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Ecosystem approach of artificial reef through trophic web modelling

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Abstract. Along the French coast of the Atlantic and English Channel in a high tidal regime, only a limited number of Artificial Reefs (ARs) had been immerged in very few localities in the aim to increase the local production of fisheries of such hard artificial substratum. Moreover, ARs design have been planned to increase the diversity, abundance and biomass of benthic species associated to hard-bottom. Does the deployment of such artificial structure improve the production and ecological functioning on such equipped areas? Trophic models describing the interaction between species at different trophic levels and based on the quantification of energy flow and matter in ecosystems are able to respond to this question. They allow the application of numerical methods for the characterization of emergent properties of the ecosystem, also called Ecological Network Analysis (ENA). Usually, these indices have been proposed as ecosystem health indicators as they have been demonstrated to be sensitive to different impacts on marine ecosystems. Here, Ecopath ecosystem models composed of 23 compartments, from phytoplankton to mammals, are built to describe the situation “Before” and “After” the implantation of ARs in two areas: the Rade of Cherbourg in the central part of the English Channel along the French coast, and in the south of the Bay of Biscay along the Landes coast. In addition, ENA indices are calculated for the two periods, “before” and “after” the implantation of artificial reefs to compare network functioning and the overall structural trophic web properties. In both areas, increase of benthic and fish compartments insure an increase of the system maturity; nevertheless, the high surge of planktinovorous fishes on the Landes AR showed a protection role of such AR than changes of planktonic preys.

1. Introduction

Artificial reefs (ARs) are human made underwater structure placed at the bottom of the sea to mimic the natural reef physical and biological functions [1]. ARs are considered as an essential tool for increasing fishery production, providing recreational fishing and diving sites and provide protection against illegal trawling [2]. For more than fifty years, ARs have been deployed in France to respond to the decline in fish stocks [3]. The main aim of these structures is to sustain artisanal fisheries and enhance fish stocks [4]. Assessments of their effectiveness, when they have been carried out, have been focused only on certain ecological components such as commercial fishes [5]. However, Salaun et al. [5] pointed out the lack of ARs monitoring. This lack of feedback raises questions regarding the real ecological role of these structures [5]. Quantitative trophic web models can be used for this purpose since they describe the interactions between species at different trophic levels as they are based on the quantification of flows of energy and matter in ecosystems. Among these different existing approaches, the Ecopath with Ecosim (EwE) model has been intensively used and developed over the last three decades [6] and was recognised by the US National Oceanographic and Atmospheric Administration

(NOAA) as one of the ten biggest scientific breakthroughs in its 200 years history [7]. This modelling approach was developed to evaluate ecosystem-based management of fisheries and allowed the application of numerical methods for the characterization of emergent properties of the ecosystem, also called Ecological Network Analysis (ENA) [8]. These joint analyses had been frequently applied to coastal and marine systems to assess changes in their functioning in response to environmental perturbations [9]. Here, Ecopath ecosystem models composed of 23 compartments, from phytoplankton to mammals, are built to describe the situation “Before” and “After” the implantation of ARs in two areas: the Rade of Cherbourg in the central part of the English Channel along the French coast, and in the south of the Bay of Biscay along the Landes coast. In addition, ENA indices are calculated for the two periods, “before” and “after” the implantation of artificial reefs to compare network functioning and the overall structural trophic web properties.

2. Materials and Methods

2.1 Study areas

Two artificial reef located along the French Atlantic coast were selected: the Rade of Cherbourg in the North Cotentin in the central part of the English Channel along the French coast, and the Capbreton concession in the south of the Bay of Biscay along the Landes coast (Figure 1).

