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# Addressing offshore wind farms compatibilities and conflicts with marine conservation through the application of modelled benchmarking scenarios

L. Couce Montero *, A. Abramic, A. Guerra Marrero, A. Espino Ruano, D. Jiménez Alvarado, José J. Castro Hernández

*Biodiversity & Conservation Research Group, Research Institute of Sustainable Aquaculture and Marine Ecosystems (IU-ECOAQUA), University of Las Palmas de Gran Canaria, Las Palmas de Gran Canaria, Spain*

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A B S T R A C T

Offshore wind power generation structures are scheduled for development in the Canary Islands, potentially resulting in spatial overlap with various maritime activities, particularly fishing. It is crucial to point out that some areas that are considered suitable for installing these structures are in protected zones that are part of the Natura 2000 network, and do not have any prior environmental impact assessments. The research delved into the efficacy of utilizing Ecopath with Ecosim software to examine the consequences of implementing this technology in the study area, employing an ecosystem-based approach. To address this question, simulations were executed by assessing three distinct scenarios. The results suggest that there would be changes in the distribution of keystone species such as top predators, alongside a conspicuous decline in the abundance and catches of target species of the fishery. The Ecospace model holds the potential to forecast the impacts of offshore wind installations; however, crucial factors must be carefully considered, such as the lack of information. Notwithstanding the constraints, research like this demonstrates the efficacy of spatial ecosystem modelling in exploring this issue.

## 1. Introduction

In the context of the global energy transition, renewable energies have emerged as a pivotal element. They not only provide a sustainable alternative to fossil fuels but also contribute significantly to mitigating climate change and reducing greenhouse gas emissions [1]. Motivated by the pressing necessity to curb greenhouse gas emissions, the expansion of Marine Renewable Energy has witnessed substantial progress over the past decade. Within the realm of these technologies, Offshore Wind Farms (OWFs) have emerged as a well-established and technologically advanced form of renewable energy [2]. However, this technology is not exempt from challenges, as it not only introduces potential conflicts with maritime sectors [3–5] and fisheries [6–9] but also poses environmental impacts.

The environmental impacts on biodiversity are multifaceted and far-reaching, but noise [10–12] and electromagnetism [13–15] play a pivotal role regarding negative effects on marine organisms. Also, offshore wind farms (OWF) can alter the abundance, distribution, and species composition of fish in an area, and can act as physical barriers and disrupt natural migratory routes of diverse species [16,17]. Nevertheless, OWFs can also provide new habitats for marine species [18], and displace fishermen from their traditional fishing grounds [19], limiting the access to areas close to the wind turbines, and may lead to reduced fishing pressure, allowing fish and invertebrate populations to recover [20]. The Canary Islands, with their strategic location and abundant wind resources, present a unique opportunity to harness the potential of offshore wind energy.

The planning of maritime space for the growth and sustainable development of European maritime areas is included in Directive 2014/89/EU, which was implemented in Spanish law through Royal Decree 363/2017, in compliance with Law 41/2010 on the protection of the marine environment. This regulation stipulates that five marine space management plans (POEM, by its Spanish acronym) must be prepared, one for each Spanish marine demarcation defined in Law 41/2010. These documents were published by the Spanish Government in 2023, following the endorsement of the Royal Decree 150/2023.

The selection process for choosing areas to install OWFs took into account the potential spatial overlap with other maritime activities and the preservation of biodiversity in each region. Marine protected areas,

* Corresponding author.
*E-mail address:* lorena.couce@ulpgc.es (L. Couce Montero).

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**Nomenclature**

*Abbreviations*

| | |
|---|---|
| EwE | Ecopath with Ecosim |
| FAD | Fish aggregation device |
| FG | Functional groups |
| IPCC | Intergovernmental Panel on Climate Change |
| LNZ-FTV | Lanzarote and Fuerteventura islands |
| MPA | Marine protected area |
| MTI | Mixed trophic impact |
| OWF | Offshore wind farms |
| POEM | Spanish marine spatial plans |
| RCP | Representative Concentration Pathways |
| Sc | Temporal and spatial scenarios |
| TL: | Trophic level |
| ULPGC | University of Las Palmas de Gran Canaria |

*Notation*

| | |
|---|---|
| A | Aspect ratio of the caudal fin |
| B | Biomass |
| BA | Bioaccumulation rate |
| d | Dummy variable to define feeding habits |
| dB/dt | Growth rate |
| DC | Proportion of diet |
| e | Emigration rate |
| E | Net migration |
| EE | Ecotrophic efficiency |
| F | Fishing mortality rate |
| g | Net growth efficiency |
| h | Dummy variable to define feeding habits |
| I | Immigration rate |
| i | Prey group |
| j | Predator group |
| k | Spatial cell |
| $L_\infty$: | Asymptotic length (cm) |
| m | Instantaneous movement rate across the boundaries of adjacent spatial cells |
| M0 | Non-predation natural mortality rate |
| P/B | Production/Biomass |
| P | Production |
| Q/B | Consumption/Biomass |
| Q | Consumption |
| R | Respiration |
| T | Temperature |
| U | Unassimilated food |
| V | vulnerability to predation |
| $W_\infty$: | asymptotic weight |
| Y | Total catch |
| Z | Total mortality rate |

*Units*

| | |
|---|---|
| C | Celsius degrees |
| g | gram |
| km | kilometer |
| m | meter |
| t | tonnes |
| y | year |

including those in the Natura 2000 network, have been considered during the development of the POEM. Natura 2000 is a network of European areas that prioritize biodiversity conservation. These special conservation areas have been established in accordance with the Birds Directive (Directive 2009/147/EC) and Habitat Directive (Council Directive 92/43/EEC of May 21, 1992) to ensure the long-term survival of species and habitat types in Europe, helping to halt biodiversity loss. It is the main instrument for nature conservation in the European Union. Nevertheless, zones with significant potential for OWFs are situated within a Marine Protected Area (MPA) known as The Eastern and Southern Marine Area of Lanzarote-Fuerteventura (LIC-ESZZ15002, by its Spanish code). This MPA is classified as Site of Community Importance and does not have a management plan, so it has not yet been declared as a Special Area of Conservation.

The Eastern and Southern Marine Area of Lanzarote-Fuerteventura is home to protected species listed in the Royal Decree 139/2011, of 4 February, for the Development of the List of Wild Species in Regime of Special Protection and the Spanish Catalogue of Endangered Species or the Law 4/2010, of June 4, of the Canary Islands Catalogue of Protected Species. These include vulnerable species like the seahorse (*Hippocampus hippocampus*) and the thresher shark (*Alopias superciliosus*), among others. The region hosts species included in the Red List of Threatened Species, such as the angel shark (*Squatina squatina*), which falls under the classification of "critically endangered" as well as other sharks and rays categorized as vulnerable such as *Alopias vulpinus*, *Centrophorus granulosus*, *Galeorhinus galeus*, *Gymnura altavela*, *Mustelus mustelus*, and *Isurus oxyrinchus*. Also, according to Ref. [21], around the easternmost Canary Islands are frequently observed finback (*Balenoptera physalus*), Bryde's (*B. edeni*), and sperm (*Physeter macrocephalus*) whales, the poorly known beaked whales (*Mesoplodon desirostri* and *Ziphius cavirostri*), several species of dolphins (*Delphius delphis*, *Tursiops truncatus*, *Stenella frontalis*, *S. coeruleaoalba* and *Grampus griseus*), and the short-finned pilot whale (*Globicephala macrorhynchus*).

In assessing overlaps with other sectors, POEM considers fishing, maritime transport, aquaculture, research-related, and military activities; nonetheless, the most significant challenge lies in fishing and its potential conflict with OWFs. The lack of data on the artisanal fleet's spatial distribution renders the information in the POEM document limited and inconclusive, since it is assumed that fishing effort is concentrated on the island shelf with minimal interactions beyond it. In the Canary Islands, all fishing vessels are artisanal and utilize a range of fishing techniques, including traps, longlines, purse seines, hand lines, and live bait, tailored to the specific target species. Most vessels operate primarily in coastal waters close to their home ports; however, during tuna seasons, vessels travel between islands to maximize their catches. Approximately the 91 % of the vessels are less than 15 m in length, so they are not required to report their positions (latitude and longitude), rendering fishing grounds unknown. Efforts have been made to collect information through citizen science methodologies; however, the results obtained are not without flaws, as they are influenced by the fishermen's participation in the surveys [22].

From an economic standpoint, official data sources indicate that the regional fishing industry contributes a small portion to the gross domestic product (GDP). In contrast to industrial fisheries, artisanal fishing holds significance beyond economic aspects. The social component is crucial as artisanal fishing significantly contributes to job creation and the preservation of coastal communities, thereby supporting their economic stability. Moreover, it triggers a multiplier effect by fostering job creation and growth in various sectors and services [23]. Based on the data released by the Canary Islands Government, in 2022, there were 206 vessels registered in Lanzarote and Fuerteventura distributed in seven fishermen's associations, with a catch value estimated at 8,799, 125.55€.

Concerning recreational fishing, 5806 new licenses were generated in Lanzarote and Fuerteventura in 2023; however, the total number of active licenses that year amounted to 15,383, given their 3-year validity period. This activity is regulated permitting only 5 kg per individual per day, but there is no obligation to declare the catches. Despite this fact, various assessments have been undertaken considering each fishing type and emphasizing the importance of this sector in the Canary archipelago [24–28], since in certain islands, the estimated catches by recreational fishermen surpass those of artisanal fishermen [25].

Restrictions on artisanal and recreational fishing in areas within the Natura 2000 network are only dictated by the existing laws at both the state and regional levels; therefore, they lack any extra protective measures. For this reason, current endeavours aim to transition to more inclusive and participatory management models for the Natura 2000 network to preserve these areas by fostering participatory processes to outline an action plan for enhancing their governance.

The objections filed against the Ministry's decree to regulate marine energy production systems in the islands of Lanzarote and Fuerteventura, as well as those in other Spanish jurisdictions, are currently being addressed. As a result, it is unknown if the areas initially mentioned in the POEM document will remain unchanged or undergo adjustments regarding their location and the technical features of the potential OWFs to be established within them.

