in recent years. Coastal territories are particularly favorable to the development of offshore wind farms due to their high energy potential. However, these areas are also hotspots of biodiversity, provide attractive landscapes and are under strong anthropogenic pressures. Preserving and sharing the natural and cultural resources of coastal territories while intensifying renewable marine energies, represents one of the most important challenges for future management of coastal environments. Consequently, systemic models that consider all the effects of offshore wind farms on ecosystems and society are essential. Here, we propose a conceptual model for studying these effects, by mobilizing the concept of *ecosystem service* in a systemic and integrated assessment approach. To that aim, we reviewed the literature and compiled experts' knowledge in order to characterize the effects of offshore wind farms on food webs during the construction and operation phases. Then, we analyzed the contribution of trophic compartments on ecosystem functions, ecosystem services and beneficiaries, and how offshore wind farms modify the relationships between these compartments of the marine coastal social-ecological systems. Our approach helps identify the causal chains that generate the most important modifications in this system. This information could then be used to predict impacts of offshore wind farms on ecosystem services, and to suggest management trade-offs. This study reveals the need for further studies relating marine biodiversity to ecosystem services, and developing systemic approaches at different scales. The analysis of the effects of offshore wind farms on ecosystem services is crucial since it is linked to strong ecological, socio-economic and political issues.

**Keywords:** offshore wind farm; ecosystem service; conceptual framework; resource management; integrated assessment

**INTEGRATED ASSESSMENT  
OF OFFSHORE WIND FARMS IMPACTS**  
*Experts' knowledge and literature synthesis*



### Graphical abstract

#### Highlights:

- The ecosystem services that are most affected by offshore wind farms are fishing, cultural and habitat maintenance.
- Changes in functional habitats, reef and reserve effects lead to the major changes in ecosystem services supply.
- Offshore wind farm impacts on ecosystem services demand lead to changes in practices, relocation of the beneficiaries and changes in cultural values.
- Taking into account the access to ecosystem services in our conceptual model allows us to consider negative and positive feedbacks on ecosystems and society.

## 1. INTRODUCTION

Helped by ambitious national and international programs of energy transition, the development of offshore wind farms (OWFs) is booming with an increasing number of higher and more productive machines (Díaz and Guedes Soares, 2020). These in turn produce a better energy yield compared to land-based wind turbines, lower landscape and noise impacts, and lower production and delivery costs (Darwish and Al-Dabbagh, 2020).

The implementation of OWFs, like any other offshore infrastructure, faces technical and environmental issues, and potentially conflicting stakeholders. These installations lead to a succession of ecological and socio-economic changes, strongly modifying the capacity of ecosystems to provide *ecosystem services* (ESs) (Rocha et al., 2015; Walker et al., 2004). Following the terminology proposed by Willstead et al. (2018), these ecological and socio-economic changes can be considered as *effects* on the ecosystemic and socio-economic components of ESs, caused by *pressures* i.e. factors associated with the exploration, construction, operation, decommissioning of an OWF. If these effects are of sufficient intensity, duration, and/or severity to cause significant changes to the receptors, then they are termed *impacts* (Willstead et al., 2018).

For marine ecosystems the impacts are highly variable (Lindeboom et al., 2011), differing according to the OWF's life cycle, location, and type of turbine installed, and the species that may interact with these infrastructures. In fact, there can be major changes in the composition and the structure of ecosystems at large scales (Mavraki, 2020). In the case of monopile OWF, there is an artificial *reef effect*. This is a process that provides a habitat function for marine biota resulting from the submergence of anthropogenic structures placed deliberately or accidentally on the seafloor (Mavraki, 2020). Reef effect is the result of a shift of a soft substrate into a hard substrate, and is considered to be the most important

ecosystem perturbation (Petersen and Malm, 2006) as it affects entire food webs through trophic cascades (Raoux et al., 2019). In particular, the underwater section of the wind turbine is rapidly colonized by filter-feeding bivalves, which represent a food source for many organisms of higher trophic compartments like flatfish and cephalopods (Degraer et al., 2019). This will result in a potentially higher global biodiversity, a stronger functional level but different species composition, and have a strong impact on natural communities (Burkhard and Gee, 2012; Lindeboom et al., 2011). This increase in biodiversity is favored by a restriction in use that creates a *reserve effect* (Hammar et al., 2016).

Through the modification of landscapes, relationships between humans and nature, and the emergence of new actors, the values of ESs and the relationships between beneficiaries are bound to evolve. These changes profoundly reconfigure the functioning of marine-coastal territories potentially leading to conflicts between maritime human activities, economic considerations, and regulatory and socio-cultural changes. These social, economic and cultural impacts of OWFs are often neglected in the scientific sphere (Busch et al., 2011; Gee and Burkhard, 2010), but they determine the local acceptability and therefore are essential to consider as part of maritime spatial planning (Gusatu et al., 2020). An important point of controversy involving fishery stakeholders is the existence of a possible *ecological spillover* effect i.e., the net emigration of juveniles, young adults and/or fish and marine megafauna adults from the core of a protected area (Di Lorenzo et al., 2020; Halouani et al., 2020). This ecological spillover is an indirect consequence of the reserve effect, similar to that observed in marine protected areas (with a lower intensity, depending on the regulation of human activities) and could directly benefit fisheries' incomes through the increase in exploitable biomass (Di Lorenzo et al., 2020).

These short- and medium-term evolutions justify the interest in studying ESs in the context of OWFs development, because ES is an interface concept (Le Clec'H et al., 2019), able to combine ecological with societal changes and analyze the causal chains that result from these. ESs can be defined as all the benefits that human populations derive, directly or indirectly, from *ecosystem functions* (Costanza et al., 1997). We define the ecosystem functions as a subset of interactions between ecosystem structure and ecosystem processes that underlie an ecosystem's ability to provide ecosystem services (EFESE-MER, 2019).

However, there are still significant barriers to applying the ES concept in the context of OWFs. First, there is a lack of accurate and measured information about most of the impacts generated by OWF (Dannheim et al., 2020). The recent literature listed some impacts of OWF such as local avoidance by marine fauna, impacts of lights, electromagnetic fields, release of metallic trace elements, but also acknowledged the uncertainty surrounding these impacts (e.g. magnitude, duration) (Degraer et al., 2020; Skov et al., 2018). Additionally, socio-economic uncertainties (i.e., effects on the economy, employment, landscape and socio-cultural values associated with the marine environment) revealed by several studies, point out that the intensity of modifications in the socio-system is context-dependent (Dannheim et al., 2020; Lange et al., 2010). The processes involved are then very variable and complex to study. Moreover, there are significant data gaps on the functioning of marine ecological dynamics (Galparsoro et al., 2012; Kéfi et al., 2019), and on the ESs assessment methods in a marine environment (Busch et al., 2010; Mongruel et al., 2018).

Consequently, the scientific community is calling for an integrated assessment of ESs in an interdisciplinary approach, seeking to investigate the consequences of OWFs on both the *supply* (the capacity of ecosystems to produce ESs) and *demand* (refers to human needs expressed in terms of ESs) of services (Potschin and Haines-Young, 2011). Integrated assessment requires mobilizing a conceptual model to organize the multidisciplinary information and to reveal causal chains that link ecological dynamics to uses. These conceptual models are both methodological and comprehensive tools for organizing environmental research, applying this concept, and understanding human-nature relationships (Östrom, 2009; Collins et al., 2011; Van Oudenhoven et al., 2012). In the marine realm, there is a lack of ES conceptual frameworks (Causon and Gill, 2018) despite a growing demand from managers of many marine ecosystems to advance research on ESs and link this knowledge to

management issues (Armoškaitė et al., 2020; Guerry et al., 2012). In this paper, we propose to fill this gap by developing an integrated conceptual model, coupled with a risk-based assessment approach, enabling to analyze the potential impacts of OWFs implementation on ESs.

## **2. METHOD**

We propose a generic and qualitative approach to study the impacts of OWFs on ESs by developing a new conceptual model as a *linkage framework* (Robinson and Culhane, 2020). The linkage framework encapsulates networks of elements or nodes of a system, associated with links representing the interactions between these nodes. In our conceptualization, the nodes of this system represent all the components associating OWFs with ESs supply. Developing this conceptual model was the first step of our work. It's based on the 'ES cascade model' of Potschin and Haines-Young (2011), one of the most comprehensive and widely used ES conceptual frameworks. We completed this model by integrating OWF components. Our adaptation was validated by experts during the data collection phases.

The application of the framework was then tested and illustrated with two main objectives: firstly, to qualify and semi-quantify the impacts of OWFs on ESs supply; and secondly, to consider the consequences on ESs demand.

The analysis of the OWF possible impacts on ESs supply is based on literature and expert knowledge while the analysis of the consequences on ESs demand is based on the analysis of the verbatims of public debates relative to the implementation of the Dunkirk OWF in France. We present the literature review and the analysis of the OWF possible impacts on ESs supply and demand in the following sections.

### **2.1 Literature review on the impacts of offshore wind farms**

We performed a literature review to collect information about the pressures generated by OWFs during construction and operational phases and their potential effects on the ecosystems and human activities. The aim of this literature review was also to prepare the experts' survey phases, complete the experts' statements, and assess the validity of our results.

The literature review was carried out in two stages: first, using Web Of Science and Google Scholar search engines, we compiled review papers published between 2000 and 2020 relating to the OWFs effects on ecosystems in order to make a list of pressures. We restricted the research to fixed OWFs, without geographic restrictions, although the majority of the studies focus on fixed OWFs in the North Sea. Second, articles dealing specifically with each pressure were searched from the same search engines based on references cited directly in the reviewed papers.

The information from 54 articles was then synthesized. Based on the works of Dannheim et al. (2020) and Degraer et al. (2019), we specified the spatial extent of the impacts of each pressure on ecosystems. These authors defined four distinct OWF pressures' spatial extents (i.e., wind turbine, wind farm, buffer zone and regional). They also mention that the impacts also vary along a water column depth gradient.

### **2.2 Analysis of the offshore wind farms possible impacts on ecosystem services supply**

As suggested in Armoškaitė et al. (2020) and Duncan et al. (2015) we considered the contribution of different trophic levels to the supply of ESs, through a set of ecosystem functions that underpin them. The analysis of the OWFs possible impacts on ESs supply consist then in the combination of a *risk-based assessment approach*, that consider the effects of OWFs on trophic networks, with an ESs supply characterization. This procedure was performed in two steps: first, specify and semi-quantify the impact intensity of the pressures previously identified on each trophic groups (receptors), and then, consider the transfer of these impacts to the ESs, by determining the ecosystem functions and ESs provided by the receptors. The objective, in fine, is to identify the possible OWFs impact pathways, associating the

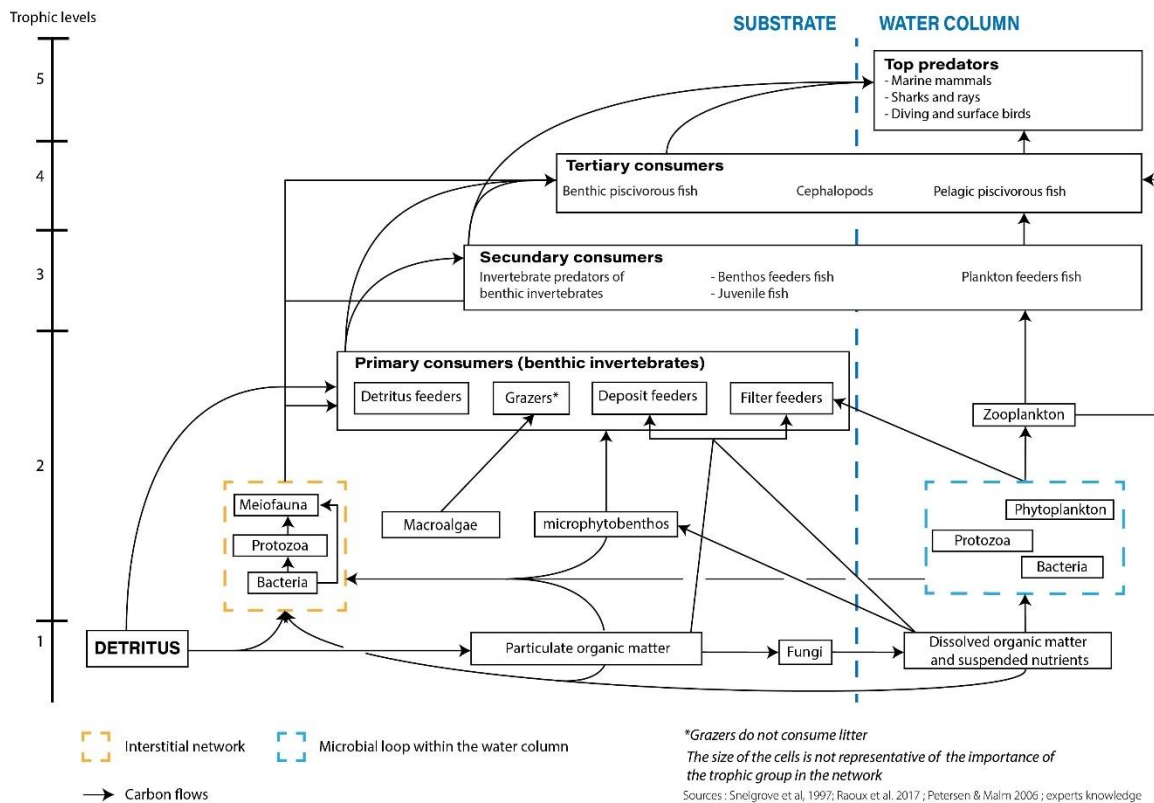
OWF pressures to the trophic groups, the ecosystem functions and ESs in a causal-effect chain. By semi-quantifying the intensity of the impact of each pressure on the receptors, we can then identify the main impacts on ESs.