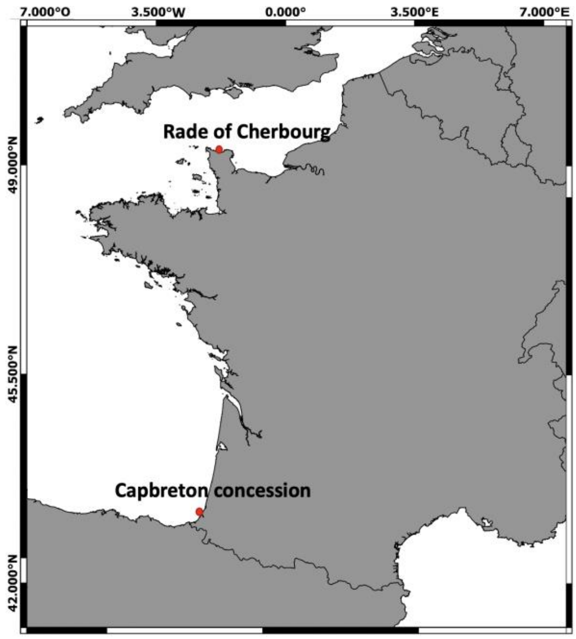

Figure 1. Locations of the Artificial Reefs of the Rade of Cherbourg and of the Capbreton concession.

Under the framework of the European project RECIF, an artificial reef system was immersed in the Rade of Cherbourg on April 2015. The experimental artificial reef was composed of 12 modules (Figure 2) grouped in 3 clusters to create a triangle structure. Each module was 3m long, 2m wide and 1.35m high (8,1m^3 each module - 32,4m^3 by cluster - 97,2m^3 in total). The RECIF project aimed to reuse marine by-products to create artificial reefs for a better management of marine resources. To do this, the RECIF project used waste shells from the shellfish industry to create artificial reef systems. Monitoring of colonisation of this experimental AR are currently being conducted under the framework the European MARINEFF project.

Figure 2. Immersion of a module on April 2015 in the Rade of Cherbourg (ESITC, Caen).

In the south of Bay of Biscay, ARs have been deployed 2km south off the head of the Canyon and 2.2km off the coast on sandy bottom at 20m depth and 20km away from natural reef [19](Figure 3). Three types of artificial reefs have been deployed by the association « Atlantique Landes Récifs »: grapes of concrete bonna pipes deployed in 1999 on three sites around 200m² each, the module "Typi" in 2010 with a 11m² footprint and the "Babel" in 2015 with a 5m² footprint (Figure 3).

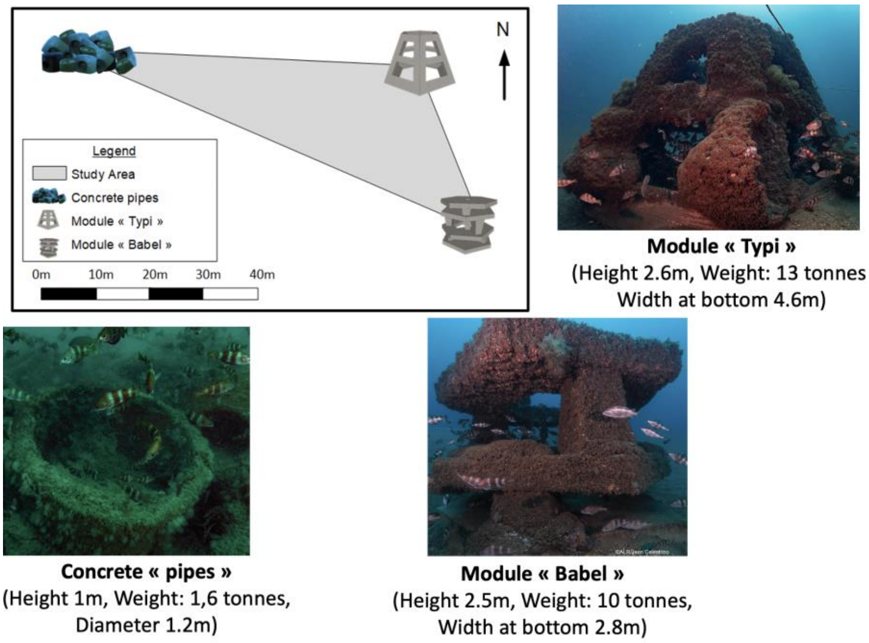

Figure 3. Capbreton concession with the three artificial reefs

2.2 Ecopath modelling approach

In order to gain further knowledge on the ecosystem structure and functioning before and after the implantation of ARs in the two areas: Rade of Cherbourg and in the Capbreton concession, trophic web models were built. The Ecopath with Ecosim (EwE) approach [20] was used to model the trophic webs at the two sites. Thus, three Ecopath models were built: two baseline Ecopath models called "Before Artificial Reef _Cherbourg" (BAR_Cherbourg) and "Before Artificial Reef_Landes"