The extensive geological and oceanographic intricacies of the eastern and southern marine region of Lanzarote-Fuerteventura result in a wide array of species and habitats as well as a marine sanctuary for cetaceans. Additionally, it is a common fishing area for the fleets of both islands. Due to these circumstances and considering the current information deficiencies, conducting accurate environmental impact assessments presents challenges. Therefore, the suggestion is to adopt alternative methodologies founded on an ecosystem-based approach.

Benchmarking scenarios is a common practice in ecosystem modelling and can provide useful information for medium- and long-term management and decision-making. Majority of the published works on this subject focused on the influence of fisheries on food webs; this includes previous studies developed in the Canary Islands [29–31]. However, there has been an increasing interest in recent years to assess the real or theoretical impact of OWFs using similar approaches [32–37]. In accordance with Royal Decree 150/2023, when a high potential OWF intersects with priority biodiversity protection zones, an analysis of its effects on the relevant MPA must be conducted. So, in this work, is explored the potential impacts of hypothetical offshore wind farms (OWFs) in a marine protected area that extends from Lanzarote to Fuerteventura islands, in the eastern-central Atlantic. The novelty of this research lies in conducting impact assessments using an ecosystem-based management approach. To achieve this, we have developed a high-resolution Ecospace model to evaluate the medium-term effects of OWFs on the food-web and identify potential conflicts that may arise.

## 2. Material and methods

Ecopath with Ecosim (EwE) software is used to develop trophic models based on mass balance, facilitating comprehension of the structure and functioning of the marine ecosystem. The software consists of three main modules.

- Ecopath: it is a snapshot of the system that provides a description of ecosystem resources, interactions, and exploitation during a defined timeframe.
- Ecosim: it is designed to explore management strategies through alternative scenarios using a time-dynamic simulation approach.
- Ecospace: using spatial optimization tools and scenarios previously defined in Ecosim, it can analyse spatio-temporal changes in the ecosystem.

To develop a spatial ecosystem model with the Ecospace module, a three-step process is required (Fig. 1). The first step is to create an Ecopath model, and once it has been balanced, it is recommended to utilize Ecosim's temporal simulations and calibration features before constructing an Ecospace model.

### 2.1. The study area

Our model represents the marine ecosystem of the Fuerteventura and Lanzarote islands (LNZ-FTV model), including their surrounding waters and the channel between both islands, from surface to 3000 m, covering approximately 15806 $km^2$ (Fig. 2). These islands share the insular shelf and therefore the biological resources. Moreover, the fleets operate indiscriminately across the study area, making it challenging to allocate the exact portion of biomass and catches to one specific island.

### 2.2. Ecopath model

The Ecopath with Ecosim (EwE) is an ecological modelling approach

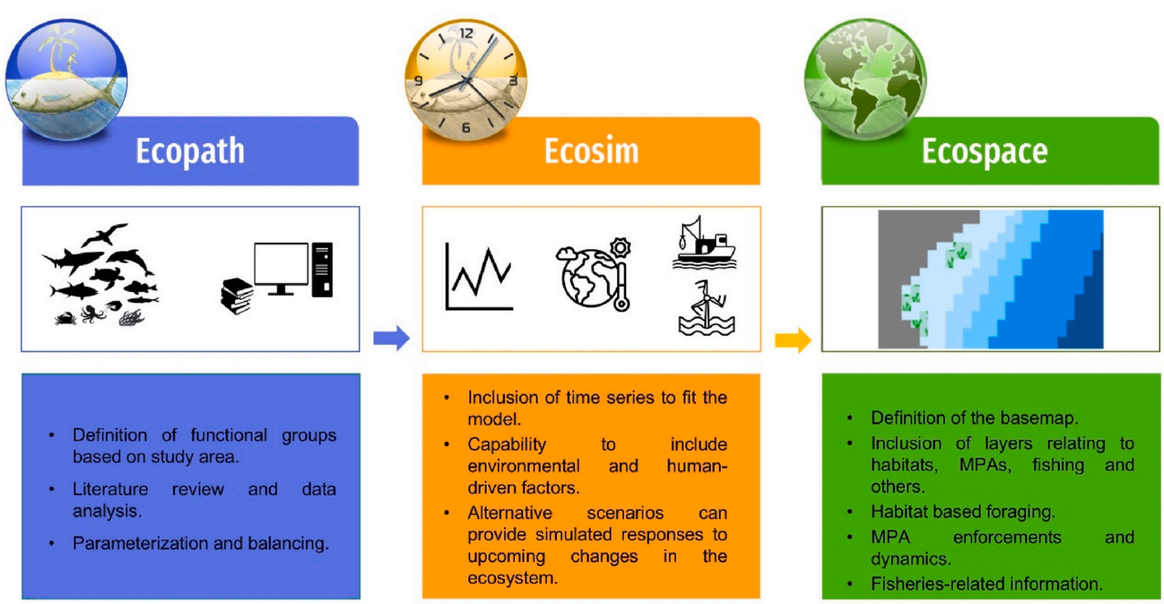


**Fig. 1.** Schematic description of the process to create an Ecospace model. Source: Author's own elaboration.

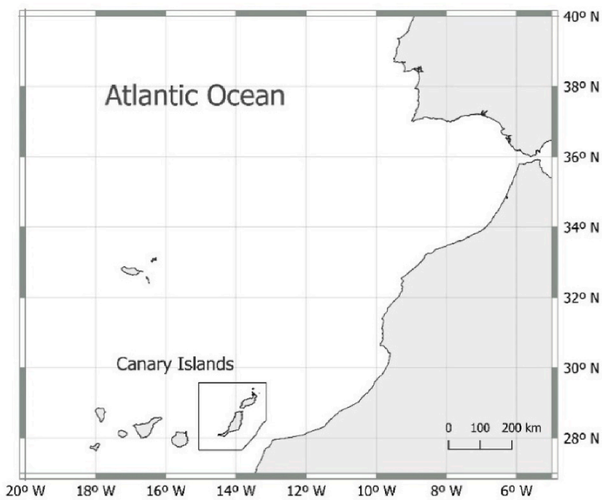


**Fig. 2.** Map of the Canary Islands, displaying the LNZ-FTV model area delineated within the polygon.

that represents the structure and functioning of food-webs by means of mass balanced energy flows among functional groups (FG) or species [38,39].

The parameterization of an Ecopath model relies on two primary equations. The first one is related with the production term:

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

where $P_i$ is the production of group ($i$); $B_i$ is the biomass of group ($i$); $Y_i$ is the total catch rate for group ($i$); $(Q/B)_i$ is the consumption of ($i$) per unit of biomass; $DC_{ji}$ indicates the proportion of ($i$) that is in the diet of predator ($j$); $BA_i$ is the bioaccumulation rate for group ($i$); $E_i$ is the net migration rate for group ($i$) (emigration – immigration); and $EE_i$ is the ecotrophic efficiency of ($i$).

The second equation describe the consumption, ensuring energy balance for each FG:

$$\text{Consumption (Qi)} = \text{production (Pi)} + \text{respiration (Ri)} + \text{unassimilated food (Ui)} \quad \text{(Eq.2)}$$

Each group is parameterised with its biomass ($B_i$, $t{\cdot}km^{-2}$), production rate ($P_i/B_i$, $y^{-1}$), consumption rate ($Q_i/B_i$, $y^{-1}$), diet composition ($DC_i$), ecotrophic efficiency ($EE_i$), biomass accumulation rate ($BA_i$, $y^{-1}$) and the net migration rate ($E_i$, $y^{-1}$).

The LNZ-FTV model represents the situation of the marine ecosystem in 2022, and species have been pooled based on habitat, abundance, feeding preferences, and other taxonomic similarities. The model consists of 33 FGs comprising the following species: marine mammal, seabirds, turtles, fishes, invertebrates, organisms in the Deep Scattering Layer (DSL), zooplankton and primary producers. Models developed with the EwE software also include at least one detritus group, which does not represent living organisms. Hierarchical Cluster Analysis and Factorial Correspondence Analysis were used to define these FG based on feeding habits and life-cycle similarities.

The Canarian artisanal fleet is characterized by being multipurpose and multispecies, so the following fishing gears or modalities have been defined in the model: polyvalent, tuna fishing, purse seine, crustacean trap, shell fishing and recreational fishing [40].

Information about major species included in each FG as well as the methodology and references to estimate the input parameters can be found in Table A1, while feeding habits and prey consumption values are presented in Table A2.

### 2.2.1. Ecosystem indicators and network analysis

Once a mass-balanced model is established, the software EwE enables the analysis of indicators derived from trophic flow descriptions using network analysis and information theory [41–45].

The mixed trophic impact (MTI) matrix [46] gives an idea of the relative impact (positive or negative) that a small increase in the biomass of a functional group can cause in the biomass of other groups/species in a steady state ecosystem.

Keystone species are those that have a significant impact on the food web even though they have a low biomass [47]. We used the keystoneness index developed by Ref. [48] to identify them in the LNZ-FTV model.

### 2.2.2. Pre-balancing

A preliminary analysis was conducted using the PREBAL module [49] to assess the biomasses of FGs and evaluate their adherence to fundamental principles of ecosystem ecology. According to these principles, biomass within FGs should exhibit a span of 5–7 orders of magnitude, and the slope of biomass on a logarithmic scale should decrease by 5–10 % across all taxa when arranged according to trophic levels. Shallow-water demersal fishes, reef-associated fishes, the parrotfish (*Sparisoma cretense*) and herbivorous/invertebrate feeder fishes do not meet these criteria, showing lower values. Biomasses of target species have been estimated from depletion models from catch data. The species in question are heavily exploited by both the artisanal and recreational fleets but, although there is information on landings by artisanal fishermen, the actual catches made by recreational fishermen remain unknown. Therefore, our analysis had to rely on the limited available data. The shrimp group exhibited a relatively low biomass. However, the estimates were derived from exploratory campaigns specifically conducted to assess the abundance of this deep-sea resource across each island of the Canary archipelago. So, in order to maintain the integrity of the data, no modifications were made to the obtained values, as they were considered the most accurate. Finally, it would be highly advisable to gather more comprehensive and detailed information about benthic invertebrate groups in the studied area in future research endeavours.