To do so, our methodological approach consisted of a two-step survey. The risk-based assessment approach was conducted with an online expert survey and the ESs supply characterization with an expert workshop. The compilation and analysis of the obtained data was then realized with Sankey diagrams.

### **2.2.1 The expert survey methodology**

Seeking a holistic analysis, we made the choice to interview researchers in functional ecology specializing in food webs, as well as benthic physicists and biologists specializing in specific trophic compartments (plankton, fishes, marine megafauna, bivalves).

The entire survey was organized around a search for specific impacts on food web linked to OWFs (see fig. 1 and appendix A for information about survey structure). The objective was to estimate the impact of each pressure at two phases of the OWF life cycle - construction and operational phases. To do so, we asked the experts to identify which OWF pressure affects each trophic level and to classify the impacts according to three modalities (no impact, non-significant impact, significant impact) depending on the potential expected changes in the species populations or species communities (Boehlert and Gill, 2010). The survey was conducted by e-mail to 49 marine experts (biologists, ecologists and physicists) between April and August 2020. Twenty-two people responded, i.e., a participation rate of 45%, which is relatively high for this type of online survey. Most of them were experts of the English Channel ecosystems, and two of the French Mediterranean ecosystems.



**Figure 1: Simplified trophic network diagram.** This diagram supported the experts survey to ensure a common baseline for assessing impacts on trophic compartments by experts. Each item in the expert survey corresponds to a specific trophic level defined in this simplified trophic network diagram. This trophic network was constructed beforehand from bibliography and validated by three marine ecologists.

### 2.2.2 The expert workshop methodology

A participatory workshop was organized in autumn 2020. Its aims were to (1) validate and complete the results of the first survey investigation phase; (2) identify the ecosystem components that determine ESs within OWFs through a mind map; and (3) identify synergies and antagonisms between the different ESs in the OWF development context while using a second mind map. The principle of a mind mapping is to associate the compartments of a system, represented by boxes, with arrows corresponding to the processes linking the compartments to each other. The expected results were to precisely describe the links between the OWF pressures and ESs supply.

The workshop included 20 participants (biologists, ecologists, geographers, industrialists, physicists, see appendix B) most of them had responded to the online survey beforehand.

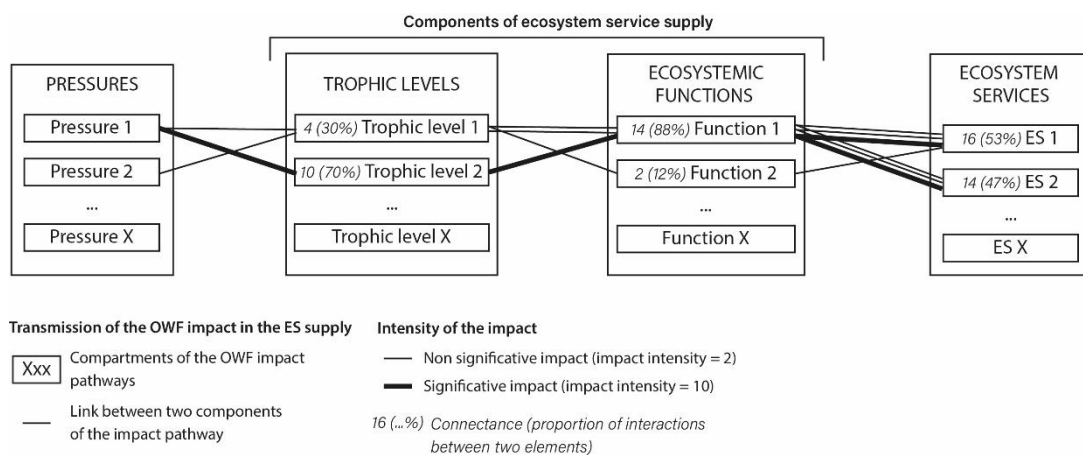
### 2.2.3 Representing the offshore wind farms possible impacts on ecosystem services supply using Sankey diagrams

We produced Sankey diagrams to synthesize and represent the possible OWFs impact pathways on ESs supply. The Sankey diagrams were constructed with the tool “ChartExpo” plug-in for Microsoft Excel and -Google Sheets. Sankey diagrams are powerful graphical tools for linkage frameworks, representing all the *connections* between a multitude of *nodes*. These connections are represented by lines of different thickness depending on their intensity (Fig. 2). Here, the structure of the Sankey diagrams follows the structure of our conceptual model. The nodes are associated with the pressures generated by OWFs and the components of the ESs supply, while the lines represent the impacts induced by OWFs and their

transmission between each component of the ESs supply. Therefore, our Sankey diagrams report the impacts of OWFs on each trophic compartment and ES.

The nature of the relationships between the nodes of the Sankey diagrams were determined using the outcomes of the expert workshop, and the intensity of the connections were determined using the outcomes of the expert survey. To semi-quantify the impact intensity of each pressure on the trophic levels, we coded the experts' answers as: 0 (no effect), 2 (not significant), 10 (significant). The impact intensity is then associated to all the functions linked with these trophic levels and all the ES associated with the functions.

The impact intensities of each pressure were then summed to obtain the *connectance* of each ES component and compare the impacts pathways. The connectance corresponds to the proportion of effective connections between two nodes of a linkage framework. This connectance can be calculated by dividing the number of effective connections by the number of theoretical possible connection. In our model, connectance corresponds to the sum of the specific impacts on each trophic compartment, ecosystem function and ESs involved. By analyzing connectances, it is possible to semi-quantify the intensity of possible cumulative impacts on ESs supply components and identify the main potential OWFs impact pathways (Fig. 2).



**Figure 2: Detailed scheme of the linkage framework, represented with a Sankey diagram. Our Sankey diagrams represent the transmission of the offshore wind farms (OWF) possible impacts within the different ecosystem services supply components (nodes). Each line (connection) represents a specific OWF impact and its intensity (connectance).**

## 2.3 Analysis of the offshore wind farms possible impacts on ecosystem services demand through the “Dunkirk project” case study

A different approach was developed to consider the impacts of OWFs on ESs demand. We conducted a textual content analysis of the public debates related to the development of a specific French OWF project: the proposed OWF of Dunkirk located in the southern North Sea.

We did not aim to fully analyze the impacts of OWFs on ESs demand by studying changes in benefits, but mostly aimed to identify the potential conflicts between ESs beneficiaries that could emerge in the context of an OWFs development.

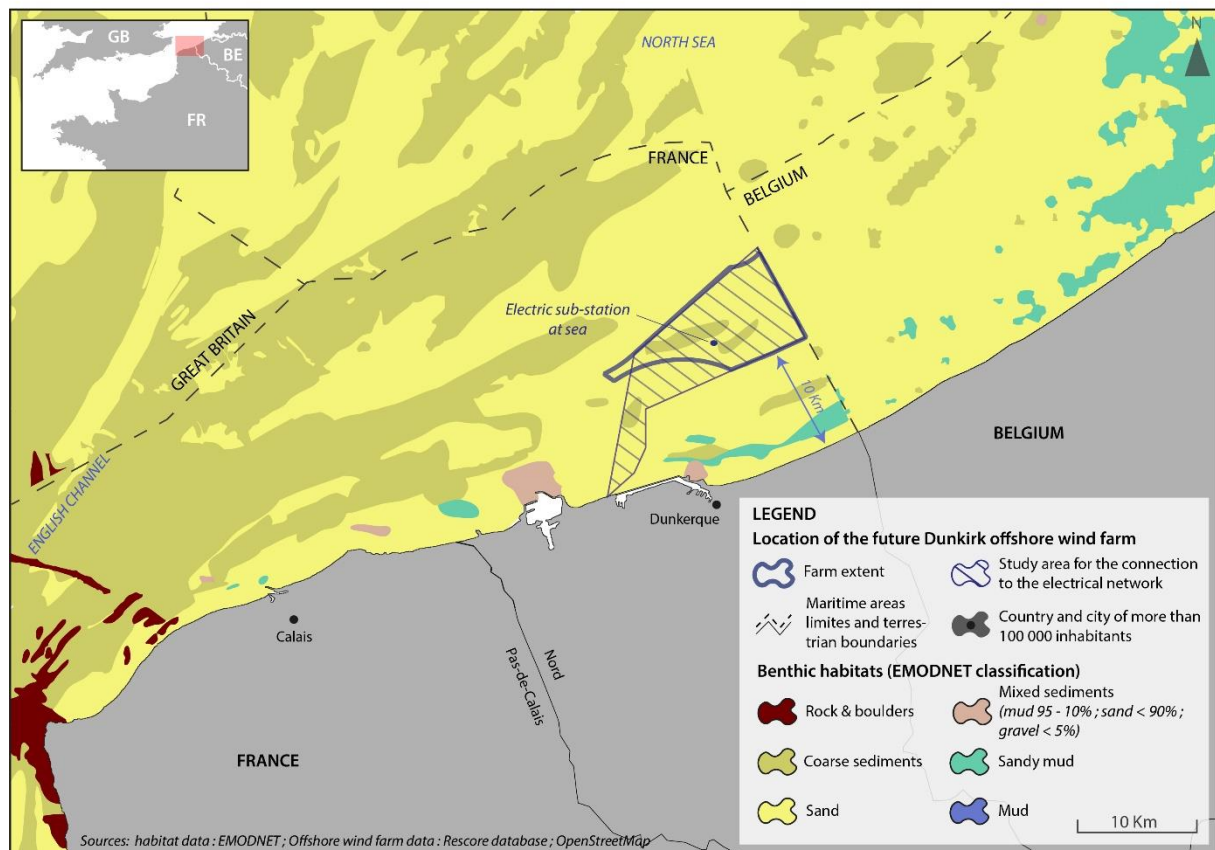
### 2.3.1 Dunkirk offshore wind farm project

The OWF project of Dunkirk (a maximum power of 600 Megawatts) will be composed of a maximum of 46 monopile wind turbines and scheduled for 2023 (Fig. 3; Appendix C.1). This project is relevant



for our study, because of the various human activities sharing the implantation area and surroundings: fishing, recreational and commercial navigation, mussel farming, dredging, and clamming. Moreover, the area is a transition zone between the French eastern English Channel, where there is currently no OWF (but six are scheduled) and the southern part of the North Sea, where eight OWFs are already operating (Appendix C.2). From an ecological point of view, the area is an important migration route for fish, marine mammals, and birds; and is a Natura 2000 zone for avifauna protection.

In the context of the implementation of this project, a public debate involving all the representatives of actors potentially impacted by the OWF took place between September 2020 and April 2021.



**Figure 3: Study area of Dunkirk offshore wind farm project and benthic habitat in the area**

### 2.3.2 Data used for the analysis of impacts on ecosystem services demand

The impact on ESs demand was limited to the identification of ESs beneficiaries potentially affected by the Dunkirk OWF through changes in their practices.

This analysis was carried out by monitoring the public debates around the Dunkirk OWF project. This qualitative follow-up aimed particularly at identifying the potential adaptations of maritime ESs beneficiaries to the implementation of an OWF through worries expressed by actors and users participating in the public debates.

To do this, we analyzed the discussions of special meetings organized during the public debates (13 special meetings between September 1, 2020, and February 16, 2021 – see appendix D.1). Our research focused on two points: who were the invited stakeholders, and what were their concerns expressed during the debates? From the discussions, we identified and categorized the ES direct beneficiaries (e.g., tourism professionals, fishing and shellfish professionals, and the offshore wind energy industry – Appendix D.2) and assigned each debate stakeholders to one of these categories. Moreover, each

concern expressed by the stakeholders allowed us to create an empirical typology of different OWF possible impacts on the practices of the ESs beneficiaries.

The report of the public debate sessions and the beneficiaries' typology are provided in the supplementary material D.

### 3. RESULTS

The conceptual model we developed was used as a comprehensive, but also a methodological tool to organize the study, while dealing with four main questions:

1. What are the OWFs pressures and how do they affect the different trophic levels?
2. What ecosystem functions do these trophic levels support?
3. What functions are involved in the provision of ESs and how could changes in trophic levels and ecosystem function affect ESs supply?
4. What are the consequences of ESs supply changes on access to ESs for the various beneficiaries?

The following sections will answer these questions. We first present the global conceptual model in a theoretical way. Then we describe the different possible OWFs impact pathways affecting the ESs supply. Finally, we consider the consequences of the OWFs implantation in term of ESs demand.