(BAR_Landes) and one model called Artificial Reef_Landes (AR_Landes) based on the data collected on the three artificial reefs of the Capbreton concession.
Ecopath is a mass-balance, single-solution model that uses linear equations to estimate flows between numbers of functional groups established a priori [8]. The parameterization of an Ecopath model is based on satisfying two equations. The first equation (Eq. 1) describes the production for each compartment in the system as a function of the consumption to biomass ratio (Q/B) of its predators (j), the fishing mortality (Yi, gC·m−2), the net migration (Ei; emigration – immigration, year−1), the biomass accumulation (BAi, year−1) and its natural mortality (1—EEi). The Ecotrophic Efficiency (EE) is the fraction of total production that is consumed in the system (by fishing activity or by predators). Its value can never exceed 1. (1-EEi) represents the fraction of mortality not explained by the model, such as mortality due to old age or diseases.

$$B\left(\frac{P}{B}\right)_i = \sum_j B_j \left(\frac{Q}{B}\right)_j DC_{ij} + Y_i + E_i + BA_i + B_i \left(\frac{P}{B}\right)_i (1 - EE_i) \quad \text{(Eq. 1)}$$

The second equation (Eq. 2) ensures energy balance, calculating consumption of the i^{th} group (Q) as the sum of its production, respiration (R), and excretion (U)

$$Q_i = P_i + R_i + U_i \qquad \text{(Eq. 2)}$$

Functional groups have been chosen to be the same on both models for the Atlantic and the English Channel. Thus, the three models developed in this study were composed of 23 functional groups or functional compartments ranging from detritus to seabirds and mammals. Seabirds were divided into two compartments, according to their feeding strategies. The "plunge and pursuit divers" compartments were mainly composed of gannets and the "surface feeders" were mainly composed of gulls and kittiwakes. Marine mammals (*Delphinus delphis, Stenella coeruleoalba and Tursiops truncatus*) were gathered in one compartment. Cephalopods were divided into two compartments: the benthopelagic ones mainly composed of *Loligo vulgaris* and the benthos ones mainly composed by *Sepia officinalis*. The model was also composed of seven compartments of fish (gadidae, piscivorous, benthos feeders, Labridae, Sparidae, flatfish and planktivorous). Gadidae, Labridae and Sparidae were not aggregated with the other compartment in order to see in details the potential impact of the reef effect on these three compartments. Benthic invertebrates were divided into six compartments (commercial decapod, predators, scavengers/omnivores, filter feeders, surface deposit feeders and subsurface selective feeders). Finally, the model was also composed of one compartment of zooplankton, one compartments of bacteria, one compartments of phytoplankton and compartments group of detritus. For all these functional compartments data were collected from the literature and/or from field measurement. For instance, for the “BAR_landes” model, the biomass of fishes and benthos species have been collected from bottom-trawl survey conducted by the EVHOE cruise, IFREMER since 1997 in the Bay of Biscay. However, for the “AR_landes” model, the fish biomass was estimated from under water visual census campaingns (the survey covered a total surface of 102m² corresponding to the footprint of the three types of ARs) and benthos biomass were estimated from benthos samples which were collected on summer 2019 and winter 2020. Six scraps, on different ARs position (inside, below, North, East, West and South) were made by divers on each ARs type, using a quadrat sampler of 20*20cm for 2019 and 30*30cm for 2020, a putty knife and a net bag (<1mm mesh size). A total of 0.553m² were sample on summer 2019 and 0.819 m² on winter 2020.

In addition, this EwE approach also allows providing measure of the ecosystem emergent properties through the calculation of Ecological Network Analysis indices (ENA). ENA is one well- known method to quantify how species interact with and influence their environment [10]. For instance, these indices enable the characterization of the flow recycling, redundancy and omnivory, or the trophic levels of each functional group [11]. Such indices have been recently proposed as ecosystem health indicators for describing the food web functioning in different contexts, including the implementation of the Marine Strategy Framework Directive in Europe [12].