### 2.2.3. Data quality assessment

The quality of data used to derive the basic inputs of the Ecopath model was assessed with the pedigree index [42]. By utilizing this routine, it is possible to describe the data origin and assign confidence intervals to different input parameters according to their origin.

## 2.3. Ecosim model

Ecosim tool [38] describes time-varying simulations through a series of coupled differential equations derived from the Ecopath master equation (Eq. (1)), given the form:

$$dB_i/_{dt} = g_i \sum_j Q_{ji} - \sum_j Q_{ij} + I_i - (MO_i + F_i + e_i)B_i \quad \text{(Eq.3)}$$

where $dB_i/dt$ represents the growth rate during the time interval dt of group ($_i$) in terms of its biomass, $B_i$; $g_i$ is the net growth efficiency (P/Q ratio), $M0_i$ the non-predation natural mortality rate, $F_i$ is fishing mortality rate, $e_i$ is emigration rate, $I_i$ is immigration rate. The two summations estimate consumption rates, the first shows the total consumption by group ($i$), while the second indicates predation by all predators on the same group ($i$). The consumption rates, $Q_{ij}$, are calculated based on the 'foraging arena' concept, assuming that predators might alter diet composition based on fluctuations of available prey.

Therefore, the consumption rate is defined as follows:

$$Qij = \frac{v_{ij} \cdot a_{ij} \cdot B_i \cdot B_j}{v_{ij} + v_{ij} + a_{ij} \cdot B_j} \quad \text{(Eq.4)}$$

where, for prey group $i$ and predator group $j$, $Q$ represents consumption; $B$ is biomass; a is effective search rate while $v$ and $v'$ represent vulnerability and invulnerability to predation exchange rate, respectively [50].

Vulnerabilities for all groups have the same values by default, assuming a mixed control within the ecosystem, so time series about catches and fishing effort were included to modify these values to accept a bottom-up control, more coherent with this marine area, and obtain a better fit of the model.

Records of catches and fishing effort were provided by the Fishing Directorate of the Canary Government, whereas recreational fishing effort and catches were calculated on the basis of reconstructed time series [24,25,27]. These time series of catches and effort have been used to achieve a better adjustment in the projections that arise.

### 2.3.1. Management scenarios

To evaluate the impact of OWFs on the conservation, as possible conflicts with fisheries, simulations where conducted based on "what-if scenarios". In all scenarios a constant fishing effort is assumed from 2022 to 2050.

- Given the structure of the model and the data gaps we can only speculate on the possible impacts in the study area derived from the prospecting and installation phases; therefore, this study focuses only on the impact during the hypothetical operational phase. Three scenarios were selected to be projected until 2050: Sc1: It represents the baseline scenario, where there is no OWFs and the impact of climate change is evaluated under the estimates of the RCP 8.5 scenario [51,52], the most unfavourable in terms of emissions.
- Sc2: Baseline scenario combined with the impact of OWFs within the Natura 2000 network, in the areas selected as most suitable considering marine environment parameters, marine conservation, oceanographic potential/limits, coastal land use and operative maritime activities. These areas were selected with application of the Decision Support System INDIMAR (Fig. 3) [53].
- Sc3: Baseline scenario combined with the impact of OWFs within the Natura 2000 network, for areas defined in the national maritime spatial plan (POEM) for Spain, including Canary Islands marine subdivision adopted and published during 2023. POEM establish areas with high potential for exploiting offshore wind energy (Fig. 3).

In both scenarios (Sc2 and Sc3), OWFs would be installed in different location but within the same MPA (the Eastern and Southern marine area of Lanzarote-Fuerteventura (LIC-ESZZ15002).

The exact power to be auctioned in the future on the islands of Lanzarote and Fuerteventura, as well as the estimated date on which these facilities could begin to develop if approved, is presently unknown. Hence, anticipating the number of OWFs that could potentially be installed in that area, along with their technical characteristics, is not feasible in the short-term. The only certainty lies in the utilization of floating turbines due to the depths of the selected areas. In scenarios Sc2 and Sc3, the assumption is that in the future, there will be a tendency to utilize the entire area identified as having high wind potential.

### 2.3.2. Forcing functions

The effects of climate change were implemented through two ways in the LNZ-FTV model: net primary production and consumption rates. Primary production forcing values are applied as a multiplier of the r parameter (P/B ratio that can be realized) in the equation linking the biomass of the primary producers with production through a saturation relationship [42]. To estimate the percentage changes of net primary production at the regional scale, future projections values under the high emission scenario RCP8.5 obtained from coupled model intercomparison projects were used as a reference [54].

The consumption rates of each fish group included in the LNZ-FTV model were estimated from the equation developed by Ref. [55]:

$$log\frac{Q}{B}=7.964-0.204\cdot log\ W_{\infty}-1.965\cdot \acute{T}+0.083\cdot A+0.532\cdot h+0.398\cdot d \quad \text{(Eq.5)}$$

where $W_{\infty}$ is the asymptotic weight calculated from $L_{\infty}$ and length–-weight relationships; $T'$ represents water temperature (°C); $A$ is the aspect ratio of the caudal fin and $h$ and $d$ are dummy variables to define feeding habits (herbivore, detritivore, carnivore, or omnivore).

To estimate the impact of climate change on the ecosystem, the temperature was modified according to the forecasts of scenario RCP8.5. These changes in consumption will act as multiplier factors on effective search rates of predators.

Both forcing functions were incorporated into the model in the form of time series, covering the period 2022–2050. The first value of each time series must be 1, considering that all parameters are initially at


**Fig. 3.** Marine protected area included in the Natura 2000 network and location of the offshore wind farms described in scenarios Sc2 and Sc3.

their baseline values.

### 2.3.3. Environmental preference functions

Environmental drivers for most species were incorporated to Ecosim module as csv files, representing the FGs' tolerance to environmental conditions (Table 1). These files included information related to temperature and depth to estimate the most suitable habitat for each FG. Degrees of suitability of habitat are derived from large sets of occurrence data available from online collection databases [56] and interpreted by the model as probabilities of occurrence, assuming values between 0 and 1. This information will be required later in the Ecospace module. In the supplementary material, Table A3 showes the predicted ranges for each FG.

### 2.3.4. Data uncertainty

Ecosampler [57] is a plug-in included in the Ecopath with Ecosim software, which allows testing alternative combinations of the inputs of the LNZ-FTV model based on the quality of the data and the confidence intervals, thus obtaining new balanced models with better adjustment. To examine the impact of uncertainty on Ecopath input parameters on Ecosim outputs, this tool was used in conjunction with Monte Carlo simulations.

The scenarios defined in Ecosim share the same time series and forcing functions in all the dynamic simulations raised, the differences lie in spatial changes in the distribution and abundance of species by the inclusion of structures in the marine environment and the fishing exclusion areas that are generated. Therefore, the analysis to determine the data uncertainty has only been executed with the baseline scenario, as the results are common to the other scenarios described.

We used a Monte Carlo approach to generate 1000 permutations to investigate the impact that random variations on biomass, production, consumption, and diets have on model outcomes, such as abundance predictions. To define the range of plausible values, we associated a coefficient of variation of ±10 % for each input considered.

**Table 1**
Outputs estimates from the LNZ-FTV model for each functional group.

| Functional Group (FG) | TL | Bf (t. km$^{-2}$) | P/B (y$^{-1}$) | Q/B (y$^{-1}$) | EE |
|---|---|---|---|---|---|
| Whales | 4.34 | **0.2250** | **0.05** | **9.02** | 0.18 |
| Dolphins and beaked whales | 4.30 | **0.1850** | **0.09** | **23.98** | 0.13 |
| Turtles | 4.28 | **0.0013** | **0.17** | **2.28** | 0.68 |
| Seabirds | 4.33 | **0.0016** | **2.72** | **62.67** | 0.00 |
| Pelagic sharks | 4.43 | **0.0546** | **0.33** | **2.76** | 0.34 |
| Benthic sharks and rays | 3.81 | **0.0169** | **0.26** | **2.38** | 0.44 |
| Tunas | 4.16 | **0.4140** | **1.11** | **5.68** | 0.47 |
| Skipjack tuna | 4.21 | **0.3020** | **1.69** | **8.12** | 0.16 |
| Oceanic pelagic fishes | 4.18 | **0.0962** | **0.91** | **4.53** | 0.66 |
| Medium-sized coastal pelagic fishes | 3.25 | **7.7849** | **2.07** | **7.94** | 0.40 |
| Beryx spp. | 3.68 | **0.7403** | **0.19** | **3.37** | 0.24 |
| Mesopelagic fishes | 3.69 | **0.4570** | **0.59** | **2.18** | 0.83 |
| Demersal serranids and wreckfishes | 3.64 | **0.6151** | **1.09** | **3.85** | 0.10 |
| Demersal sparids | 3.60 | **0.5621** | **0.85** | **4.64** | 0.80 |
| Pagrus pagrus | 3.44 | **0.3173** | **0.83** | **4.89** | 0.15 |
| Shallow-water demersal fishes | 3.16 | **0.9209** | **1.87** | **5.92** | 0.41 |
| Reef-associated fishes | 3.05 | **1.4747** | **1.14** | **3.42** | 0.40 |
| Sparisoma cretense | 2.32 | **1.1469** | **0.71** | **10.07** | 0.09 |
| Herbivorous/Invertebrate feeders fishes | 2.38 | **1.0891** | **0.96** | **11.93** | 0.13 |
| Moray eels | 3.88 | **0.3050** | **0.27** | **3.17** | 0.16 |
| Pelagic cephalopods | 3.38 | 2.5447 | **2.45** | **16.78** | **0.95** |
| Benthic cephalopods | 3.35 | 3.2926 | **1.94** | **6.05** | **0.95** |
| Shrimps | 3.25 | **0.3797** | **2.58** | **7.69** | 0.99 |
| Crustaceans | 2.29 | 7.8438 | **2.16** | **8.07** | **0.95** |
| Molluscs | 2.02 | 13.9927 | **0.93** | **5.69** | **0.95** |
| Urchins | 2.00 | 1.4369 | **0.40** | **8.88** | **0.70** |
| Benthic invertebrates | 2.28 | 13.7716 | **2.42** | **6.55** | **0.95** |
| Jellyfishes | 3.31 | 0.0013 | **3.13** | **10.53** | **0.95** |
| DSL | 2.73 | **6.1317** | 8.80 | **18.20** | **0.95** |
| Zooplankton | 2.00 | **7.1430** | **22.79** | **58.51** | 0.87 |
| Seagrass/Seaweed | 1.00 | 6.8609 | **23.53** | | **0.50** |
| Phytoplankton | 1.00 | **10.0270** | **71.37** | | 0.34 |
| Detritus | 1.00 | **34.3400** | | | 0.41 |

Trophic level (TL); final biomass (Bf); production/biomass ratio (P/B); consumption/biomass ratio (Q/B) and ecotrophic efficiency (EE). Basic inputs of the model are in bold.