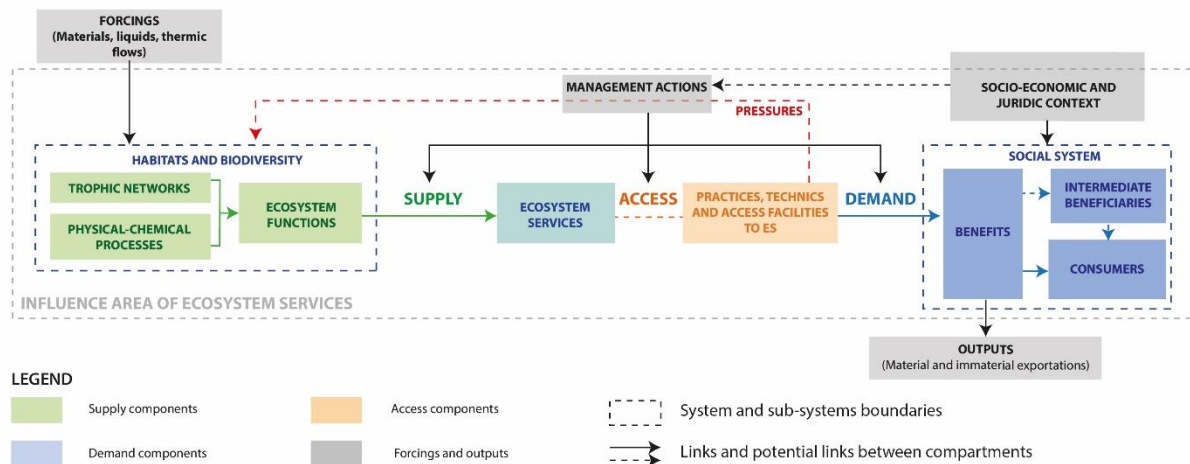
#### 3.1 Adaptation of the services cascade framework to the offshore wind farms issue

Our conceptual model (Fig. 4) includes the main components of the ES cascade model: (1) the biophysical processes and ecosystem functions that provide ESs, and (2) the benefits, corresponding to the needs in terms of services, expressed by the beneficiaries. The main adaptation we have made is the addition of a component often neglected in the study of ESs, namely *access to services*. Access is defined here as the processes that allow beneficiaries to gain from the ESs provided (inspired by Ala-Hulkko et al., 2016). These processes could mobilize practices, tools, facilities and mobility that define the *material access*, but also legislation, economy, labor force, knowledge, commitment or cultural investment, for the *socio-cultural access* to ESs. Access to ESs conditions the nature and intensity of the potential exploitation of ESs by beneficiaries and thus most of the pressures on ecosystems and potential conflicts of uses. In the context of the present study, OWFs and the infrastructures necessary for their functioning and the delivery of the electricity produced for consumers are considered as *access facilities* to the 'wind provision ES'. In the marine environment, two fundamental parameters determine ES material access: depth, and distance from the coast (Galparsoro et al., 2014).

Our conceptual model also differs from that of Potschin and Haines-Young (2011) by incorporating *boundaries* to our system. Indeed, considering boundaries allows us to include information about ESs management actions, to address ESs management scales issues and to consider some phenomena, outside the domain of local stakeholders, affecting the supply and demand. By regulating the supply, access, and demand of services, management actions help to maintain the sustainability of ESs. Boundaries refer also to the existence of a potential *influence area* of an OWF that could be spatially modelled and beyond which the influence of an OWF on ecosystem and society can be considered as limited. These boundaries are generally "porous", and some *external forcings* can potentially affect the supply and demand of ESs. For example, climate change is an external biophysical forcing affecting ESs supply and is important to consider in OWF context (Nogues et al. under review). Besides, ESs can produce *outputs*, potentially influencing other systems. Spatially, we define the boundaries in a theoretical way, corresponding to the OWF footprint and associated infrastructures, as well as the ES

supply, access, and demand areas associated within that *OWF space*. So, these boundaries can evolve as a function of ES dynamics and the influences of external forcings.

Classifying and defining ESs and the functions that underpin them is a prerequisite for any ESs assessment. Therefore, we reframed a typology of ecosystem functions and ESs present in the OWF area based on De Groot et al. (2010) and the Common International Classification of Ecosystem Services (CICES 2018, v 5.1 - Haines-Young and Potschin, 2018) (see tables 1 and 2 and in Supplementary materials, the tables E.1 and E.2 for the definitions of the different functions and ESs).



**Figure 4: Ecosystem service (ES) cascade model adapted to the study of offshore wind farms (OWFs) effects on marine/coastal area.** This diagram represents theoretical pathways among the components of ES in an OWF area. The ES are at the center of this system, driven by habitats and biodiversity and by social demand.

**Table 1: Relevant ecosystem functions in offshore wind farm context and associated trophic compartments**

Type	Ecosystem functions name	Associated trophic compartments
<i>Production</i>	Trophic relationships and biotic interactions	Whole trophic network
	Specific and genetic diversity	Whole trophic network
	Secondary production	Whole trophic network
	Primary production	Primary producers
	Nutrient production and recycling	Whole trophic network
<i>Habitat</i>	Habitat formation	Biotope; organic matters, detritus; primary producers; primary consumers
	Biogeochemical cycles	Organic matters, detritus; primary producers; primary consumers
	Presence of essential habitats	Biotope; organic matters, detritus; primary producers; primary consumers
	Weather-oceanic conditions	Biotope
	<i>Landscape</i>	Existence and variety of spaces with potential recreational uses
Biophysical parameters contributing to pleasant landscapes		Biotope; primary consumers; top predators
Educational and scientific interest of the marine environment		Whole ecosystem

**Table 2: Relevant ecosystem service typology in offshore wind farm context and associated ecosystem functions**

Type	ES	Associated ecosystem functions
<b>Provisioning</b>	Bio-resources for nutritional purposes	Primary production; secondary production; Specific and genetic diversity; Trophic relationships and biotic interactions; Habitat formation; Presence of essential habitats
	Bio-resources for material purposes	
	Water used for materials (energy, shipping)	Weather-oceanic conditions; Habitat formation
	Wind used for materials (energy, air navigation)	
	Mineral and non-mineral substances or ecosystem properties used for materials (energy, extraction and deposit or materials)	
<b>Regulation</b>	Regulation of water, substrate quality and contaminants in organisms	Nutrient production and recycling; primary production; trophic relationships and biotic interactions; weather-oceanic conditions; biogeochemical cycles; habitat formation
	Protection of baseline flows and extreme climatic events	Weather-oceanic conditions; habitat formation
	Lifecycle maintenance, habitat and gene pool protection	Primary production; specific and genetic diversity; trophic relationships and biotic interactions; habitat formation; presence of essential habitats; biogeochemical cycles
	Regulation of weather and air quality	Trophic relationships and biotic interactions; Weather-oceanic conditions; biogeochemical cycles
<b>Cultural</b>	Physical and recreational interactions with the natural environment	Primary production; secondary production; weather-oceanic conditions; specific and genetic diversity; presence of essential habitats; Existence and variety of spaces with potential recreational uses; Biophysical parameters contributing to pleasant landscapes
	Contribution to culture and territorial identity	
	Contribution to science and education	Whole ecosystem functions

### **3.2 Defining the impacts of offshore wind farms on ecosystems and their spatial extent**

From our literature review synthesis, during the construction phase of a monopile foundation OWF, we identified three major pressures synergistically affecting the ecosystem (Table 3). The resulting impacts vary in spatial extent, but are only present during construction: *rearrangement of benthos* and the *digging and crushing of the substrate* are localized directly around the wind turbines, while *noise and vibrations* extends beyond this.

During the operational phase (Table 4), most impacts are localized within a radius of 100 m around the wind turbines, and are more complex to study. Some specific pressures impact a buffer zone around the farm like some impacts on birds (*barrier effect*, *change in functional habitat*, and *lights emissions*), impacts linked to *hydrodynamic conditions* and the *reserve effect*, with a possible associated ecological spillover.

The pressures generated during the dismantling phase are very poorly documented. Nevertheless, the expected effects would be similar to those of the construction phase, given that European regulation require the pre-construction ecosystem status to be rehabilitated, and therefore all the foundations removed.

**Table 3: Typology of the potential pressures of an offshore wind farm on ecosystems during construction phase.**

Pressures	Spatial extent	Impacts	References
<b>CONSTRUCTION PHASE</b>			
Rearrangement of benthos	Wind turbine (<100m around the turbine)	This disturbance increases turbidity and alters organic matter and detritus fluxes. This results in possible benthic anoxia, lowered light levels for primary producers, physical damage to filter and suspension feeders, and eggs smothering for secondary and tertiary consumers.	(Dannheim et al., 2020; Lange et al., 2010)
Digging and crushing of the substrate	OWF	Bottom digging and crushing for the installation of foundations and cables result in mortality of endofauna and sessile species and loss of essential habitats. Stress and avoidance behaviors are to be noted for species able to move away from the construction site.	Degraer et al., 2019
Sound and vibrations	Buffer zone (500m to 4km around the farm)	Disturbances generated by pile driving (installation of the wind turbine foundations in the sediments) that cause physical damage and stress to the species. Avoidance behavior of the construction area and changes in the distribution of the most sensitive groups of species are observed (top predators, particularly marine mammals, and some species of fish and crustaceans to a lesser extent).	Dannheim et al., 2020; Degraer et al., 2019; Lindeboom et al., 2011; Petersen and Malm, 2006

**Table 4: Typology of the potential pressures of an offshore wind farm on ecosystem during the operational phase.**

Pressures	Spatial extent	Impacts	References
<b>OPERATIONAL PHASE</b>			

Reef effect	Wind turbine (<100 m around the turbine)	The most documented effect. It affects the entire food web, providing new colonization supports and new essential habitats for hard substrate species. The reef effect will generate changes in the structure of communities, the evolution towards a more complex ecosystem, marked in particular by an increase in the diversity and biomass of filter-feeding bivalves, and pelagic fishes, the aggregation of top predators and increased predation. A stepping stone effect for non-native hard substrate species can also be observed.	Lange et al. 2010; Dannheim et al. 2020; Degraer et al. 2019; Petersen and Malm 2006; Lindeboom et al. 2011; Raoux et al. 2017; Glarou et al. 2020; Mavraki 2020; Burkhard and Gee 2012; Mangi 2013
Reserve effect	Buffer zone (500m to 4km around the farm)	As fishing is limited to the OWF, the target species of fisheries will benefit from a reserve effect, which can, in the long term, promote the ecological spillover effect and increase the fish biomass around the farm.	Busch et al., 2011; Glarou et al., 2020; Lange et al., 2010; Lindeboom et al., 2011; Mangi, 2013; Petersen and Malm, 2006
Barrier effect/avoidance	Region (until 20km from the farm)	For migratory species of fish, birds and marine mammals. Species have an increased energy expenditure as they seek to avoid farms by a long distance (up to 3 km).	Garthe and Hüppop, 2004; Lange et al., 2010; Lindeboom et al., 2011
Change of functional habitat	Wind turbine (<100m around) and buffer zone (500m to 4km) for birds	Some soft substrate species (infauna, certain primary producers) and some diving and surface birds are concerned.	Burkhard and Gee, 2012; Degraer et al., 2019; Lindeboom et al., 2011
Sounds and vibrations	Wind turbine and region (until 20km from the farm)	Muffled noises from the rotation of wind turbine blades and vibrations disturb some species of macroinvertebrates (crustaceans), fishes, marine mammals and birds.	Dannheim et al., 2020; Lindeboom et al., 2011; Petersen and Malm, 2006
Lights and flickering shadows	Wind turbine and region (until 20km from the farm)	Lights and flickering shadows can affect certain species of fishes, birds and chiropteres.	Garthe and Hüppop, 2004
Electromagnetic field	Wind turbine and region (until 20km from the farm)	Electromagnetic fields can cause changes in behavior, stress, disruption of migration, and decreased predation efficiency.	Dannheim et al., 2020; Öhman et al., 2007; Petersen and Malm, 2006
Collisions	Wind turbine	The masts and blades of wind turbines generate collisions with birds.	Garthe and Hüppop, 2004

Hydrodynamic modifications	Region (until 20km from the farm)	The hydrodynamic modifications linked to the presence of wind turbines lead to erosion, a phenomenon of "sediment sorting" leading to a modification of the particle size of the substrate, changes in currents, temperature and the resuspension of sediments and nutrients in the wake of the wind turbines. Primary producers and consumers can be affected insignificantly.	Busch et al., 2010; Dannheim et al., 2020; Degraer et al., 2019; Lindeboom et al., 2011
Metal emissions	Region (until 20km from the farm)	A release of metallic trace elements, mainly aluminium, is to be expected due to the anti-corrosion devices (sacrificial anodes). These emissions would remain below the threshold values of toxicity for species and human health.	Golding et al., 2015; Kirchgeorg et al., 2018
Enrichment of organic materials and detritus	Wind turbine	Enrichment of organic materials and detritus is expected, as an indirect consequence of the increase in bivalve abundance. The decomposition process may release small quantities of hydrogen sulfide (H <sub>2</sub> S)	Dannheim et al., 2020

### 3.3 Offshore wind farms' impacts on ecosystem services supply

Several results and figures are used to analyze the impacts of OWFs on ESs supply:

- Fig. 5 and 6 represent the global Sankey diagrams with all impact pathways between OWFs pressures and ESs,
- Appendix G for detailed impact pathways for some ESs,
- Appendix F for additional qualitative information about impacts on ecosystem functions.

During the OWFs construction and operational phases, changes in ESs supply differ. The literature review and the qualitative information obtained in the survey allowed us to describe these changes for each ES:

**1) Bio-resource ESs supply.** In both phases of the OWFs life cycle, more than the half of the system changes affect the three ecosystem functions determining the bio-resource services (*secondary production; specific and genetic diversity; and trophic relationships and biotic interactions*). During construction, these changes result mainly from the *digging and crushing of the substrate*, acting on the whole benthic ecosystem, followed by a *rearrangement of benthos* that will lead to a loss accounting for more than 27% of the primary producers and primary consumers groups (Fig. 5). During production, the *reef effect*, the *reserve effect*, and *change of functional habitat* are the most affecting pressures on the ecosystem. They result in a global increase in the abundance and diversity of pelagic fish exploited by fisheries, aquaculture, or for material purposes (e.g., pharmaceuticals) within the farm and nearby, despite increased predation from top predators. In contrast, the loss of soft substrate habitat may decrease the abundance and diversity of flatfish. Finally, the intensity of the impacts on these services depends on three parameters: (1) the species fished locally; (2) the regulation of activity within the OWF; and (3) the intensity of the ecological spillover effect.

