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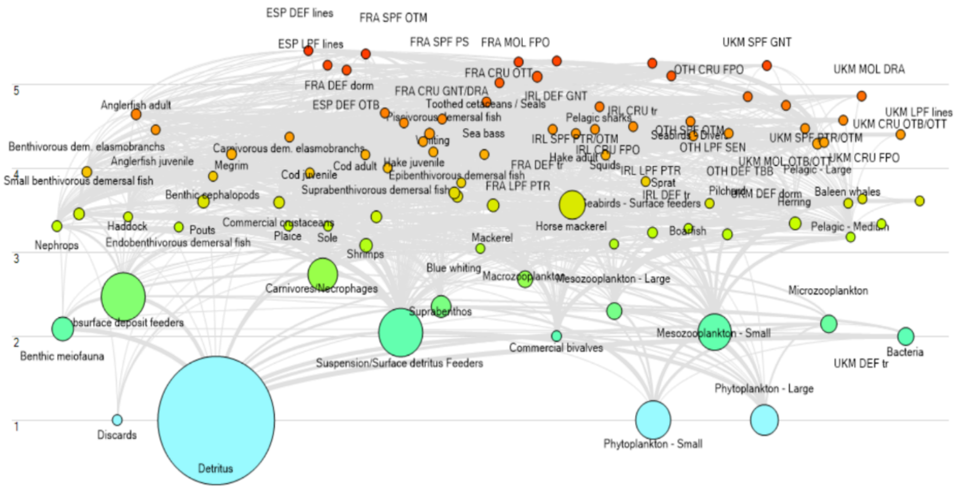
Investigating temporal and spatial impacts of mixed fisheries fleets on the Celtic Sea ecosystem in the frame of climate change through trophic modeling

Par: Mikaëla POTIER



Celtic Sea Ecopath model (derived from Hernvann et al., 2020 and modified)

Soutenu à Rennes le 16/09/2021

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The impact of climate change is increasingly visible on marine ecosystems (Bindoff et al. 2019, Mérillet et al. 2020). The latter causes many changes: increase in water temperature, acidification of the oceans, decrease in the level of dissolved O_2 in the water (IPCC 2020). Changes in abiotic factors trigger changes in biotic components from primary production to distribution patterns of species (Dulvy et al. 2008, Bindoff et al. 2019), resulting in potential « mismatches » between prey and predators in the same ecosystem (Dulvy et al. 2008). At the same time, fishing has a strong and long-lasting impact on communities and ecosystems: the average trophic level and the average size of individuals decrease (Bindoff et al. 2019) and the phenomena of "fishing down the marine food web" (Pauly et al. 1998) and "fishing through the marine food web" (Essington et al. 2006) are observed in several part of the word such as (e.g. Northeast Atlantic, Pauly et al. 1998). Some fishing gears result in high levels of incidental catches in the environment, which are estimated to account for around 40% of global catches (Davies et al. 2009). Indirectly, certain fishing techniques such as bottom trawling can cause high mortality of benthic epifauna, changes in the composition and relief of the sediment of these habitats and thus affect the productivity of ecosystems based on these habitats (Collie et al. 2017). In addition, climate change and fishing could have cumulative effects. Fishing reduces the spawning biomass and the number of year-classes in harvested populations, which results in a reduced ability of populations to buffer the effects of climate change and in a decreased ecosystem complexity (Planque et al. 2010).

In the light of these impacts on ecosystems, fisheries must be managed to limit these effects. However, there is a current focus on commercial species in fisheries management (Garcia & Cochrane 2005, Cury et al. 2015, Mérillet et al. 2020), whereas the adoption of an ecosystem approach and management is more necessary than ever. The ecosystem approach to fisheries (EAF) is defined in a range of documents, including the Code of Conduct for Responsible Fisheries (FAO 2003). According to the FAO, the ecosystem approach to fisheries involves "balancing diverse societal objectives, taking into account knowledge and uncertainties about biotic, abiotic and human components of ecosystems and their interactions and implements an integrated approach to fisheries within ecologically meaningful boundaries" (FAO 2003, Cury et al. 2015). It therefore promotes both the conservation of healthy and productive ecosystems and the sustainable use of resources within that ecosystem (FAO 2003, Cury et al. 2015). The watchword is precaution, as there are still many uncertainties in our knowledge of these ecosystems (FAO 2003, Cury et al. 2015). This approach is difficult to implement and requires robust scientific tools to improve our knowledge of ecosystems and subsequently decide on management measures (Garcia & Cochrane 2005, Cury et al. 2015).

Ecosystem modelling is a favored tool for developing this type of integrated approach (Coll et al, 2015). In particular, it makes it possible to assess the impact of exploitation on whole food webs and to highlight the effects of the environment (and in particular climate change) on the dynamics of the system and on the fisheries themselves. Ecosystem modelling thus makes it possible to analyze the combined ecosystem effects of resource exploitation and climate change. Among the existing categories of ecosystem models (Ecotroph, Osmose, Atlantis...), the Ecopath, with Ecosim and with Ecospace trophic models (Polovina 1984, Christensen & Pauly 1992, Walters et al. 1997, Walters 1999) provide the necessary tools for the thinking of a future implementation of EAF (Coll et al. 2015). These models have numerous applications worldwide for understanding these cumulative effects (e.g. (Ainsworth et al. 2011, Araújo & Bundy 2012, Corrales et al. 2017, Hernvann 2020). EwE models are especially useful for understanding these effects as they allow for end-to-end modelling, i.e., a representation of ecosystems, from primary producers to large predators and fisheries, impacted by trophic interactions and the abiotic environment (Coll et al. 2015, de Mutsert et al. 2021).