## 2.4. Ecospace

Ecospace module [39] is a tool that brings the spatial component to the LNZ-FTV model after the adjustments to ensure model stability in Ecosim. For every cell, the biomass dynamics of each group is predicted by:

$$\frac{dB_{ik}}{dt} = e_i Q_{ik} - Z_{ik} B_{ik} - \sum_{k} m_{ikk'} B_{ik} + \sum_{k'} m_{ik'k} B_{ik'} \qquad \text{(Eq.6)}$$

where $B_{ik}$ is the biomass of FG $i$ in spatial cell $k$, $e_i$ is conversion efficiency of food intake by group $i$ into net production, $Q_{ik}$ is the total food consumption rate by group $i$ in cell $k$, $Z_{ik}$ is the total mortality rate of group $i$ in cell $k$, $m_{ikk'}$ is instantaneous movement rate of group $i$ biomass from cell $k$ to cell $k$', $m_{ik'k}$ is movement rate of group $i$ biomass from cell $k$' to cell $k$. The initial summation shows movement away from cell $k$, while the second summation shows movement into cell $k$ from four adjacent cells $k$'. Modifying the dispersal rates (m) can result in less movement into cells with 'bad' habitat types and more movement into cells with more suitable habitats.

Christensen et al. (2008) provides a comprehensive explanation of the other equations associated with this module, as well as the variables necessary for spatial dynamics adjustments.

Ecospace habitat layers were created in QGIS (version 3.28.5) using georeferenced data available at Geoportal Ecoaqua ULPGC (http://www.geoportal.ulpgc.es/), while temperature and depth layers were obtained from Copernicus Marine Service (https://data.marine.copernicus.eu/). To represent the biomass distribution of FGs, we establish a georeferenced base map with a grid resolution 400 × 400m. Further, was included in the model marine protected area, La Graciosa - Marine Reserve and Northern Islets of Lanzarote. Later. in the spatial model were included fishing fleet base ports (Fig. 4A) habitats defined in the model (Fig. 4B). For scenarios Sc2 and Sc3, were included OWFs areas with 2 km buffer zone of influence (Fig. 5). In Sc2 and Sc3, within defined offshore areas and related buffer zones, model considers that fishing is forbidden.

### 2.4.1. Habitat assignment

Species distribution is highly influenced by benthic and pelagic habitats preference, so the assignment of FGs to habitats was based on a combination of data obtained from Fishbase, Sealifebase, research [58, 59] and expert criteria. Table A4 showes the designated habitat allocation for each FG.

The most representative seabird in the study area is the Cory's shearwater (*Calonectris diomedea*), but there are no real data about the effect that OWFs would have on this species. Taking as a reference their flight height, a recent study determined that the probability of collision with the turbines would be very low (<0.02 %) [60]. For the other species included in the seabirds group, similar species were considered in other regions for which the collision risk could be assessed [61–63]. After this review it was concluded that for the species present in the area the risk of collision would be low as it seems that they would not be attracted by the turbines. On other hand, noise exposure and electromagnetism can disrupt critical behaviours of cetaceans, turtles and fishes, such as feeding [14,15,64–67], socializing [10–12,61,68,69] or nursing [70,71].

It's assumed that OWFs exert a artificial reef effect (sensus [72] as

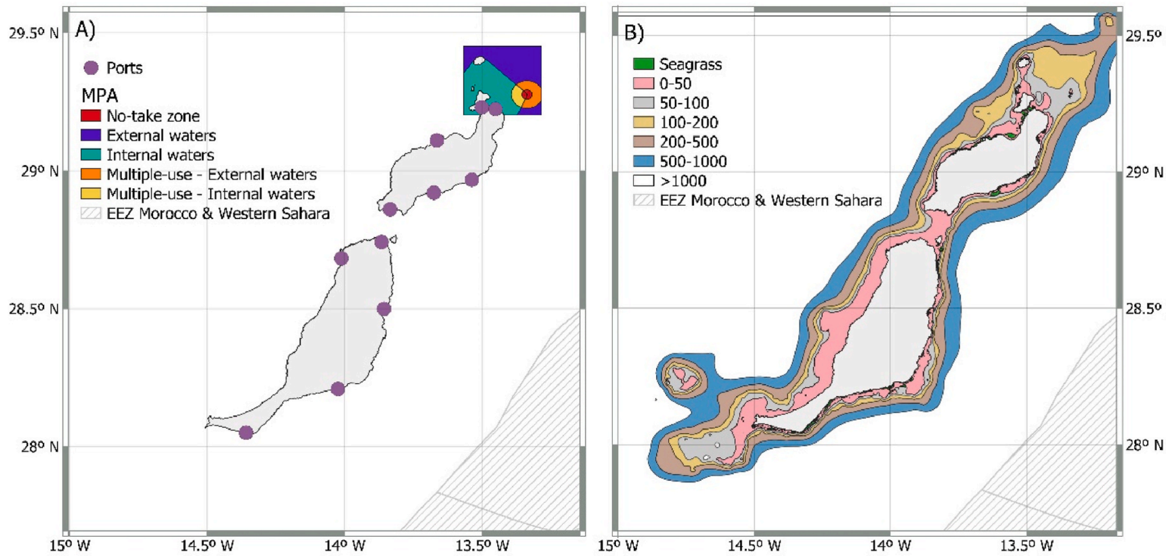


**Fig. 4.** Spatial layers defined in the model relating to habitats, ports and the Marine Reserve of La Graciosa and Islets of North Lanzarote.

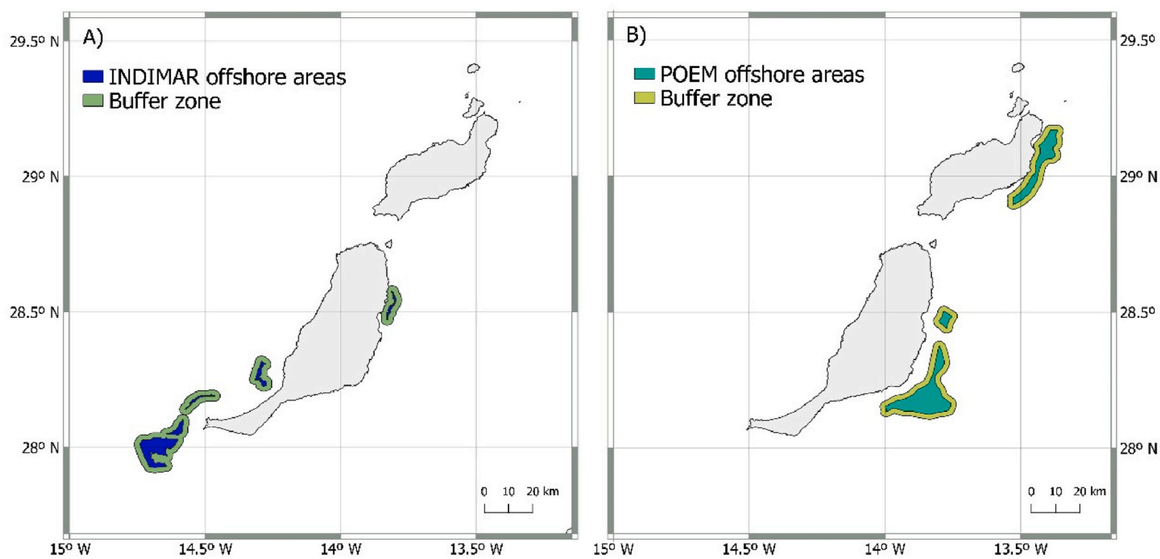


**Fig. 5.** Spatial layers defined in the model to incorporate OWFs. A) the scenario Sc2 and B) for the scenario Sc3.

the turbine column reaches the bottom. In the case of floating OWFs, the turbine is anchored to the bottom and different configurations can occur such as spar buoy, semisubmersible, barge, pendulum floater, tension leg platform or advanced spar [69]. Since the study analyses a hypothetical case, it would be complex to evaluate this reef effect on the populations of invertebrates and benthic and reef-associated fishes. Instead, we investigated the potential for floating OWFs to function as fish aggregation devices (FADs). The attraction of pelagic FGs to the OWFs was simulated assuming the highest preference for the habitat corresponding to offshore areas and a high preference in buffer zones [36,73–75]. To enhance the analysis of how OWFs affect the distribution of FGs, the model accounted for habitat preferences in Table 2 and simulation responses to environmental preference functions.

In Ecospace, a fraction of the biomass of each cell is moving according to the base dispersal rate of the FGs. This parameter represents the rate the organisms would disperse because of random movements. For LNZ-FTV model, we chose five different dispersal rates: 1000 km/year for top predators, 600 km/year for pelagic functional groups, 300 km/year for faster moving demersal fish FGs, 30 km/year for the rest of fish and zooplankton FGs and 3 km/year for nearly stationary or sessile groups. The relative dispersal rate in bad habitats was defined five times greater than in preferred habitats (sensus Dickson et al. [76]), as species attempt to move elsewhere with better conditions. It was further assumed that groups were twofold more susceptible to predation in bad habitats compared to their preferred ones. The distribution of fishing activity was mapped out based on target species, fishing gear features, and distance from base ports. Spatial limitations were established for each fleet based on MPA zoning, as well as limited access in areas where the OWFs would be located and their buffer zones of influence.