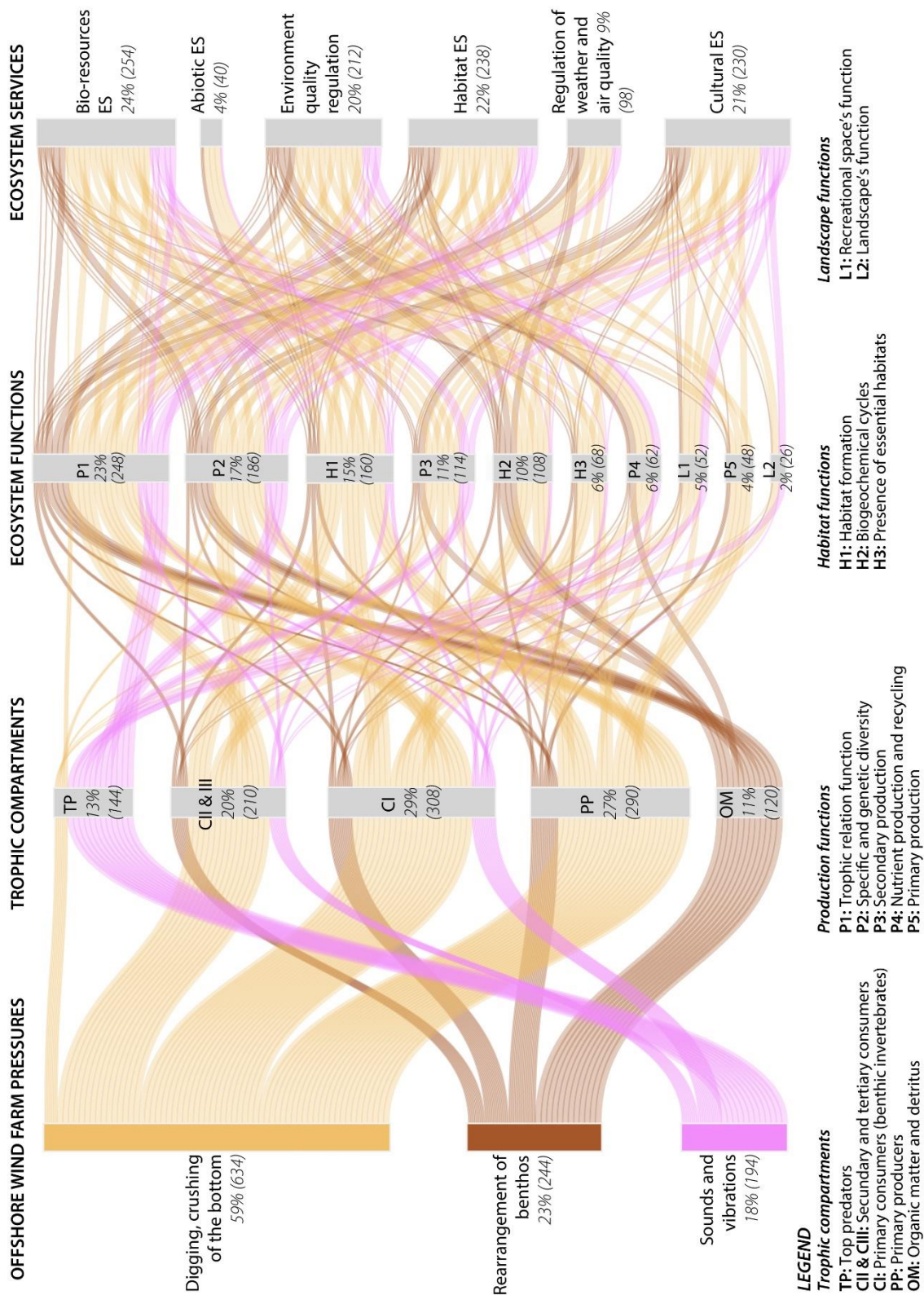
**2) Regulation of the quality of the environment ES supply.** The expected main effects are modifications in water filtration, nutrients production, and recycling. These processes will be reduced during the construction phase, due to the *rearrangement of benthos* (leading to a resuspension of materials and pollutants and an increased turbidity), and the increased mortality rate of filtering-organisms. However, the filtration production and recycling of nutrients will improve afterwards during the operational phase, with an increase in abundance of filtering bivalves, the most affected group. Moreover, this service would be affected by two threats: (1) the introduction of invasive and/or toxic

species, facilitated by the *reef effect*; and (2) the potential transfer into the food web of *metal emissions*, even though this pressure lead to only 4% of the modification of the system (Fig. 6). During the workshop, the experts noted that this ES depends strongly on the local climatic and oceanic conditions, the OWFs location (e.g., near a seaport or an estuary), and the water dilution capacity in the area.

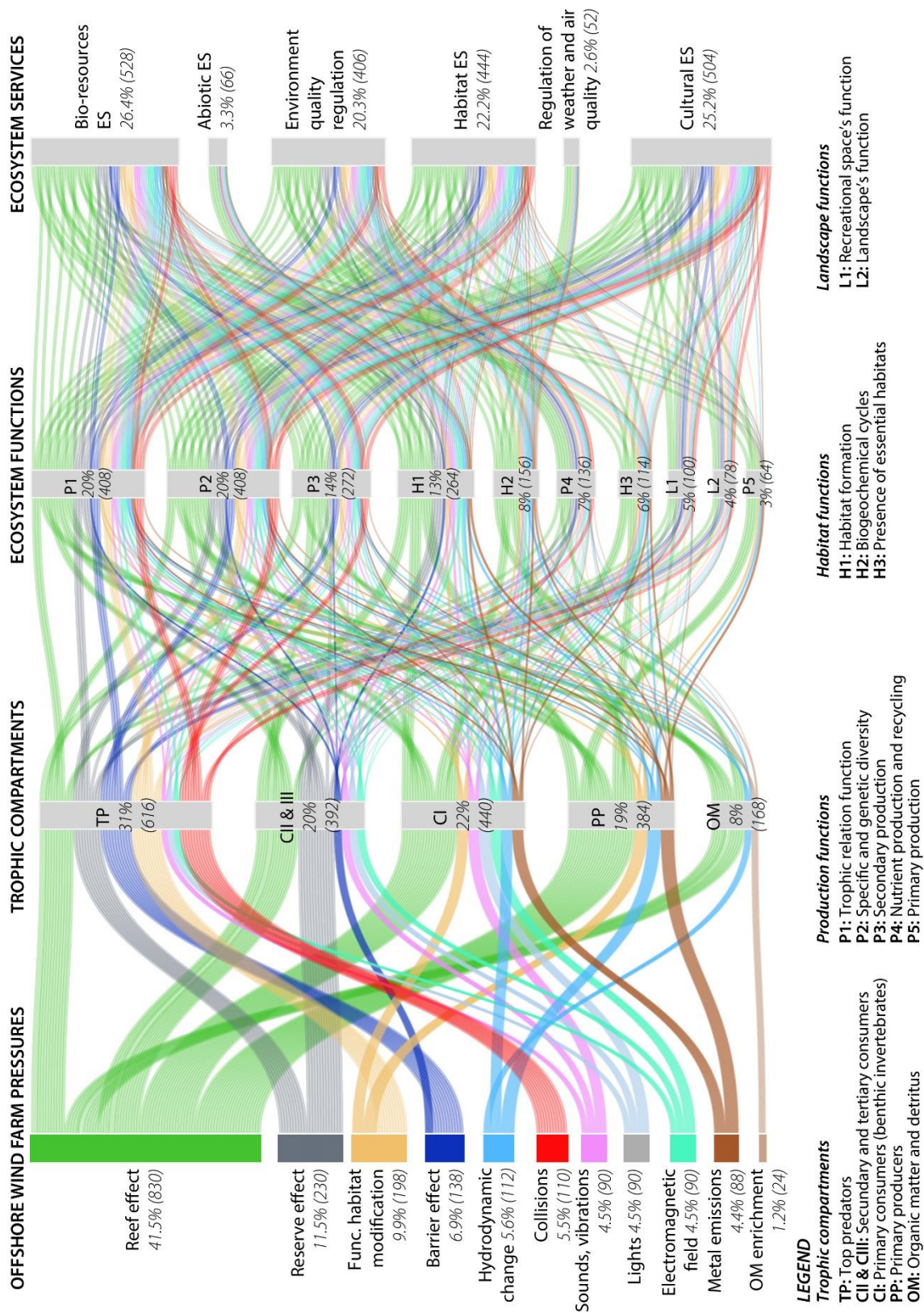
**3) Habitat ES supply.** The supply of this ES is strongly affected by changes in the ecosystem substrate, structure, and functioning. During the construction phase a strong loss of benthic and pelagic functional habitats is expected to occur (mainly from the *digging, crushing of the substrate* and the *rearrangement of the benthos* – Fig. 5). Conversely, for the operation phase, new functional habitats (nurseries, reproduction, spawning, feeding and refuge habitats) for hard substrate species appear in the surrounding area of foundations, cables and scouring protections with the *reef effect*. These new habitats can indirectly promote the establishment of non-native species. Moreover, the same types of functional habitats for soft substrate species may disappear. The migratory routes of some top predators can also be strongly affected (13% and 31% of the impacts are related to top predators during construction and production phase respectively). Avifauna is particularly sensitive to these changes: some species show avoidance behaviors in the North Sea (e.g., *Somateria mollissima*, *Fulmarus glacialis*), while others are attracted towards the OWF area (e.g., *Phalacrocorax carbo*). The latter are consequently more exposed to collisions.

**4) Cultural ESs supply.** More than 21% of the impacts are expected in cultural ESs supply, because they are associated with almost all ecosystem functions (Fig. 5 and 6). During construction, marine megafauna and avifauna, which are ‘charismatic species’, are expected to avoid the OWF area. In contrast, during the operation phase the greater secondary production and specific and genetic diversity would promote the aggregation of top predators of heritage interest, and fisheries resources of recreational interest. Also, the increased water filtration (changes in biogeochemical cycles and nutrient production and recycling functions) contributes to a clearer and more attractive seascape. The coupling of these different effects on species will increase the variety of sea spaces with potential recreational uses, even if the landscape functions are among the less impacted functions. On the other hand, impacts on birdlife, particularly migratory birds, will negatively impact ornithology and observation activities.





**Figure 5: Offshore wind farm’s impact pathways affecting the ecosystem service (ES) supply during the construction phase of the farms. In this Sankey diagram, the size of the links represents the impact intensity of each potential offshore wind farm (OWF) impact pathway affecting the ES supply components. The numbers and percentages in parentheses represent the connectance of each element of the Sankey diagram (OWF pressures, trophic compartments, functions and ES).**



**Figure 6: Offshore wind farm’s impact pathways affecting the ecosystem service supply during the operational phase of the farms.** In the diagram, the size of the links represents the impact intensity of each potential offshore wind farm (OWF) impact pathway affecting the ES supply components. the numbers and percentages in parentheses represent the connectance of each element of the Sankey diagram (OWF pressures, trophic compartments, functions and ES).

### 3.4 Modeling the impacts of offshore wind farms on ecosystem service access and demand

We define four types of change in ES access (Fig. 7), that will lead to a gain or a loss of benefits (financial or not) for ESs beneficiaries.

The first type of ES change is associated with the modification of practices. This could lead to the appearance of new practices (e.g., marine and coastal leisure tourism, educational, or museum exhibitions) or conversely, a loss or a limitation of practices for safety reasons (e.g., navigation restrictions, limitations on the boats' size, types of fishing gear, restricted access to wrecks and heritage features).