3. Results

For the moment, only the model representing the present initial state of the ecosystems, depicting the ecosystem before the installation of AR in the Rade of Cherbourg and in the Capbreton as well as after the installation of the three artificial reefs of the Capbreton concession, have been analysed. Thus, here, we only present the first results based the comparison of the BAR_Landes and the AR_Landes models (Table 1 ; Figure 4).
Results showed that the total living biomass was higher after the installation of the ARs. In fact, the total living biomass increased by approximately 28% after the installation of the three ARs of the Capbreton concession. This increase was mostly due to the increase in Labridae and fish benthic feeders, flatfish which showed an increase by a factor of approximately 10, 7, 3 respectively, after the installation of ARs.
In the both Landes models (BAR and AR), trophic levels (TL) of the functional groups ranged from 1 for primary producers and detritus to a maximum of 4.8 for marine mammals that can be thus considered as top predators in the area (Table 1; Figure 4). As mentioned below, TL 1 was composed of two compartments (primary producers and detritus, as imposed by the model construction) and represented approximately 54 % and 46 % of the total biomass in the BAR and AR model respectively. TL 2 was composed of six functional compartments (Bacteria, zooplankton, benthic invertebrate subsurface and surface deposit feeders and filter feeders) making up approximately 24% and 32.5% of the total biomass in the BAR and AR model respectively. TL 3 encompassed the fish functional group major part (such as flatfish, benthos feeders, planktivorous, Sparidae) and it was composed of nine functional compartments. It represented 18 and 17% of the total biomass in the BAR and AR model respectively. Finally, the TL 4, was composed of five functional compartments in the BAR model and of six functional compartments in the AR model. TL 4 which corresponded to top predators represented only 3 and 4% of the total biomass in the BAR and AR model respectively. Thus, the TL contributing most to the total biomass in the both models was the TL 2.

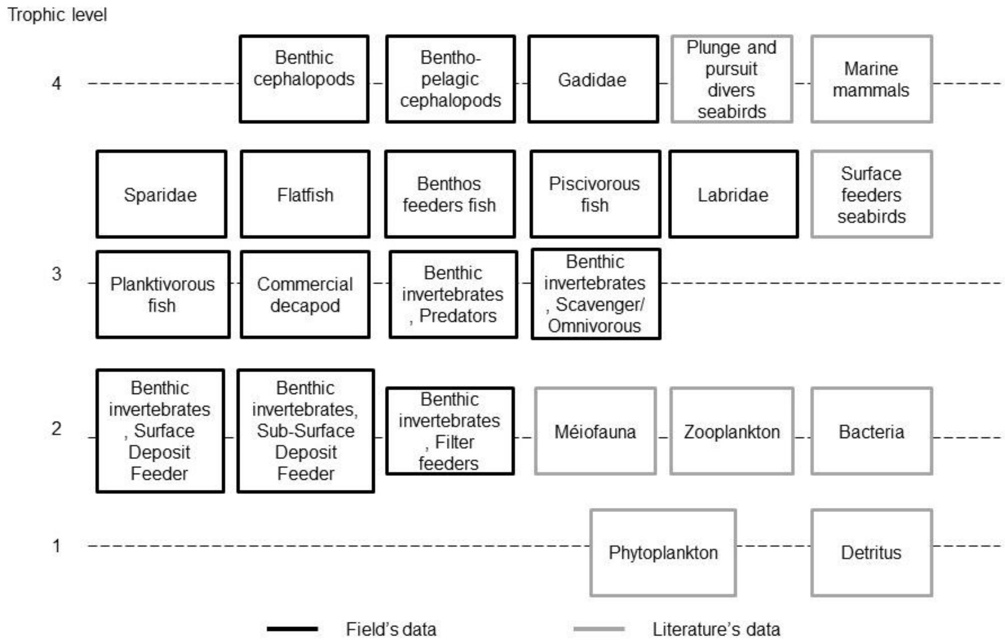

Figure 4. Trophic modelling of the Capbreton before installation of Artificial Reefs (BAR_Landes model).