## 3. Results

Uncertainty in Ecopath input parameters was assessed by using the Monte Carlo routine. Due to ecological inconsistencies, approximately 30 % of the estimated versions were discarded. After randomly reviewing several trials from the sample list of alternate mass-balanced models, it was determined that there were no apparent problems with alterative mass-balanced parameter sets.

**Table 2**
Ecological indicators and summary statistics of the LNZ-FTV model.

| Statistics and flows | LNZ-FTV | Units |
|---|---|---|
| Total system throughput | 4464.60 | $t.km^{-2}y^{-1}$ |
| Sum of all consumptions | 1977.72 | t.km |
| Sum of all exports | 547.79 | t.km |
| Sum of all respiratory flows | 631.68 | t.km |
| Sum of all flows into detritus | 1307.42 | t.km |
| Sum of all production | 1921.36 | t.km |
| Calculated total net primary production | 1169.18 | t.km |
| Total prim. prod./Total respiration | 1.85 | |
| Net system production | 537.51 | $t.km^{-2}y^{-1}$ |
| Total prim. prod/Total biomass | 7.81 | |
| Total biomass/Total throughput | 0.034 | $year^{-1}$ |
| Total biomass (excluding detritus) | 149.71 | $t.km^{-2}y^{-1}$ |
| Mean transfer efficiency | 17.23 | % |
| Pedigree | 0.65 | |
| Fishery indices | | |
| Total catches | 0.84 | $t.km^{-2}y^{-1}$ |
| Mean trophic level of the catch | 3.57 | |
| Gross efficiency | 0.001 | |
| Network flow indices | | |
| Finn's cycling index (of total throughput) | 17.30 | % |
| Finn's mean path length | 3.78 | |
| Connectance index | 0.18 | |
| System omnivory index | 0.25 | |
| Information indices | | |
| Ascendency | 24.88 | % |
| Overhead | 75.12 | % |
| Capacity | 19738 | Flowbits |

### 3.1. Trophic structure of the LNZ-FTV food-web and network analysis

The structure of LNZ-FTV marine ecosystem, the biomass of FGs, and predator-prey relationships are represented in Fig. 6, showing a high contribution of biomass in the groups corresponding to the primary producers and species of the lower trophic levels (TLs). Results also emphasized the important role of the deep-scattering layer, crustaceans, molluscs, and other benthic invertebrates in linking TL II with higher TLs from the pelagic and demersal habitat. Highest TLs (>4) are occupied by pelagic sharks, cetaceans, and seabirds, followed by turtles, oceanic pelagic fishes, and skypjack and tunas (Table 1).

The system summary statistics as well as some ecological indicators are included in Table 2. The pedigree obtained by the model was 0.65 over 1. Production and consumption dominated the Total System Throughput, followed by flows to detritus. Regarding fishery indices, mean TL of catches exhibited a high value, which means the fleets are mainly focused on target species with TLs higher than 3. This index combined with the value of the gross efficiency of the fishery, reflect the importance of high TL species in the landings.

Connectance index showed that 18 % of the possible links occurred in the food web and the system omnivory index obtained 0.22, indicating an intermediate degree of connectivity among groups.

### 3.2. Mixed trophic impact matrix and keystoneness analysis

The groups playing important structuring roles in the food-web, from a remarkable pelagic energy pathway, involve three apex predators, whales, dolphins and beaked whales, and pelagic sharks. Demersal serranids and wreckfishes, demersal sparids and moray eels are keystone species in the benthic domain.

From the MTI matrix, it has been determined how these keystone species, directly and indirectly, impact, both positively and negatively, on the other FGs (Fig. 7). The MTI matrix indicates positive or negative impacts on a relative scale, so this indicator does not have units and impact will be higher or lower depending on the value assigned. The keystone groups have a direct negative impact through predation, and on themselves derived from intraspecific competition and cannibalism (Table A2). The impacts on FGs lower than 0.05 have been combined in Groups + effect and Groups– effect, considering whether they are positive or negative, respectively.

Slight increases in the biomass of keystone species have the highest positive impacts on their predators (Fig. 7) but, indirectly, they can also benefit other groups by reducing predation on them. This is the case of mesopelagic species such as shrimps, deep-sea fishes, and organisms found in the DSL, that would be favoured if cetacean populations increase. Sea urchins are the populations in the benthic domain that has the most advantage from these indirect effects derived from predator-prey relationships among other FGs. Negative impacts of pelagic sharks are concentrated in four groups, all with TLs > 3.75 (Table 1).

### 3.3. Fisheries impacts on the marine ecosystem

Mixed trophic impacts of fishing fleets on FGs have a strong negative effect on their target species and positive indirect impacts on species that benefit from decreasing the biomass of their predators in the ecosystem (Fig. 8). The impacts on FGs lower than 0.05 have been combined in Groups + effect and Groups – effect, considering whether they are positive or negative, respectively.

Purse seine, crustacean trap and shellfishing showed impact values

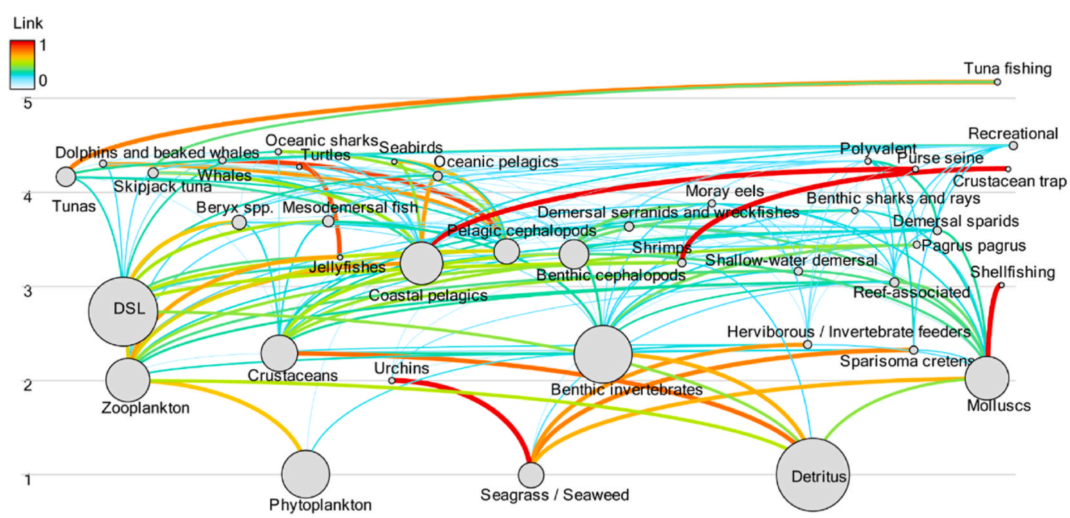


**Fig. 6.** Flow diagram of the LNZ-FTV food-web, representing the functional groups (FGs) according to their TLs, which range from 1 to 5. The circles are proportional to the biomass of each FG and the lines show the trophic connections among FGs, displaying weaker connections in blue and stronger ones in red.

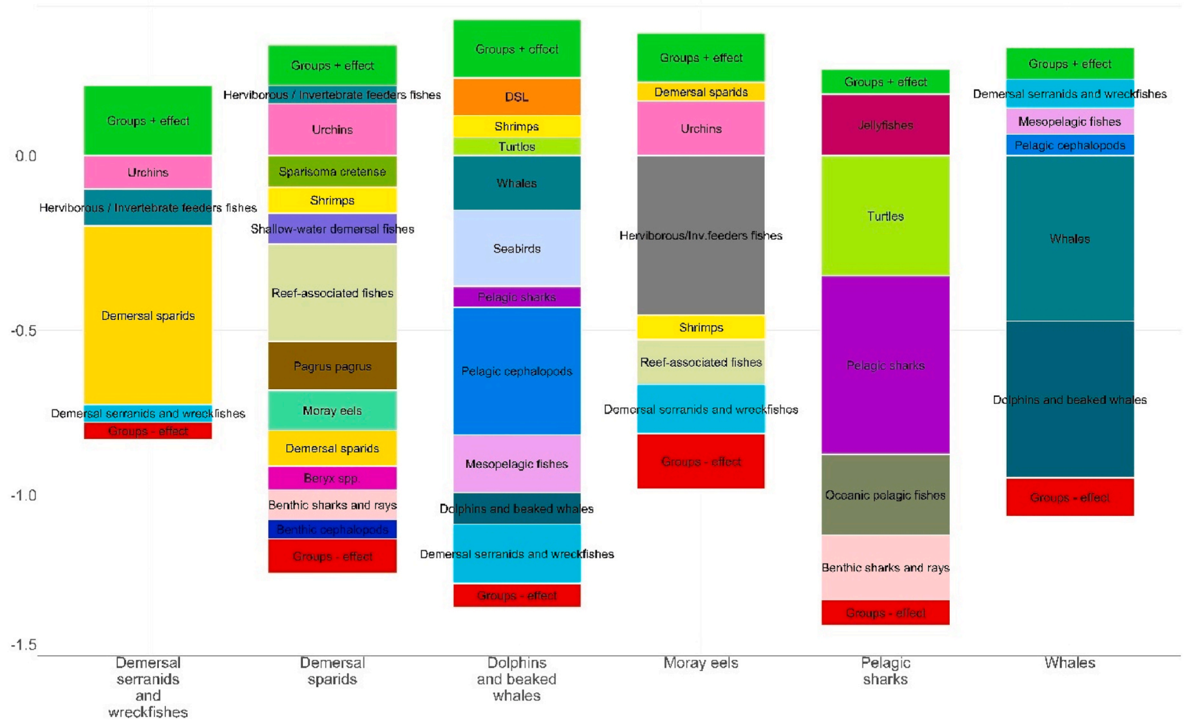


**Fig. 7.** Cumulative plot of the mixed trophic impact indices of the FG with highest keystoneness values. Positive and negative impacts are represented according to the symbol of the axis. Impacts <0.05 were grouped together under Group + effect (positive values) or Group – effect (negative values).