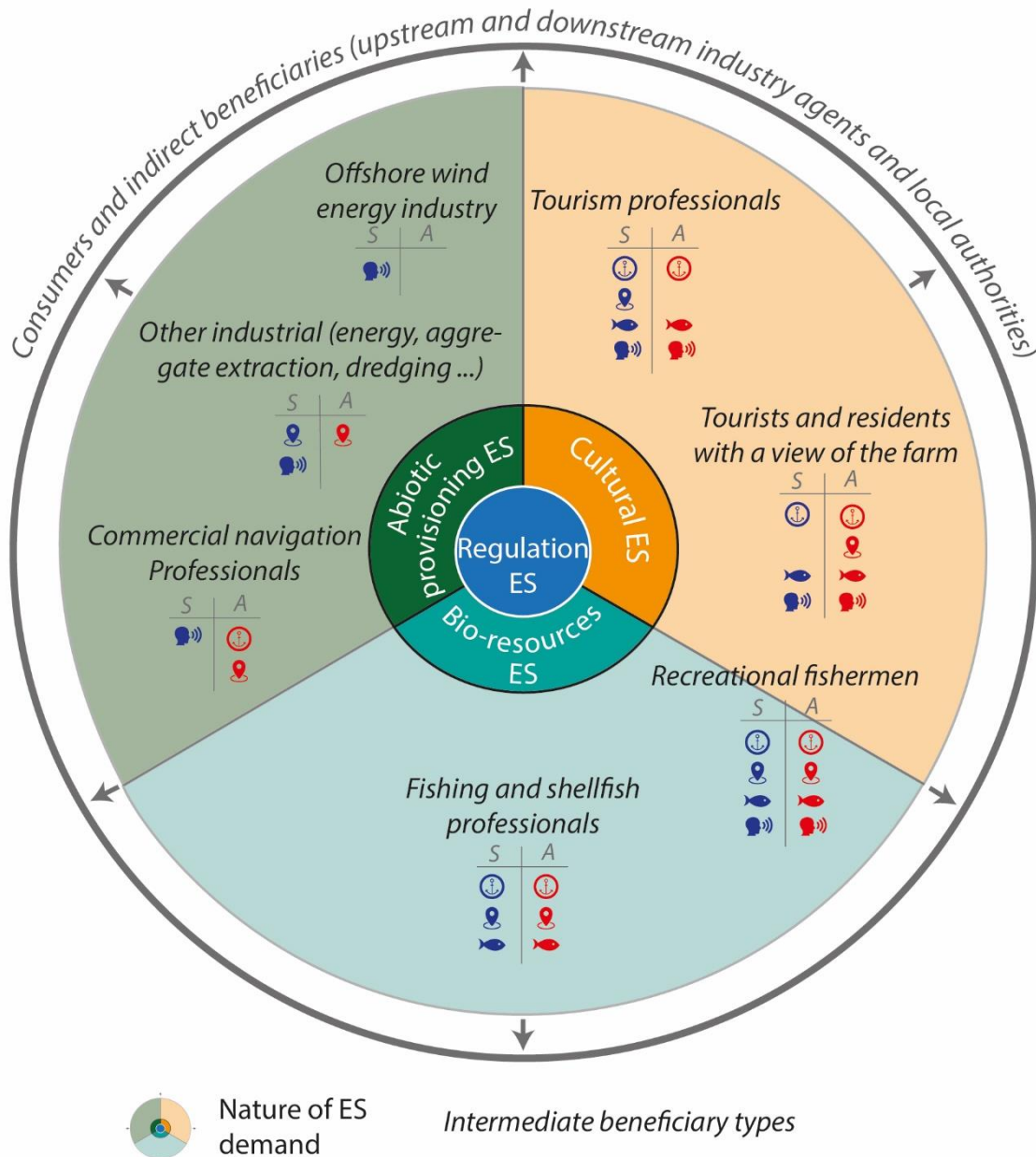
The second type relates to the spatialization of the beneficiaries resulting from *co-uses* or spatial shifts. Co-uses could be defined as the possibilities for direct beneficiaries to gain from ES, which were not present within the OWF area before its construction (e.g., aquaculture, tourist walks to visit the farms, hydrogen). However spatial shifts for some direct beneficiaries will occur if a total ban on access to some practices within the farms is adopted.

The third type relates to potential biomass changes and reduced or increased access to bio-resources due to the impacts on ESs supply.

Finally, an important concern expressed by users during the public debates relates to a change in the marine environment social values: for example, a loss of some essential qualities of the sea (e.g., the feeling of wilderness, open spaces, or freedom from anthropic structures) or conversely, the development of an image of a territory developing renewable energy. Wind turbines corresponding to a new landscape element can act as a source of additional inspiration. Losses or gains of knowledge or skills (e.g., for fishing) can also be observed. These modifications affects the socio-cultural access to ES.

The target shape of the diagram (Fig. 7) expresses that trade-offs between ESs are partly determined by the access of ESs. Beyond the changes in ESs access, it should be noted that antagonisms and synergies between ESs are partly determined by the quality of regulating ESs that support ecosystem resilience to pressures. That is why regulating ESs are at the center of the target diagram: this reflects that changes in regulating services will affect the supply of both provisioning and cultural ESs, and specific attention from policy makers in this relation is needed. Second, change in the access to ESs at the local scale can be transmitted in the marine-coastal territory and have far-reaching consequences for the entire production, export and consumption pathways of ESs, affecting consumers and indirect beneficiaries (represented at the borders of the target diagram).

**Diagram of antagonistic and synergistic demands between ES and offshore wind farms**



**Figure 7: “Target diagram” of synergistic and antagonistic ecosystem services demands in offshore wind farm context.** Each target segment represents direct beneficiary types associated with the supply of bio-resource, abiotic and cultural ecosystem services. Changes in the access to ecosystem services induced by offshore wind farms are indicated with pictograms below each beneficiary type.

## 4. DISCUSSION

The aim of this study is to propose a conceptual framework for applying the ES concept to the context of OWF development. This conceptual model highlights the interactive mechanisms that lead to modifications of ESs. It organizes the information in a coherent way while adapting to the practical needs of the users. This results in a model comparable to other studies.

The application of this framework, derived from empirical information suggests that all trophic compartments should be affected by OWFs with varying intensities. In addition, we identified six main pressures of OWFs affecting ESs supply in recent literature (Dannheim et al., 2020; Degraer et al., 2019; Negro et al., 2020; Pezy et al., 2020). From these results, we highlight the potential consequences on access to ESs and demand of ESs.

In light of these findings, it appears that: (1) OWFs change ESs in a complex synergetic way and at several scales; (2) several research gaps and promising avenues of reflection have been revealed by the application of the framework; and (3) having a general ES conceptual framework, adaptable to multiple contexts enriches the tools available to managers and helps to identify management trade-offs between ESs.

### 4.1 The complex mechanisms of ecosystem service changes caused by offshore wind farms

The experts consulted estimated that all ESs would be affected by OWFs. These modifications result in major changes in the *production ecosystem functions* (except primary production), showing strong damage to trophic interactions. For example, a change in *secondary production* or *specific or genetic diversity* can lead to a gain or loss of biomass, triggering beneficiaries like fishermen to adapt their practices. This situation is characteristic of an *ecosystem regime shift*, modifying the abundance and diversity of most species. The supply of all ESs determined by these functions is then impacted, revealing synergistic responses among services to common causes of modifications (Bennett et al., 2009).

Within the OWF context, this regime shift is mainly caused by the *reef effect*, which will develop in the long term a richer and more complex ecosystem than the soft substrate ecosystem existing prior to construction (Petersen and Malm, 2006). It is known that ESs supply is linked to high biodiversity (Cardinale et al., 2012; Biggs et al., 2012). As a result, the *reef effect* will be of benefit to the ESs supply in different ways: (1) the increase in abundance of some fish species and top predators will benefit the supply of provisioning and cultural ESs, while (2) regulating ESs will be promoted by an improvement in system functionality. Moreover, changes in biotic compartments result in numerous indirect ‘top-down’ and ‘bottom-up’ cumulative effects, linked to trophic cascades. The result of these processes is the development of a food web dominated by filter-feeding bivalves (Mavraki et al., 2020) which are keystone organisms playing a major role in the provision of many ESs, e.g., by filtering large volumes of water, by decreasing turbidity, and by accumulating nutrients (Armoškaitė et al., 2020).

However, the regime shift contributes to a large-scale ecosystem homogenization and to a decrease in the diversity of functional traits in the marine environment (Degraer et al., 2019). The implementation of OWFs can thus be seen as favorable for the supply of most ESs at the local scale, but at the same time contributes to the decline of specialist species, which is a global issue (Clavel et al., 2011; Olden et al., 2004).

OWFs lead to further modifications at the regional scale associated with the change in ESs access and the ability of the various beneficiaries to adapt their practices. These modifications of practices may result in three types of indirect impacts on marine/coastal territories: (1) an over-exploitation of the services (e.g., over-fishing or over-use of the coastline) in response to the relocation of the beneficiaries around the OWFs; (2) conflicts of use resulting from the exploitation of one service at the detriment of

another; and (3) pressure on the ecosystems adjacent to the OWFs, which can modify their capacity to provide services at a large scale. Consequently, when considering all the effects of OWFs on coastal territories, one needs to consider the indirect impacts, relative to these beneficiaries' adaptations. These indirect impacts are social aspects of the durability which are often forgotten (Frederiksen et al., 2021).

These elements reveal diverse and strong spatial and temporal fluctuations of the impacts of OWFs on ESs. The intensity and the modifications they generate on the territory are difficult to anticipate because they are subject to strong contextual variability (ecological, socio-economic, politic and cultural - Duncan et al., 2015). Overall, it appears that characterizing the impacts of marine renewable energy is a complex challenge that requires a systemic understanding of the dynamics involved. However, this could be made possible by the application of ES conceptual frameworks, like the one developed in this paper.

## **4.2 Research gap and promising venue for a quantitative evaluation of impacts on ecosystem services**

The study of the pressures on ESs can help identify common processes, cascading effects, and bring to light synergies and antagonisms between ESs. Considering relationships between OWFs, trophic networks, and ESs can serve as a framework for the implementation of management actions (Bennett et al., 2009). For this purpose, coupling ecosystem models, which seek to model trophic relationships in a holistic way (Heymans et al., 2012), with the ES concept is highly promising. Trophic modeling has already been developed from different studies related to OWFs, e.g., to explore the impact of the *reef effect* on food webs (Raoux et al., 2017); to simulate the ecological spillover related to a cessation of fishing within OWFs (Halouani et al., 2020); and to model the cumulative impact of OWFs and different anthropic perturbations (Le Marchand, 2020; Nogues et al., 2021). The use of trophic models to quantify trophic interactions greatly improves our understanding of the anthropogenic impacts on coastal marine territories and ESs supply (Nogues et al., under review; Heymans et al., 2012).

We propose the use of specific trophic modeling indicators (Ecological Network Analysis -ENA indicators) to characterize the ecosystem functions and quantify the ESs supply (Safi et al., 2019). For example, the indicator 'relative redundancy' could be used to assess the *trophic relation function*, and the biomass of species of heritage interest for the *landscape functions*. Our model provides information to weight the relative contribution of each function quantified with the ENA indicators to assess the services. We advise to use this type of information to build a phenomenological model and map marine ESs (Lavorel et al., 2017; Townsend et al., 2014). However, as we also semi-quantify the impacts of OWFs on ESs supply, our model could provide other coefficient factors allowing the analysis of cumulative impacts of different OWFs pressures.

The critical analysis of our methodology reveals that participatory workshops are particularly adapted to the study of subjects linked to a high level of uncertainty, such as OWF impacts. This approach makes it possible to obtain multidisciplinary and co-constructed information, to invite debate, and to limit as much as possible the uncertainties linked with the contrasting perceptions of the ES concept (Barnaud et al., 2011; Scemama et al., 2022). This approach has been shown to inform quickly managers to characterize ESs (Campagne and Roche, 2018). It should be noted, however, that there can be an important bias when using experts' opinions. For example, there is the potential of 'over-estimation' in regard to some better-documented items compared to others (e.g., there is more information available regarding *reef effect* than other OWFs pressures). This method therefore, provides useful trend-information, particularly about the spatial and temporal variability of the processes, but with little precision (Campagne and Roche, 2018). For a more precise qualification and quantification of the impacts on ESs, as the OWFs impacts potentially vary between different regions (IUCN, 2021), our results should be adapted to the local context and the OWF projects studied (e.g., by identifying the local species, reviewing the list of ecosystem functions and services).

Furthermore, changes in physicochemical parameters and *habitat functions* have not been fully considered in this study. These functions are strongly modified in the OWF context and have an important role in ecosystem resilience (Cardinale et al., 2012) - habitat formation and the presence of critical habitats support biodiversity and functional traits diversity. This indicates that consideration of the effects of OWFs on hydrology, substrate grain size, and chemical fluxes between the benthic and pelagic domains could accentuate the intensity of changes on *habitat functions* and the magnitude of fluxes modeled in our Sankey diagrams. This is the main limitation of our study.

The use of Sankey diagrams complements the comprehensive approach to synthesizing expert knowledge. The main limitation of this tool is that it is not suitable for in-depth analysis of the feedback between components of ES – this study does not consider the relationships between ecosystem functions for example.

In addition, it could be interesting to test the applicability of the developed conceptual model and the usefulness of the Sankey diagrams to the study of other OWF foundation types (e.g., floating foundations), marine renewable energies, or pressures caused by the implementation of other infrastructures facilitating access to marine ESs (e.g., offshore oil plants). Another improvement of our conceptual model could be to consider the impacts of the OWFs decommission phase which is beginning to be studied (Hall et al., 2022), and the cumulative impacts of different adjacent OWFs given the exponential development of marine renewable energies worldwide in recent years.

### **4.3 Ecosystem service management recommendations in the context of marine renewable energy development**

The development of OWF raises many societal issues. It is an alternative energy source to fossil resources that is expected to strengthen the sustainability of marine/coastal territories, provide economic security for local territories through taxation and job creation, and benefit certain trophic compartments and uses. On the other hand, it increases the risks of dissemination of non-indigenous species and habitat homogenization on a large scale, as well as decreasing sea safety and raising fears of losing socio-cultural environmental values (Nogues et al. under review). In the face of these contradictions, it is not possible to formulate answers on a global scale as to whether the impacts caused by OWF are “positive”, “negative”, or “neutral” (Causon and Gill, 2018). The challenge first and foremost, is to implement measures to facilitate the integration of these new uses of the sea, while reducing possible impacts.

The expert-survey approach and the literature review allowed us to identify research areas lacking in knowledge. In particular, we noticed the impacts are poorly documented for some trophic compartments, like zooplankton or primary consumers (excluding filter feeders); or that some results are contradictory (e.g., some studies report both avoidance and attraction behavior within the OWF for some bird species - Blew et al., 2008; Skov et al., 2018). Also, at the end of our study we observed that the trends identified by the experts were consistent with the information available in the literature. This justifies the use of the ES approach and demonstrates its validity for assessing impacts of marine renewable energy development.