Results based on the ENA indices analyses revealed a combination of changes in the ecosystem structure and functioning after the installation of the three ARs of the Capbreton concession. After the installation of the three ARs of the Capbreton concession, the maturity of the ecosystem tends to increase (according to ecological theories developed by Odum, 1969, 1971 [13, 14], and Ulanowicz, 1986 [15]).

Table 1. Biomass values (gC.m^{-2}) and Trophic Levels, in the two Ecopath models ("before" (BAR_Landes) and "after" (AR Landes) the construction of the artificial reef).

	Biomass		Trophic Level	
Functionnal groups	**BAR model**	**AR model**	**BAR model**	**AR model**
Plunge and pursuit divers seabirds	0.0001	0.0001	4.06	4.11
Surface feeders seabirds	0.0001	0.0001	3.93	3.94
Marine mammals	0.0018	0.0018	4.85	4.83
Benthopelagic cephalopods	0.0096	0.0037	4.31	4.17
Benthic cephalopods	0.0240	0.0371	4.10	4.06
Gadidae	0.0487	0.0409	4.03	4.00
Fish, piscivorous	0.1758	0.3065	3.98	4.20
Fish, benthos feeders	0.0246	0.1705	3.78	3.43
Labridae	$3{,}9 \times 10^{-6}$	4×10^{-5}	3.51	3.31
Sparidae	0.0263	0.0089	3.56	3.62
Fish, flatfish	0.0208	0.0672	3.53	3.36
Fish, planktivorous	0.2231	0.2670	3.15	3.15
Commercial Decapod	0.0322	0.1543	3.13	3.12
Benthic invertebrates, Predators	0.2920	0.6161	3.16	3.22
Benthic invertebrates, Scv/O	0.8228	0.2827	3.14	3.20
Benthic invertebrates, Filter feeders	0.3073	1.2196	2.28	2.32
Benthic invertebrates, sDF	0.2690	0.3366	2.44	2.36
Benthic invertebrates, ssDF	0.2883	0.4126	2.22	2.22
Meiofauna	0.2642	0.2642	2.29	2.21
Zooplankton	0.3600	0.3600	2.15	2.15
Bacteria	0.3940	0.3940	2.02	2.02
Phytoplancton	1.3800	1.3800	1	1
Detritus	2.8467	2.8467	1	1

4. Discussion

Trophic network modelling has been developed over decades and has been applied to various marine ecosystems around the world. This approach has been particularly used to understand the effect of fisheries on the entire ecosystem [5]. Recently, this approach has been extended to other research domains such as management of Marine protected Area [16] or to simulate the effect of wind farming on the ecosystem [9, 17]. Like Offshore Wind Farms (OWF), ARs are mostly deployed on soft bottom habitats. They create hard substrate that will be colonized by different populations. One of the main results of this study was the increase in ecosystem maturity after the installation of the three ARs of the Capbreton concession which is in accordance with the results of Raoux *et al.*, 2017, 2019 [9, 18] and Wang et al., 2020 [19]. In fact, Raoux et al. (2017) [5] analysed the potential effect of OWFs and more particularly reef effects on ecosystem energy flows by describing the pre- and post-construction state of the Courseulles-sur-mer ecosystem using biological data and hypothetical scenarios after 30 years simulated by Ecosim. The results also indicated an increase in ecosystem maturity. However, these studies were based solely on simulated future scenarios instead of using actual post-construction field investigations. Finally, Wang et al. (2019) [19], also built an Ecopath model applying it before and after the construction of the Rudong OWF (Jiangsu coastal ecosaystem, China) based on biological field data collected before and after the construction of the OWF. These results also indicated that the ecosystem tended to develop towards higher maturity following the OWF construction with the reef effect. ENA comparison between the model "Before Artificial Reef _Cherbourg" and «After artificial Reef_Cherbourg » could also confirm this trend. In this study, using ENA on this AR ecosystem makes it possible to highlight the trophic modification linked to the introduction of hard substrate on soft habitats. Thus, these results indicate the interest of using a large set of ENA indices to characterise different trophic functioning attributes, essential for a complete view of the induced changes [18].

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