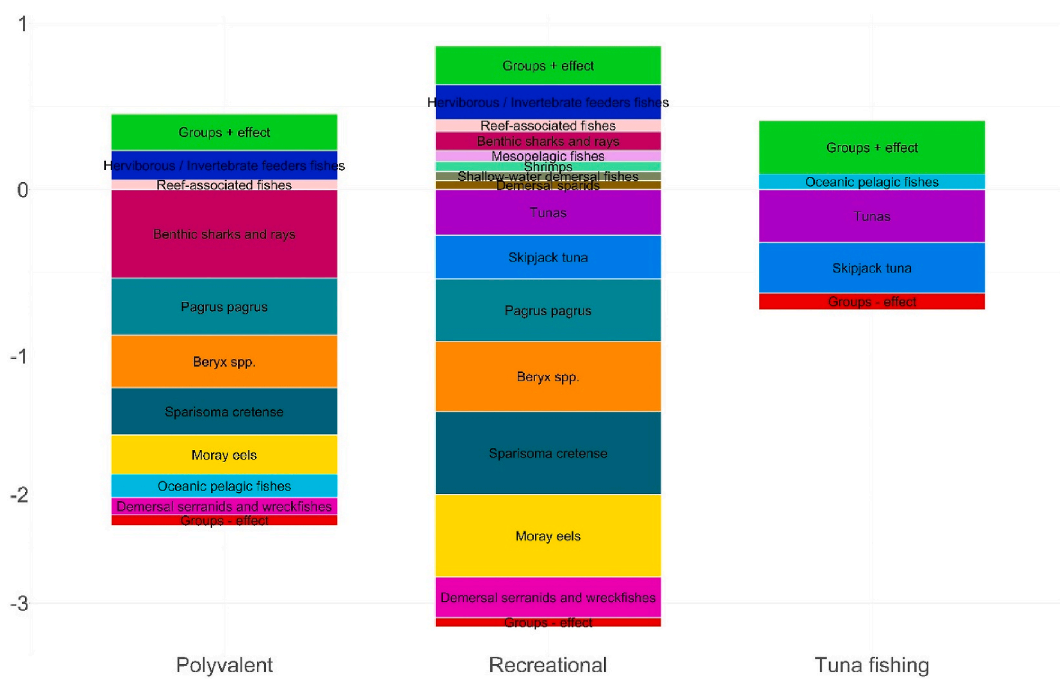


**Fig. 8.** Cumulative plot of the mixed trophic impact indices of the fleets. Positive and negative impacts are represented according to the symbol of the axis. Impacts <0.05 were grouped together under Group + effect (positive values) or Group – effect (negative values).

< 0.01 in all groups, so they have been discarded from this analysis. The species within Groups + effects that benefit from the tuna fishery are mainly apex predators, medium-sized coastal pelagic fishes and some mesopelagic species. Artisanal fleet and recreational fishing compete for the same resources, mostly benthic and demersal fish species [24,25]. A striking fact is the negative effect that recreational fishing has on these groups, that is greater than that caused by the artisanal fishermen, in the same way that was pointed out by Jiménez-Alvarado (2016). The exception is shown in the group of benthic sharks and rays, since there is no recreational fishing directed toward these species in the studied area (Fig. 8).

### 3.4. OWFs and effects on keystone species in the study area

The indicators outlined in Table 1 offer insights into the present condition and resilience of the marine ecosystem, with fishing being the primary activity that can influence it. Identifying the key species within the ecosystem is crucial as fluctuations in their populations can significantly impact the ecosystem's functionality. OWFs defined in the Sc2 and Sc3 scenarios introduce a new stressor to the ecosystem. Hence, it is crucial to differentiate the impacts solely attributable to fishing (scenario Sc1) from those resulting from OWFs or the combined influence of OWFs and fishing activities.

To assess the effect of OWFs on key ecosystem species, biomasses obtained in 2050 from the climate change baseline scenario (Sc1) were compared with those obtained if OWFs were operational in the areas defined by the INDIMAR tool (Sc2) or in those zones outlined in the marine management plan (POEM) for the study area (Sc3) (Fig. 9). In the model, the biomasses of each FG are expressed in tonnes/km$^2$; therefore, an adimensional scale is used to visually compare the results between different groups, as well as within the same group. It was used the same colour gradient, but the scale was modified to fit the biomass of each group. Blue indicates losses, white indicates equal or very similar values, and red indicates gains.

For cetaceans there are no significative changes in terms of relative biomass for 2050 by comparing INDIMAR or POEM scenarios against the baseline scenario. However, in terms of distribution, the impact that OWFs have on these FGs is more noticeable (Fig. 9).

Toothed whales would move to the east side of the islands in the Sc2 and Sc3 scenarios. The same pattern is observed for dolphins and beaked whales' group in the scenario Sc2. However, in the scenario Sc3 these populations would tend to accumulate their relative biomass in the south of the island of Fuerteventura, the channel that separates both islands, and the islets north of Lanzarote. Both scenarios showed a decrease in biomass for pelagic sharks in the waters closest to the coast, although in scenario Sc3 these species would concentrate in the OWFs areas. Biomass losses of pelagic sharks in the Sc2 and Sc3 scenarios are less than 2 % when compared to the baseline scenario Sc1; white cells represent very subtle variations in biomass.

Changes in the distribution of keystone benthic and demersal species in the LNZ-FTV model are shown in Fig. 10. In scenario Sc2, the biomass of demersal sparids decrease in the area near to the seamounts of Banquete and Amanay, at south of Fuerteventura island, where the OWFs would be located, as well as in the MPA of La Graciosa, and the species would move or concentrate mainly on the west coast of Fuerteventura. Demersal serranids and wreckfishes showed a similar situation under this scenario, except for these populations approaching the east and west coast of Lanzarote.

The scenario Sc3 lead to average biomass decrease of around 4 % for demersal serranids and wreckfishes compared to the baseline scenario. The decline in relative biomass for demersal sparids is most pronounced in regions close to the island shelf while the biomass of the demersal serranids and wreckfishes showed a similar distribution to the baseline scenario of climate change.

### 3.5. OWFs and conflicts with fisheries

To evaluate potential conflicts between wind energy and fisheries, the study concentrates on the main target species. Variations in abundance and catches across fleets are documented in Sc1. Therefore, when contrasting Sc2 and Sc3 scenarios with this baseline scenario, the observed alterations can be attributed to the impact of OWFs.

Comparing the impact of installing OWFs in fishing grounds (scenarios Sc2 and Sc3) to what would happen without them (scenario Sc1) reveals potential conflicts between OWFs and local fisheries. Under this premise and considering only variations equal to or greater than 5 %, OWFs directly affect fisheries, resulting in noticeable changes in biomasses and catches of target species in the studied area as shown in

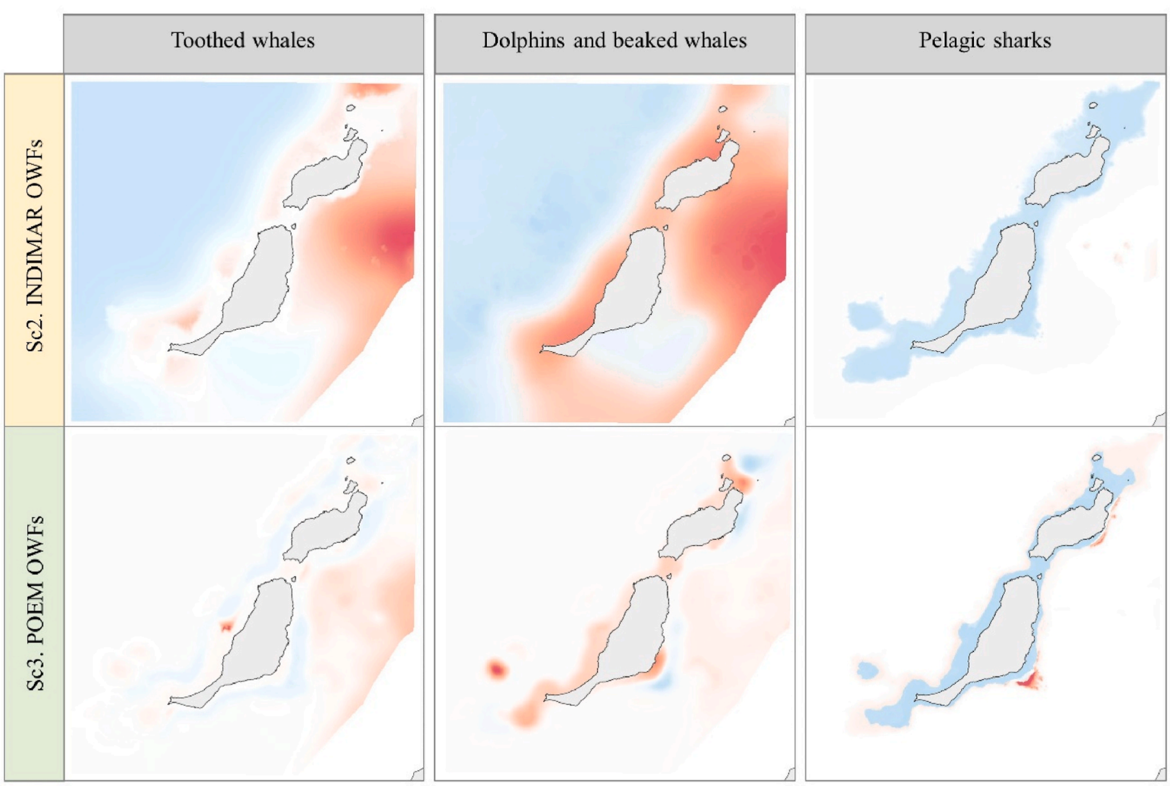


**Fig. 9.** Changes in the distribution of apex predator biomasses when comparing the baseline scenario of climate change (Sc1) against the other two scenarios (Sc2 and Sc3). Differences are shown in relative scale, where blue indicates the loss of biomass, red indicates the increase, and white indicates little changes with respect to the baseline scenario (<5 %).