Studying the linkages between ‘access to wind ES - supply and demand of ES’ is a promising approach. It allows us to identify the main OWF causal impacts chains, that is an important information for management. Our model can then help to develop an activity-stressor-receptor-impact relationship approach, that is recommended to assess the impacts of renewable marine energy projects (Boehlert and Gill, 2010; Shadman et al., 2021).

Our study provides general information about relationships between OWFs, ecosystems and sea uses. However the intensity and nature of the impacts of OWFs described in this paper may vary depending on: (1) geographical context parameters - namely proximity to other OWFs, conservation issues, marine space multifunctionality, and local development strategies (Le Visage et al., 2021); (2) perception of

natural environments (Hastik et al., 2015); (3) regulation and adaptability of ES beneficiaries to resulting impacts (Degraer et al., 2019); (4) technical and engineering characteristics of the farms, in particular the foundation type, the number of turbines, their size and the distance to the shore distance (Le Visage et al., 2021); and (5) the state of biodiversity and potential synergistic impacts from other pressures (Nogues et al., 2021). When choosing the location and spatial extent of these farms, the decision-makers must consider these parameters in consultation with the different beneficiaries of the area in a regional development context (Hastik et al., 2015). All these elements can feed into our conceptual model to improve its operational application.

Our approach could help when applied to maritime spatial planning. In particular, the adapted cascade model allows us to consider the pressures associated with the development of OWF on the supply, access and demand of ESs in a systemic and integrated approach. This invites us to consider the interactions and positive and negative feedback between ESs. In this way, our approach could help to identify the environmental and socio-economic parameters to monitor the global impacts of an OWF, anticipate possible conflicts between human activities, identify the cumulative ecological impacts and trade-offs between ESs (Shadman et al., 2021). Furthermore, controlling the access to ESs could be an important management policy action (Galparsoro et al., 2014). In this way, our conceptual framework can help in addressing the most important challenges of marine spatial planning: prioritizing socio-economic stakes at sea, while ensuring a sustainable development of coastal territories (Frederiksen et al., 2021).

## **5. CONCLUSION**

One of the major challenges for the sustainable management of coastal territories is the preventive identification of ‘threatening changes in the relationships between ecological and socio-economic systems (Kopf et al., 2015; Weise et al., 2020). Such an objective implies that the diagnosis of the status of marine/coastal ecosystems must evolve to account for the ecological and societal components of the coastal territories and the variables modifying its dynamic. Integrated conceptual frameworks, like the one developed in this article, can serve as a basis for the construction of such a diagnostic and constitute the first step toward the development of a long-term observation of the effects of OWFs on ecosystems and societies.

Its application as a linkage framework allowed us to identify the causal chains that generate the main potential OWFs impacts in the ecosystems and human activities. We particularly highlighted that the fishing provisioning ESs, the habitat maintenance ES and the cultural ESs are the most impacted. These impacts are related to changes in food webs and ecosystem functions underpinning ESs supply, caused mainly by the change of functional habitat, and reef and reserve effects during construction and operation phases of the OWFs. The changes in ESs demands are driven by these modifications and will lead to a modification in the material and socio-cultural access to ES through the practices, the location of the beneficiaries and a potential loss or a gain of cultural values. This information can then be used to predict the impacts on ESs from OWFs, identify trade-offs and illustrate the need for a systemic approach of the links between marine biodiversity and ESs.

### **Acknowledgements**

Yoann Baulaz was funded by the University of Littoral Opal Coast (ULCO) and France Energies Marines, and the study is part of WindServ project funded by France Energies Marines and the National Research Agency under the Investments for the Future program (ANR-10-IEED-0006-34). Through this research we acknowledge the expert contribution of stakeholders who participated in the online survey and workshops. Finally, we really thank the two reviewers for their helpful feedback and Miss. Grace Turner for her review of the English grammar.

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## **7. SUPPLEMENTARY MATERIAL**

### **Appendix A: Survey**

The first appendix presents the online survey that was used to retrieve the expert assessment of the impacts of offshore wind farms (OWFs) on trophic compartments and Ecosystem service (ES) supply. The Sankey diagrams that were produced in this study (figures 5 and 6) are based on the data acquired by this survey. The structure of the survey and its detailed contents are presented in the following subsections.

The reuse of all or part of this survey should be considered in the context of the study and the panel of experts targeted. Please report to the Discussion 4.2 of the main part of the article to understand the scope of this online survey and by extension, the methodology used in this study.

#### **Appendix A.1 Survey structure**

The questionnaire was organized into three parts. The first one is related to the respondent profile, the second one focuses on the impacts during the construction phase and the last one on the operational phase. The first part consisted of open-ended questions, asking each expert to define in one or two sentences their field of expertise and to evaluate their geographical scale of knowledge about OWF environmental impacts (local, regional, national and global).

The other two parts were organized in the form of matrices. Each trophic compartment was presented in columns and three questions were asked in the lines of the matrices. The objective for the expert was to answer the questions for each trophic compartment. The first question, a closed question, aimed to evaluate if the trophic compartments were strongly or weakly modified because of OWFs. The two others were open questions, aiming to specify the nature of the effects to which they referred and to specify if certain species were particularly affected. The last question invited the experts to specify their answers and explain how they had evaluated the effects on the compartment. To help identify the effects and to ensure that the experts were responding according to the same frame of reference, a simplified food web diagram was provided as an appendix to the survey (see above). To ensure the reliability of the results, each expert was asked to answer the questions about which they were most knowledgeable about.

#### **Appendix A.2 Survey**

**Title: Characterize effects of offshore wind farms (posed) on coastal ecosystems of oriental English Channel**

##### **Context of the study:**

The contribution of marine renewable energies in mitigating the effects of climate change is undeniable but negative impacts on ecosystems can be generated by these structures. Nevertheless, we can see also some positive effects of offshore wind turbines such as the reef effect and the reserve effect. Moreover, these structures have been proposed as potential complementary entities to the biodiversity reserve network. This leads to the idea of a "win-win" strategy by taking advantage of offshore wind development in order to reconcile clean energy production with the preservation of biodiversity and related ecosystem services. To achieve this, it is essential to understand and predict the impacts of offshore wind farms on ecosystems, to assess ecosystem services and to predict future changes.

##### **Objectives of the survey:**

The following survey is intended for marine experts from different fields. It aims to make a synthesis of the effects (positive and negative) of offshore wind turbines on the coastal ecosystems of the English Channel and to estimate their intensity. In this matrix survey, you will be asked to answer the different questions by considering the effects on ecosystems during two "life phases" of an offshore wind farm project: the construction phase and the "operational phase". Although the future offshore wind farm in Dunkirk (construction planned for 2025) is used as a reference site, the results of this survey can be applied to the general context of offshore wind farms in France. It is therefore not necessary to have precise knowledge of the ecosystems of Dunkirk.

To enrich your answers, some additional information is available in the tabs of this spreadsheet (food web, mapping of benthic habitats near Dunkirk). Do not hesitate to refer to it [the additional information in question here were the trophic network and figure 1 and appendix C.1 and C.2].

Please take the time to answer the following questions, record your answers, and return the completed survey to us at the following address: XXX

Estimated duration of the survey: 20 to 30 minutes

### **A. profile of the interviewee**

*A.1 To which field are your work themes linked?*

- Biology
- Ecology
- Physical oceanography
- Human and social sciences
- Ingeniery
- Other (precise)

*A.2 Precise the privileged study sites: .....*

*A.3 Can you present your activity in one sentence?*

*A.4 At which geographical extent does you evaluate your knowledge about offshore wind farm?*

- International
- National
- Inter-regional
  - Bay of Bisquay
  - English Channel
  - North Sea
  - Mediterranean Sea
- Local
- No specific knowledge on offshore wind farm

### **B. The effects of the offshore wind farm implantation on trophic network of Eastern English Channel**

*B.1 Can you fill the following matrix, while indicating:*

*- What will be the effect of the construction of a fix offshore wind farm on the trophic groups of the ecosystem of the Eastern English Channel?*

*- Precise if some species seems to you more sensitive than others*



**\*Possible answers: 1. No impact, 2. non-significant impact, 3. Significant impact, 4. No answer**

*[we also define what significantly means here]*

Offshore wind farm project phase	CONSTRUCTION of an offshore wind farm		
TROPIC GROUPS	Impacts on the group*	Specific impact on some species, precise which species (optional)	Elements of explanation of your answers
Phytoplankton and microphytobenthos			
zooplankton			
Benthic Macroinvertebrates			
Secondary consumers			
Tertiary consumers			
Top predators			
Interstitial network			
Organic matters and nutrients			

**C. The exact same matrix was proposed for the operational phase of the farm.**

## Appendix B: Workshop participants

The results obtained with the online survey were validated and completed in a participatory workshop with experts. The following table shows the distribution of the participants' areas of expertise. Although the objective of the workshop was exclusively to define the components of potential ES supply, we wanted to encourage an interdisciplinary approach between ecological sciences, humanities, social sciences and economic actors. Consequently the expertise of the workshop's participants is varied, mostly composed with ecologists, but not exclusively.

We insist on the need to validate the answers obtained via an online survey. Indeed, the understanding of the questions is not always equal among the participants of the survey. The use of such a workshop to validate and complete the survey answers is an interesting and important approach here.

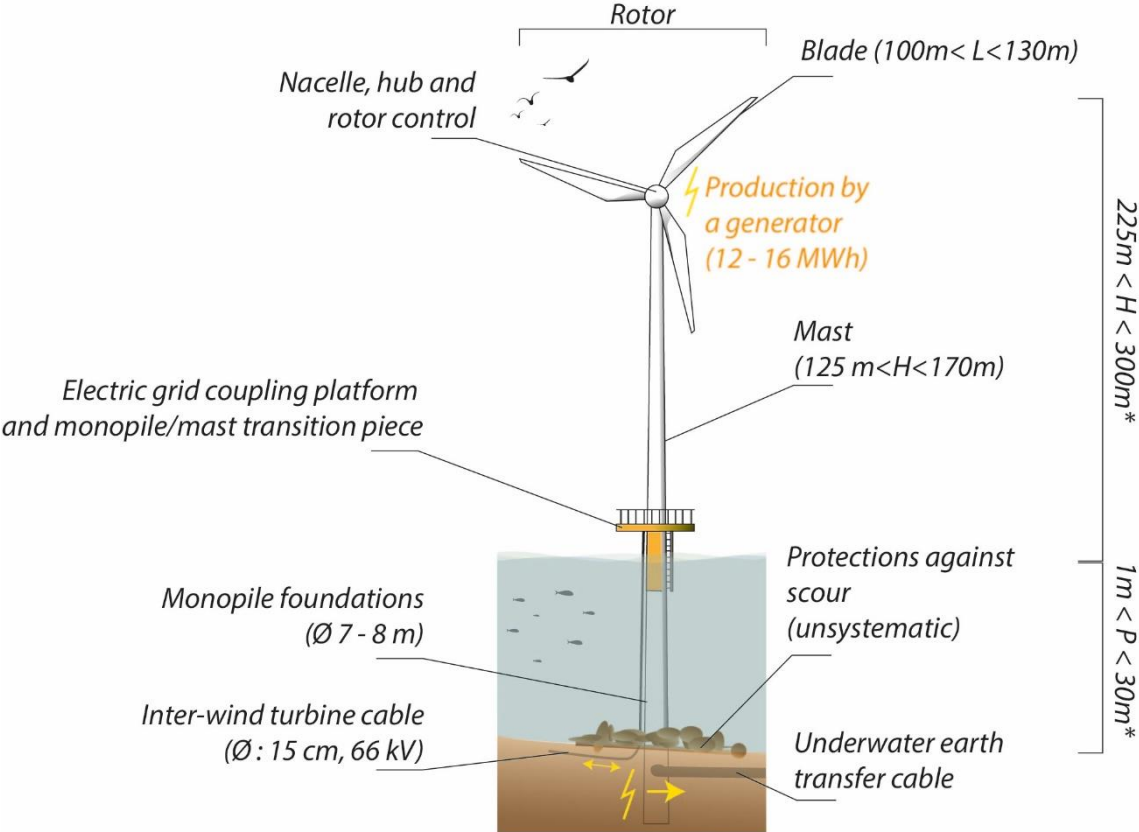
### Number of workshop participant and their area of expertise

Participants' area of expertise	Number of participants
Ecologists (Trophic modelization)	6
Biologists (specialists in specific trophic compartments)	Top predators: 1 Fishes: 1 Benthic macroinvertebrates: 1
Physicists	Substrate: 2 Hydrodynamism: 1
Ecologists (specialists in relationships between OWF and ecosystems)	3
Industrialists (Offshore wind energy)	2
Geographer (Sea uses and governance)	3

### Appendix C: Dunkirk offshore wind farm context

We have chosen to conduct the analysis of the impacts of OWF on ES access and ES demand based on a specific OWF French project. The figures below provides some of the information available at the time of the study, allowing the chosen study site to be compared with other OWF projects, especially those in the southern North Sea.