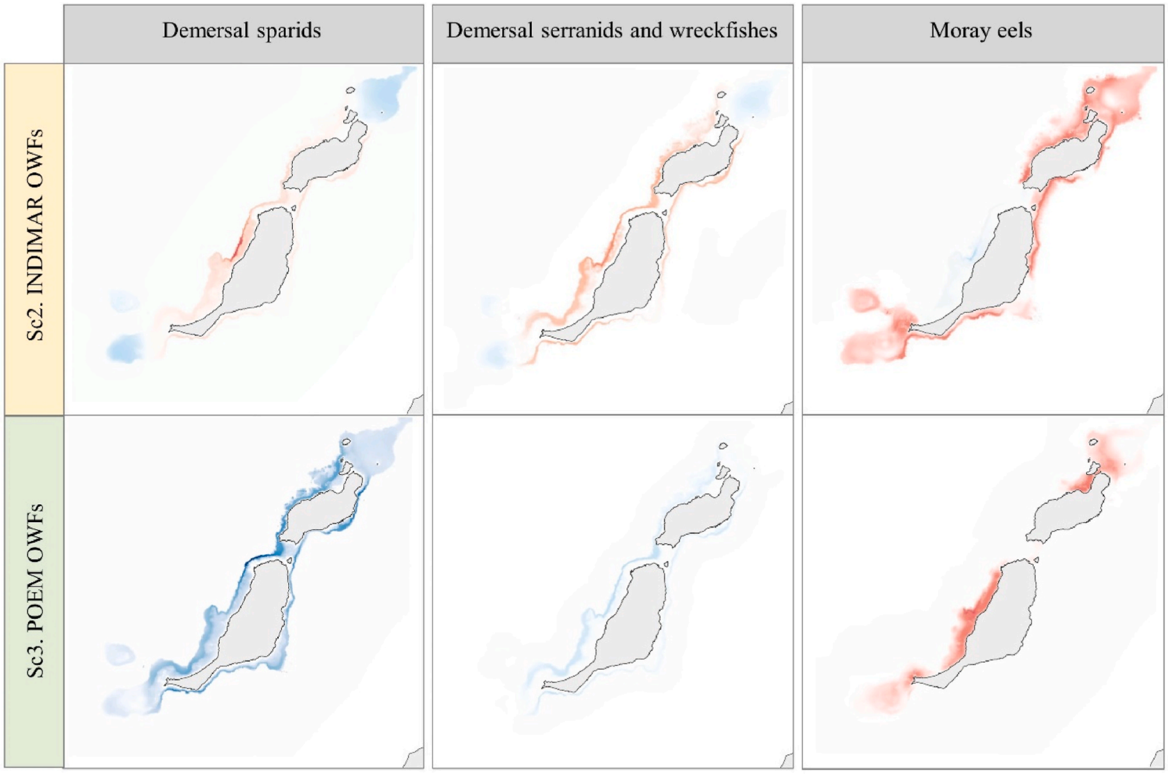


**Fig. 10.** Changes in the biomass distribution of benthic and demersal keystone groups when comparing the baseline scenario of climate change (Sc1) against the other two scenarios (Sc2 and Sc3). Differences are shown in relative scale, where blue indicates the loss of biomass, red indicates the increase, and white indicates little changes with respect to the baseline scenario (<5 %).

Figs. 11 and 12.

Ecological interdependencies play a role in the increase of oceanic pelagic fishes' biomass, as they are favoured from the decline in their main predators' stocks (Fig. 11). Positive changes in reef-associated fish biomasses are attributed to the increased availability of their prey, mostly invertebrates, due to the reduction in predator pressure by OWFs (Fig. 11).

By 2050, scenarios Sc2 and Sc3 showed a significant decline in catches of tuna and coastal pelagic fishes, mainly due to the notorious decrease of biomass of these species. The differences observed in Sc2 and Sc3 scenarios in catches of oceanic pelagic fishes (Fig. 12) are related to the spatial distribution of these species conditioned by environmental response functions, in combination with the location of OWFs. The observed increases in the catches of some groups are a consequence of abundance decreasing of their predators, as well as a possible attraction effect in the areas where the OWFs are located (Fig. 12).

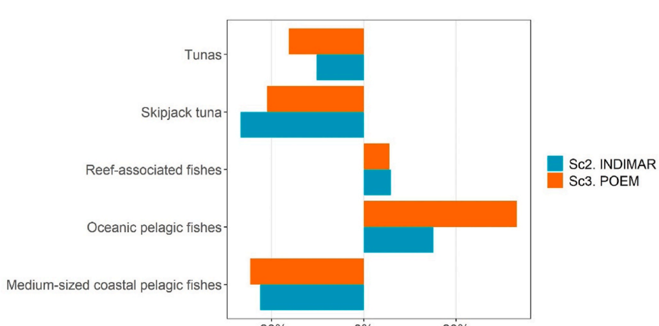


**Fig. 11.** Percentage of biomass changes of target fish species when comparing the baseline scenario of climate change (Sc1) against the other two scenarios (Sc2 and Sc3). Only groups with changes exceeding 5 % were included.

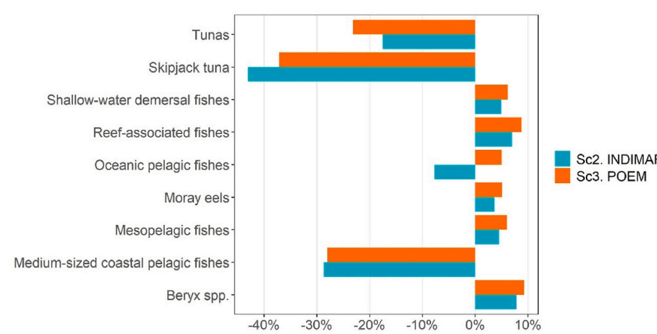


**Fig. 12.** Percentage of catch changes of target fish species when comparing the baseline scenario of climate change (Sc1) against the other two scenarios (Sc2 and Sc3). Only groups with changes exceeding 5 % were included.

## 4. Discussion

For a proper interpretation of the results acquired in this study, it is crucial to consider the singularities of the Canary Islands, as they have implications for biodiversity, species abundance and marine ecosystem integrity. Islands shelves are very narrow and abrupt, with steep slopes very close to the coast and separated from each other by great depths, of the order of 2000 m, and between these and the nearby African platform. This geographic configuration leads to several ecological implications. Specifically, the benthic and demersal species stocks differ in each ecosystem since adult individuals do not travel across open ocean waters [77], although this behaviour does not apply to fish larvae or pelagic and oceanic species. Nevertheless, resource evaluation initiatives relying on consistent monitoring campaigns are not currently in place, leading to estimations primarily derived from indirect methodologies utilizing catch data and temporal trends.

Despite the introduction of regulatory measures limiting the use of certain fishing gears since 1986 and the establishment of marine protected areas on several islands, most of the fish stocks of the Canary Islands are nowadays overfished [78]. The bentho-demersal species have been showing symptoms of overfishing for a long time [40,79]. Probably, bentho-demersal species have experienced excessive fishing pressure more quickly due to the small size of their populations, the low carry capacity of the ecosystem, and the high economic value they achieve, fresh, in local markets, similar to what happens in other European artisanal fisheries, especially in the Mediterranean [77]. By contrast, pelagic-coastal species have traditionally had a lower market value due to their relative greater abundance and, perhaps for this reason, it has long been assumed that they were underexploited. Nevertheless, Castro et al. [40] pointed out that, in the most populated islands, the average abundance of bento-demersal species targeted in by the local fishing fleet has decreased by almost 90 % in the last 50 years. But also, most of the target fish species have experienced a significant reduction in average size [80], due to high fishing pressure on large individuals. That is, the ecological system is showing evolving from a recruitment overfishing, and maybe a genetic overfishing, to an ecosystem overfishing [81].

The Canary Islands encounter a significant deficiency in information, posing a major weakness. In this regard, the use of ecological models allows to examine issues linked to human activities and their impacts on marine ecosystems from a multidisciplinary perspective. These models have already been used to examine the repercussions of alterations in the structure and operation of the food web resulting from OWFs [35], as well as the cumulative effects of marine renewable energy and climate change on the ecosystem [82].

Understanding the status of the marine ecosystem is pivotal before introducing new stressors like OWE. Consequently, a portion of this research is dedicated to comprehending the structure and operation of an already stressed marine ecosystem due to fishing activities.

### *4.1. Ecosystem functioning and resilience before the installation of OWFs*

The development of the LNZ-FTV model represents a notable progress in comprehending the structure and functioning of this marine ecosystem, enabling an assessment of how human activities are impacting on it. The pedigree corresponds to the values reported for the previous EwE models of Gran Canaria [83] and Tenerife [29], and higher than that obtained for the El Hierro model [31].

Indicators based on trophic flows, network analysis and information theory [41,44,45,84,85] were used to determine the state of development of the marine ecosystem and its level of resilience. Lower trophic levels showed the highest biomasses and is observed that a large portion of primary production is directed toward the detritus, demonstrating not only the importance of detritivores species in ecosystems but also its ecological role.

The mean transfer efficiency is an indicator related with the primary production required to sustain a particular fishery [86]; so, considering the high value obtained in combination with other indicators, such as mean trophic level of catches and gross efficiency, demonstrate the impact that fisheries have on this marine ecosystem. To quantify the complexity of the food-web we focused on the connectance index and the System Omnivory index, which showed moderate values suggesting a relatively simple food web, and consequently denoting a system that is not fully mature.

The process of ecological maturation will result in an increase in the diversity and complexity of the links and flows that connect species within the food-web and the surrounding environment, becoming it more resilient [41,87]. The relative balance between ascendency and overhead observed in the ecosystem suggests that it is still in development, which is consistent with the other network flow and information indices. Ecological indicators, coupled with statistics derived from the Ecopath model, suggest that the LNZ-FTV marine ecosystem is under stress and has not yet attained maturity or stability. The most likely explanation for these findings is associated with the combined impact of intensive fishing in the region and the limited availability of resources.

Employing the methodology devised by Valls et *al.* [48], this research has identified the keystone species within the ecosystem. As outlined by these authors, a keystone specie is a predator that holds a significant and widespread influence on the food web, despite its low biomass.