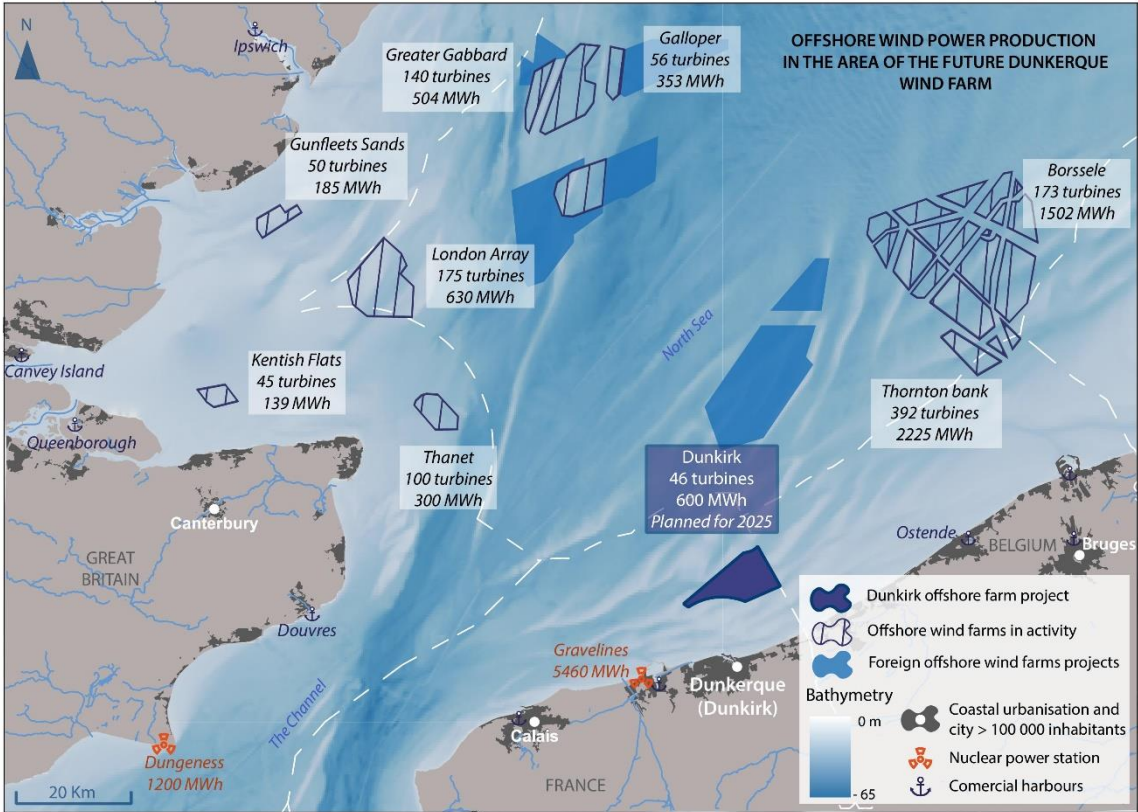
#### Appendix C.1: Operating diagram of an offshore wind turbine used in Dunkirk area (the characteristics mentioned in this figure may be subject to change by the time of construction)



\*The diagram is not to scale.  
The depth is relative to the lowest tide level (0 hydrologic)

Realization: according to experts and the report of the owners of the offshore wind farm off Dunkirk and its electrical connection (2020)

### Appendix C.2: Map of the Dunkirk offshore wind farm (OWF) project, and the other OWF projects in the southern North Sea



Sources : Open Street Map, SHOM, Corine Land Cover 2018, Ministère en charge de l'Environnement 2017 ; parc-eolien-en-mer-de-dunkerque.fr, 4coffshore.com.

## Appendix D: Beneficiaries typology construction

Based on the information available from the public debates relative to the OWF Dunkirk project, we have listed the ES beneficiaries and the possible impacts of OWF on ES access and ES demand.

This information is taken from various meetings and documents from the public debates in the context of the Dunkirk OWF development. The list of these documents is presented below. The appendix D.2 shows how the typology of ES beneficiaries was constructed from a review of the different representatives of human activities involved in the public debates of the Dunkirk OWF.

### Appendix D.1: List of the analyzed public debates and associated documents

Date	Name (theme)	Documents analyzed
16/09/2020	Opening Session: Crossing Perspectives (project presentation)	(1) Report of the debate, (2) Project presentation by owners (3) Debate transcripts
23/09/2020	Associate the territories (landscape impacts)	(1) Presentation support: owners (2) Report of expertise of visual simulations by Jeanne Vezien (3) Debate transcripts
30/09/2020	Stakeholder's point of view: industrials	Debate transcripts
08/10/2020	Deepening the issues (economic benefits)	(1) Report of the debate (2) Presentation support: owners (3) Presentation support: Energy regulation commission (CRE) (4) Presentation support: Regional office for the environment, development and housing (DREAL) (5) Debate transcripts
15/08/2020	Deepening the issues (biodiversity impacts)	(1) Presentation support: owners (2) Presentation support: Regional office for the environment, development and housing (DREAL) (3) Presentation support: Le CLIPON association (4) Presentation support: National museum of natural history in Brussels (5) Presentation support: Geoscience and Oceanology Laboratory (UMR LOG) (6) Debate transcripts
21/08/2020	Associate the territories (local energy politics)	(1) Report of the debate (2) Debate transcripts
27/10/2020	Deepening the issues (navigation issues)	(1) Presentation support: owners (2) Presentation support: Maritime regional administration (prefecture maritime) (3) Debate transcripts
5/11/2020	Mid-term synthesis	(1) Presentation support: owners (2) Presentation support: Regional office for the environment, development and housing (DREAL)
12/11/2020	Stakeholder's point of view (fishing activities issues)	(1) Presentation support: owners (2) Presentation support: Departmental direction of sea territories (DDTM) (3) Report about socio-economic impacts on professional fishing activities of the Dunkirk offshore wind farm (4) Debate transcripts

26/11/2020	Stakeholder's point of view (tourism issues)	(1) Presentation support: owners (2) Presentation support: "Vues sur mer" countryside study (about the potential touristic economic benefits) (3) Debate transcripts
02/12/2020	Public meeting (terms of implementation of the project)	(1) Presentation support: "Vent Debout 59" association (2) Debate transcripts
16/12/2020	Public hearing: all stakeholders	Debate transcripts
16/02/2021	Public debate report	(1) Public debate report (2) Debate transcripts

### Appendix D.2: Typology of ecosystem service beneficiaries consulted in the public debates of Dunkirk offshore wind farm project

Stakeholder name	Demand type*
Infrastructure manufacturers	Direct subtractive demand
OWF maintenance operators	Direct subtractive demand
OWF builders	Direct subtractive demand
Actors supporting the industrial sector	Direct subtractive demand
Port stakeholders	Direct subtractive demand; Direct non subtractive demand
Nautical armament	Direct subtractive demand
Association for green energies development	Direct conservation demand
Naturalist associations	Direct conservation demand
Environmental and technical consulting firms	Observers
Chamber of commerce and industry	Indirect conservation demand
Citizen, tourists	Consumers
Energy regulation commission	Indirect conservation demand
National public debate organization commission	Observers
shellfish farmers	Direct subtractive demand
Maritime safety actors	Direct conservation demand
Maritime prefecture	Indirect conservation demand
Energy government representative	Indirect conservation demand
Land use planning administration	Indirect conservation demand
Local representative	Indirect conservation demand
Local education representant	Direct non subtractive demand; Observators
Real estate sector representative	Direct non subtractive demand
University and research groups	Direct non subtractive demand; Observators
Fishmonger, wholesaler, merchant	Direct subtractive demand
French Biodiversity office	Indirect conservation demand
Local tourism office	Direct non subtractive demand
Commercial service providers	Direct conservation demand
Anglers	Direct subtractive demand
Fishermen	Direct subtractive demand
Citizen representative	Direct conservation demand
OWF project managers and owner	Direct subtractive demand

\*The typology of beneficiaries is from Mongruel et al., 2018.

## Appendix E. Detailed definitions of ecosystem functions and ecosystem services

There are many definitions of ecosystem functions and ESs. In order to facilitate the applicability of the conceptual framework proposed in this study in other contexts, we propose here a set of definitions of the components of ES provision.

Such a list can also help to understand how the OWF impacts on ESs have been defined in this study. These definitions of ESs helped the experts' debates in the workshops by providing a common reference framework.

### Appendix E.1 Relevant ecosystem functions in the offshore wind farm context and definitions

Type	Ecosystem functions	Acronym	Definition	References used
<i>Production</i>	Trophic relationships and biotic interactions	Trophic relation function (P1)	Interactions between species linked by food webs and energy transmission in food webs: top-down control, bottom-up (trophic cascades).	Barbault 2000; Lacroix & Danger 2008
	Specific and genetic diversity	P2	Diversity in the number of species occupying a habitat and infraspecific genetic diversity within a species.	Barbault 2000; Lacroix & Danger 2008
	Secondary production	P3	Amount of animal organic matter produced by consumers of an ecosystem (heterotrophic organisms that feed on primary producers or other consumers by predation). It results from the increase in the number and weight of individuals per unit of time and space.	Fletcher et al. 2011; Schoenn et al. 2013; EFESE 2019; Carpenter & Kitchell 1993
	Nutrient production and recycling	P4	Transformation, degradation and transport of matter (nutrients, oxygen and carbon) through biogeochemical processes within the biotic and abiotic compartments of ecosystems.	Fletcher et al. 2011; Schoenn et al. 2013
	Primary production	P5	Amount of organic matter synthesized by plant organisms. It represents the mass of organic matter (or its energy equivalent) neoformed from simple mineral precursors by all autotrophic organisms during a given time interval.	Pourriot & Meybeck 1995
<i>Habitat</i>	Habitat formation	H1	Formation of the physical and chemical properties of habitats necessary for the survival of species and the proper functioning of the ecosystem.	Barbault 2000; Lacroix & Danger 2008
	Biogeochemical cycles	H2	Transformation and transport of matter through biogeochemical processes.	
	Presence of essential habitats	H3	Presence of habitats that allow the conservation of the specific and genetic diversity of the ecosystem.	CGDD 2010

	Weather-oceanic conditions	H4	Abiotic physical and chemical parameters the condition the structure of the biotope.	
<i>Landscape</i>	Existence and variety of spaces with potential recreational uses	Recreational space's function (L1)	Formation of attractive spaces for recreational activities due to the presence of species of heritage interest, endowed with a strong symbolic charge and spaces serving as support for recreational activities.	EFESE-MER 2019
	Biophysical parameters contributing to pleasant landscapes	Landscape's function (L2)	Attractive properties of water and the variety of landscapes visible on the water, underwater, from the shores and at heights that offer a contemplative interest for recreational uses, and social, cultural, artistic practices.	Vernex, 1985
	Educational and scientific interest of the marine environment	(L3)	Presence of cognitive interest of marine ecosystems for research, observation, teaching, environmental awareness for local populations and tourists and sentinel's ecosystems of local, regional and/or global changes.	



## Appendix E.2 Relevant ecosystem services in the offshore wind farm context and definitions

Type	Ecosystem services	Acronym	Definition	Reference used
<i>Provisioning</i>	Bio-resources for nutritional purposes	Fishing service	Animals or plants taken from the natural environment for consumption.	CICES 2018, v 5.1 – Haines-Young and Potschin, 2018
	Bio-resources for material purposes	n.a.	Animals or plants taken from the natural environment intended for direct use for non-food purposes.	
	Water used for materials (energy, shipping)	Water energy ES	Use of hydraulic power, thermal properties of water or water as support for uses.	
	Wind used for materials (energy, air navigation)	OWF ES	Use of wind power, thermal properties of air or air as a support for uses.	
	Mineral and non-mineral substances or ecosystem properties used for materials (energy, extraction and deposit or materials)	Ground energy ES	Mineral substances or thermal properties of soil and subsoil exploited for material or energy uses.	
<i>Regulation</i>	Regulation of water, substrate quality and contaminants in organisms	Environment quality regulation ES	Set of ecological processes participating to filtering, sequestering, storing, self-purifying waste and toxic substances of anthropogenic origin and regulating the level of abundance and diversity of parasitic, invasive and/or diseased species and diseases.	
	Protection of baseline flows and extreme climatic events	n.a.	Regulating the flows of water in our environment and protecting people from winds and fire.	
	Lifecycle maintenance, habitat and gene pool protection	Habitat ES	Presence of nursery areas, spawning grounds, feeding areas, refuge area, rest areas, migration corridors for all flora and fauna. Set of processes ensuring the maintenance of specific and genetic diversity.	
	Regulation of weather and air quality	n.a.	Regulation of local weather conditions and mitigation of the impacts of global warming.	
<i>Cultural</i>	Physical and recreational interactions with the natural environment	Recreation ES	Elements and characteristics of ecosystems that allow the practice of activities promoting health, rest or pleasure through active, immersive, passive or observation interactions.	
	Contribution to culture and territorial identity	Identity ES	Elements of ecosystems that have a symbolic, sacred, religious meaning, which resonate in terms of culture,	

			history or heritage and image of the territory.
	Contribution to science and education	n.a.	Characteristics of ecosystems as a support for scientific research, education and knowledge.

## **Appendix F: the main causal chains linking offshore wind farms to ecosystems and ecosystem functions**

To complete the analysis of the OWF impacts on ES, we have detailed here some additional information on the transmission of impacts between trophic compartments and ecosystem functions.

According to our survey results, the main compartments modified during construction are primary producers and primary consumers, each accounting for more than 25% of the changes to the food web (Fig. 5). These changes result mainly from digging and crushing of the substrate, the rearrangement of benthos, and noise and vibrations. The primary consumers are affected by these three pressures, the high trophic levels, mainly through noise and vibrations, and low trophic levels, through the reorganization of benthic communities and the resuspension of materials and pollutants.

During the operational phase, the reef effect, the reserve effect, and change of functional habitat are the most impacting pressures on the ecosystem; followed by the barrier effect, hydrodynamic change and collisions for avifauna (Fig. 6). Top predators, especially birds, are the most affected, followed by primary consumers, then secondary, and tertiary consumers and primary producers; each accounting for about 20% of the network impacts. These modifications result from the change in the ecosystem regime and the accumulation of different impacts. Finally, organic matter remains, as in the construction phase, the least modified compartment.

Following our conceptual model structure, these trophic impacts affect ecosystem functions. In the construction phase, the most affected ecosystem functions are: (1) trophic relation function; (2) specific and genetic diversity; and (3) habitat formation. In the production phase, the two functions mainly affected remain the same as in the construction phase, the secondary production being the third most affected ecosystem function. Subsequently, the majority of the changes in the ES supply materialize from the impacts on these four functions.

Conversely, landscape functions and primary production represent less than 6% of the impacts.

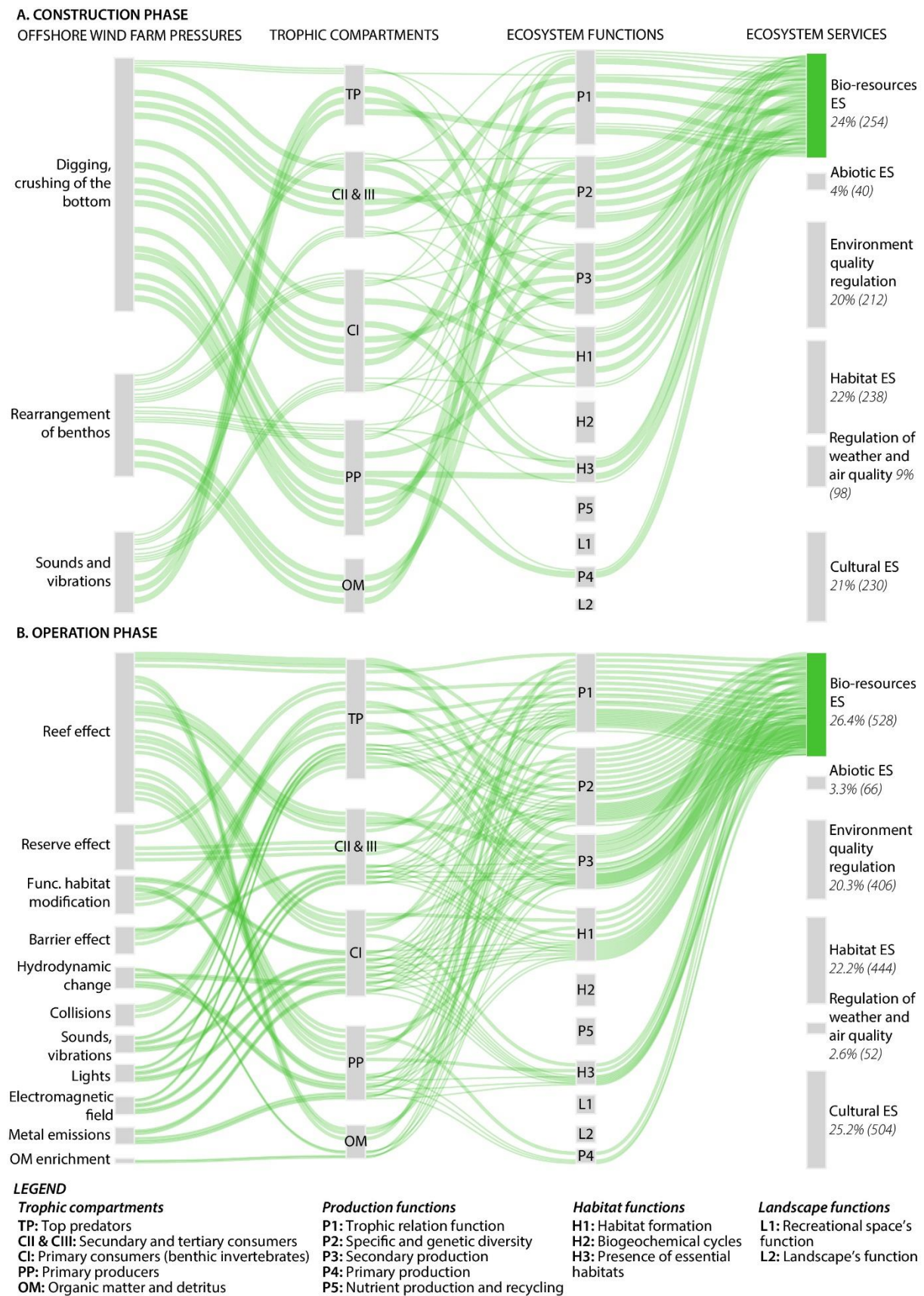
## **Appendix G: The impact pathways for the ecosystem services (ES) mainly affected by offshore wind farms development.**

The Sankey diagrams proposed in the paper (Fig. 5, 6) provide a graphical representation of the impact pathways linking OWFs pressures to ES. The interest of such a model is to highlight the complexity of the interactions between the components of the ES supply and to compare the OWF impacts in a cumulative impact assessment approach.

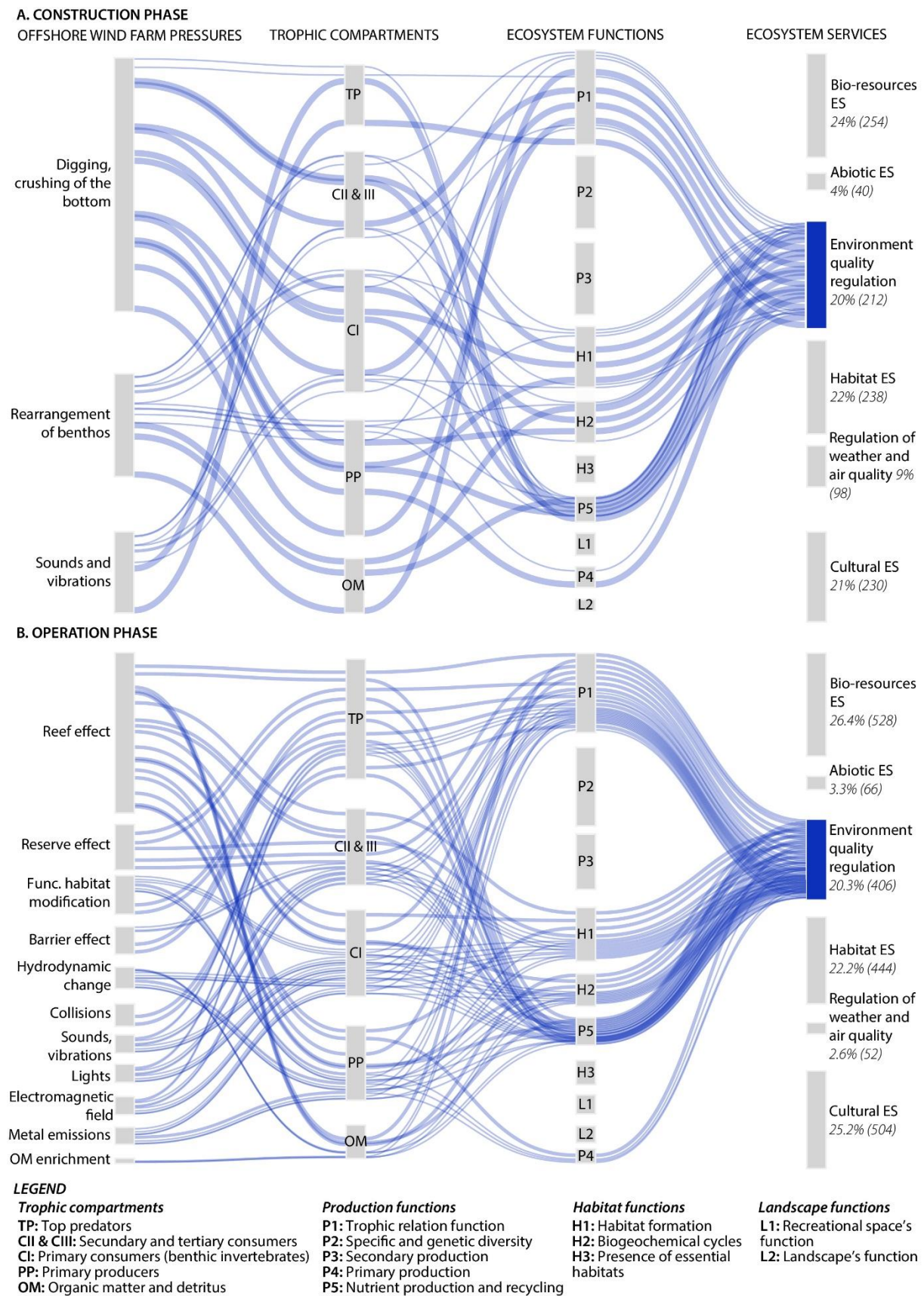
However this representation has a shortcoming related to the difficult reading of the impact pathways between trophic compartments, functions and services. To compensate this shortcoming, we propose different Sankey diagrams for some ES studied here.

These diagrams also allow for an easier comparative analysis of the impacts occurring between the OWF construction and operation phases. The study of these figures, in addition to the figures 5 and 6 presented in the article, has made it possible to define precisely the nature and intensity of the impacts of offshore wind farms on the supply of ES.

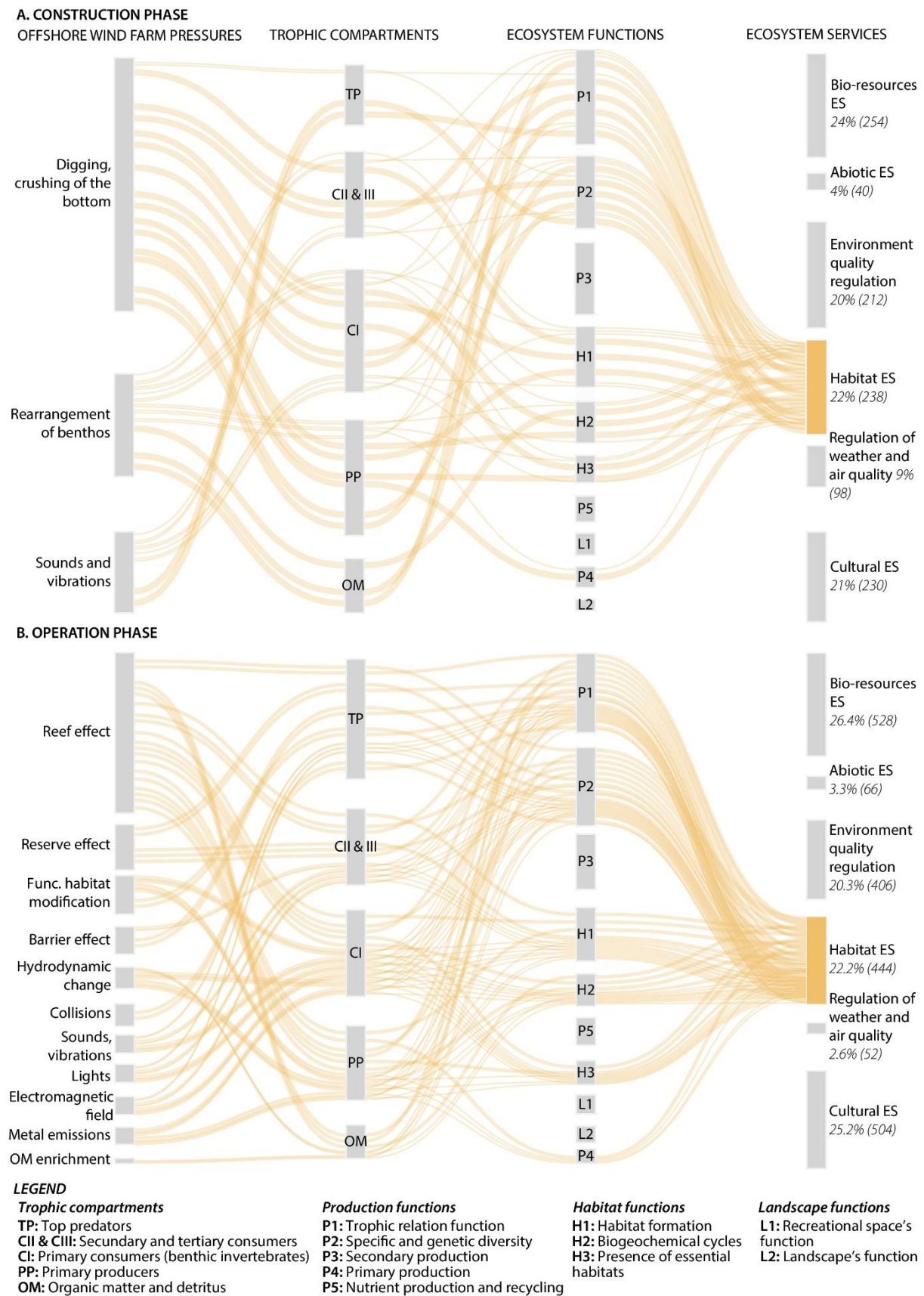
## Appendix G.1: Detailed impact pathways for the provisioning of bio-resources ESs



## Appendix G.2: Detailed impact pathways for the Environmental quality regulation ES



## Appendix G.3: Detailed impact pathways for the habitat maintenance ES



## Appendix G.4: Detailed impact pathways for the cultural ESs