The keystoneness analysis revealed that top predators (cetaceans and pelagic sharks) and bentho-demersal groups, which occupied intermediate trophic levels, are key structuring groups in the ecosystem. Top predators have a crucial function in the food chain and serve as sentinels of the marine ecosystem status [88]; therefore, variations in the abundance of these species can be indicative of changes in the health of the marine ecosystem. Keystone species analysis also highlights the importance of demersal sparids, demersal serranids and moray eels on benthic domain. Besides their significance in the food web, it is essential to highlight that the species composing these groups hold substantial economic value for artisanal fishing and are also commonly caught by recreational anglers.

### *4.2. OWFs, fisheries and trophic impacts*

The issue of delineating areas within MPAs for the placement of OWFs is not exclusive to the Canary Islands. Similar challenges exist in the Mediterranean region, where zones designated for OWE intersect or adjoin territories within the Natura 2000 network. An analysis conducted recently scrutinized the harmony between OWFs and their impact on MPAs in the Western Mediterranean [89]. The study emphasized the imprudence of generalizing findings from other areas, as ecosystems exhibit unique functionalities, underscoring the need for extreme caution in ecosystems with substantial information gaps.

This study is a first attempt to assess the environmental impacts and conflicts of installing hypothetical offshore wind farms (OWFs) within the coasts of Fuerteventura and Lanzarote islands as has been included in the Royal Decree 150/2023 approved by the Spanish Government. For this exploratory analysis, we selected the high potential areas defined in the POEM and also those indicated as most suitable delivered by INDIMAR DSS [53], a tool based on spatial planning in the Macaronesian region. Unaware of the maximum number of turbines to be authorized in the future and their characteristics, we assumed floating turbines installed throughout the areas intended for OWFs, with buffer zones around them closed to all fishing activities.

Biomass and catches of target species, keystone species, and mixed trophic impacts were considered to evaluate the impact during the exploitation phase of OWFs on the food-web and on fishing yields. The overall changes in biomass and catches of target species were presented as percentages of changes in relation to the baseline scenario which includes only climate change projections.

Noise induced by OWFs have a repulsive effect on cetacean species causing habitat displacement to avoid damage [10–12,15,61,90]. These studies were used to achieve a more accurate spatial distribution of these functional groups within the study area. There were no significant changes in the overall biomass values of cetacean groups and pelagic sharks. However, noticeable changes were observed in the distribution of these species. In the scenario Sc2, the OWFs are mostly on the southwest coast of Fuerteventura, so it is logical that the cetaceans move east in response to their environmental preferences along with a greater availability of their prey, given the influence of the African upwelling [91]. For scenario Sc3, the dispersion of toothed whale populations would be greater due to increased conflict between the location of OWFs and the environmental preferences of these species. The same reasoning can be applied to dolphins and beaked whales, as their environmental preferences and the distribution of their prey would lead to populations being concentrated in coastal areas. Fuerteventura and Lanzarote showcase as an exceptional hub of cetacean diversity, hosting a total of twenty-eight registered species within the Marine Protected Area (MPA) examined in this study. Furthermore, this region serves as a crucial breeding and feeding ground for the bottlenose dolphin (*Tursiops truncatus*), specie listed in Annexes II and IV of the Habitats Directive (Council Directive 92/43/EEC). Hence, thorough and intricate impact assessments are essential to evaluate the effects on the ecology and biology of these populations resulting from alterations in their spatial distribution. Likewise, there has been a surge in ecotourism enterprises specializing in cetacean observation in this region. Now, there are twenty-one vessels in Lanzarote and Fuerteventura authorized by the Canary Islands Government to develop this activity; so, it is another factor to consider when determining the impacts from changes in the distribution of species. No economic evaluations have been conducted regarding this activity in the study area. Nevertheless, previous studies in other islands of the Canary archipelago and Macaronesia have highlighted its significance for tourism [92].

The group of pelagic sharks shows similarities when comparing both scenarios, as these species, as well as some of their main prey, would be attracted by the effect of the OWFs because they work as FAD [93–95]. The issue arises since both Lanzarote and Fuerteventura have high biodiversity, but low population biomass. Over time, the abundance of prey in areas near OWFs will decrease, causing sharks to migrate to other areas. In the year 2050, pelagic sharks still exhibit a notable concentration in the regions where OWFs specified under scenario Sc3 are situated. This can be attributed to the larger spatial coverage of OWFs in comparison to the Sc2 scenario, coupled with the fact that their primary prey, oceanic pelagic fish, tend to aggregate in those areas [95].

Changes in the distribution of bentho-demersal keystone groups were observed in relation with the baseline scenario which cannot be explained by alterations in overall biomass, as it remains below ±5 %. Demersal sparids, demersal serranids and wreckfishes and moray eels are in constant competition for resources and against each other due to the intricate dynamics of prey-predation relationships. But on this is the significant influence of fishing, as both the artisanal fleet and recreational anglers compete for the same fish species along the whole the islands fishing ground [25]. The disparities observed in scenarios Sc2 and Sc3 for this FGs can be attributed to a combination of those factors, including the placement of OWFs, as well as the habitat preference forcing functions.

Given that tuna and other pelagic species demonstrate a strong attraction and/or aggregative response towards floating aggregating devices (FADs) [75,93,96–99], it is reasonable to assume a comparable behavioural pattern considering the characteristics of floating OWFs. Tuna fishing holds great significance in the Canarian archipelago as their seasonal captures alleviate the strain on benthic-demersal fishes throughout the tuna season [100]. The decline in the biomass of these species is directly linked to their capture. When OWFs attract and concentrate them, they become more vulnerable to fishing [101,102], since fishermen can achieve higher catch yields in localized areas with reduced effort due to the fish aggregation mediated by floating OWFs [93]. The problem stems from the fact that tuna species hold considerable economic value, and not all of them have assigned catch quotas. As a result, fishermen would strive to maximize their catches to optimize their economic gains which could compromise the sustainability of stocks in the medium- and long-term. The decline in pelagic species estimated by the model in scenarios involving offshore wind farms (OWFs) might result in losses of around 1,500,000 €, considering the present market value of these species. Family traditions are the foundation of artisanal fishing in the Canary Islands, with most catches being destined for local consumption. Consequently, these findings suggest a potential socioeconomic impact on the sector.

The rise in catches of specific target groups can be attributed to the positive externalities resulting from the interactions between different fishing practices and within themselves. As the pressure on specific fishery resources rises, it can lead to different externalities [103]. One possibility is that the abundance of other species may increase due to a decrease in predation on them, resulting in what is known as competitive coexistence [104]. Another possibility is that the availability of a limiting resource, such as space or food, may increase, leading to competitive release [105,106].

Although the sites for the hypothetical OWFs are located within a marine protected area, this appears not be a specific barrier preventing the implementation of this renewable energy source, especially if it is economically feasible. This consideration is one of the factors that led to the selection of the area near the seamounts of Banquete and Amanay as an alternative location for the OWFs. The Eastern and southern marine area of Lanzarote-Fuerteventura is characterized by its unique and diverse marine ecosystems, encompassing many habitats that cater to a wide range of species, playing a vital role in providing essential breeding, feeding, and nursery grounds for numerous marine organisms. However, although there have been evaluations conducted in this marine protected area, they fall short in providing the comprehensive Marine Environmental Impact Assessment necessary to thoroughly analyse the potential impacts that may arise from OWFs during all stages (installation, operation, and decommissioning).

The research is focused on potential conflicts and incompatibilities with fishing activity because there is limited spatial information available and it is biased, as reflected in the marine spatial management plan approved by the Spanish Government concerning the Canary Islands marine demarcation. Furthermore, there is a significant opposition from artisanal fishermen regarding the establishment of these facilities, prompting them to lodge complaints with the Spanish Government. They argue that their objections have been disregarded in determining the locations for OWFs as they overlap with the fishing grounds, and the fact that several designated areas encompass protected species has not been considered.

A major hurdle in refining the model was establishing the allure or aversion effect of offshore wind farms (OWFs) on each functional group, given the current lack of information regarding the features and scope of these OWFs. To address this issue, the study considered the noise levels produced by turbines in the marine environment, particularly from floating turbines, along with the electromagnetic levels emitted by submarine cables. These factors were merged with scientific data on species' tolerance ranges within the research area. The model used the spatial information layers integrated into the Ecospace module to examine the overlap between OWFs and fishing operations.

This preliminary investigation holds promise for enhancement and broadening, given the limited data available posing challenges in forecasting future environmental repercussions. Althought this methodology involves uncertainties, the ongoing environmental impact assessments within the region are not exempt from them, due to scientists, stakeholders, and consultants work on the same data. Thus, the utilization of ecosystem models is suggested as an effective approach for complementing these evaluations, enabling the integration of new data for model refinements as they are acquired.

## 5. Conclusions

Offshore wind energy expansion must refrain from encroaching upon marine zones designated for the conservation of species and habitats, such those included in Natura 2000 network. The presence of offshore wind farms within the marine protected area, regardless of their specific locations, poses a significant conflict with artisanal fishing activities which has the potential to result in economic and social consequences in the medium term. Offshore wind farms can act as Fish Attracting or Aggregating Devices (FADs) for pelagic species. As a result, there is a notable decrease in the biomass of tunas and medium-sized coastal pelagic species, making them more susceptible to fishing pressure. The changes detected in the distribution and abundance of keystone species can modify the structure and functioning of the ecosystem, compromising its resilience and stability. Prior to the installation of offshore wind farms, a thorough evaluation of the marine ecosystems' status and ongoing activities, particularly fishing, should take precedence. This proactive approach aims to ensure that the future advancement of such marine renewable energy aligns harmoniously with biodiversity conservation efforts. The use of ecosystem models, which can be optimised and adjusted as new information is acquired, can provide a useful tool for this purpose, allowing anticipation of possible negative impacts that may occur in the ecosystem as well as spatial conflicts of use.

## CRediT authorship contribution statement

**L. Couce Montero:** Conceptualization, Methodology, Software, Writing – original draft. **A. Abramic:** Supervision, Writing – review & editing. **A. Guerra Marrero:** Writing – original draft, Investigation. **A. Espino Ruano:** Investigation. **D. Jiménez Alvarado:** Investigation. **José J. Castro Hernández:** Supervision, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2024.114894.

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