Our case study, the Celtic Sea (ICES area 27.7 except 27.7.d) is a fisheries zone of major interest and one of the most heavily exploited European seas, heavily fished for more than a century (Doring et al. 2010, Guénette & Gascuel 2012). The area experienced an increase in fishing pressure between the 1950s and 1990s (Pinnegar et al. 2002, Hernvann et al. 2020, Hernvann & Gascuel 2020). This has led to depletion of stocks of exploited species since the Second World War and a large reduction in the abundance of large demersal fish. In the 1990s, the historical minimum levels of the stocks are reached and after this period was observed a stabilization, then a reduction of fishing effort in the mid-2000s thanks to fisheries management (Hernvann & Gascuel 2020). These measures have allowed the recovery of the ecosystem state but only to a degree similar to that of the 1980s.

Furthermore, the Celtic Sea is subject to highly complex international mixed fisheries (Mateo et al. 2017, Moore et al. 2019, ICES 2020a). Indeed, it is an emblematic case of a fishery with a wide variety of gears targeting a wide variety of species assemblages fisheries (Mateo et al. 2017, Moore et al. 2019, ICES 2020a). For example, otter trawl fisheries target various species of gadoids (cod, haddock or whiting), but also target crustaceans such as nephrops or mollusks such as cephalopods (ICES 2020a). Several countries operate in the area. France, the UK and Ireland are the main countries represented. Spanish and Belgian vessels also fish in Celtic Sea waters as well as a few other countries with very small landings (Portugal, the Netherlands and Germany).

Mixed fisheries lead to difficulties in fisheries management because of multiple interactions between stocks. In particular, stocks of distinct productivities are fished at the same time, while nowadays, the main management measure is single species fishing quotas. Consequently, reducing the fishing quota on a stock, as the current Common Fisheries Policy does, has direct consequences on the exploitation of other stocks. Thus, the complexity of mixed fisheries needs to be addressed in order to think of a less stock-based management for a more fleet based management that would takes into account the mixed fisheries' interactions (Gascuel et al. 2012, Ulrich et al. 2017).

So far, the known effects of climate change on the Celtic Sea are a decrease in productivity via hydroclimatic variations in the North Atlantic, and a possible worsening of the effects of fishing for some stocks in the 1990s (Hernvann & Gascuel 2020) such as herring (*Clupea harengus*) or whiting (*Merlangius merlangus*). These effects were studied by reconstructing changes in the biomass of the exploited species and then comparing them with time series of climatic indices and hydroclimatic variables.

An Ecopath with Ecosim model was developed by Guénette and Gascuel (2012) for the Celtic Sea and Bay of Biscay area. This model was then improved (Bentorcha et al. 2017, Moullec et al. 2017). Finally, for the Celtic Sea only, a last model was developed, integrating the Ecospace module (Hernvann et al. 2020). This model was used to analyze past ecosystem dynamics and the expected effects of climate change on resources and fisheries (Hernvann 2020, Hernvann et al. in prep). However, the latter does not include an optimal representation of the Celtic Sea mixed fisheries, as each fleet in the model only harvests one species group.

Thus, in the current study, a new modelling step is presented in which the fleets are redefined and integrated into the model in order to address the following problems: What are the ecosystem effects of each of the Celtic Sea fleets and their interactions via food webs in the context of climate change? And vice versa: how is climate change (CC), through its ecosystem effects, likely to affect each of the Celtic Sea fleets? This new stage will also take into account the spatio-temporal distribution of fishing effort.

1. Material and method

1.1. Description of the EwE model of Hernvann et al. (2020)

1.1.1. The EwE modeling framework

The ecosystem model developed by Hernvann *et al.* (2020) used the Ecopath with Ecosim and Ecospace (EwE) framework (Pauly et al. 2000, Christensen & Walters 2004a).

Ecopath (Polovina 1984, Christensen & Pauly 1992) is the main component of the EwE software and gives a picture of the ecosystem for a given time period (usually a year), representing it through synthetic functional groups. Functional groups have similar characteristics in terms of trophic niches and life-history strategies, and exchange matter and energy through trophic interactions. The Ecopath framework is based on a mass balance assumption. The main equations are the production equation (1) and the consumption equation (2). The production P_i of the functional group i, equals the sum of predations on i, plus other mortalities, exportations, catches and biomass accumulation of i (equation (1)):

(1) Production = Predation + Other mortalities + Exportations + Catches + Biomass accumulation

(1) $B_i \times (\frac{P}{B})_i = \sum_{j=1}^{N} Bj \times (\frac{Q}{B})_j \times DC_{ji} + (\frac{P}{B})i \times Bi \times (1- EE_i) + Y_i + Ex_i + Bacc_i$

where B_i is the biomass, $(P/B)_i$ the production rate, EE_i the ecotrophic efficiency, Y_i the total fishery catches, Ex_i the net emigration rate and $Bacc_i$ the biomass accumulation. Each predator j of i, within the N predators of i, has a consumption rate $(Q/B)_j$. $DC_{j,i}$ represents the proportion of i in the diet of j. For each functional group i, the input parameters in Ecopath are: Bi, $(P/B)_{i,}$ $(Q/B)_i$ and $EE_{i.}$ 3 out of 4 of these parameters must be specified in Ecopath, for the model to estimate the last unknown parameter.

In Ecopath, the consumption Q_i is equal to the sum of production P_i ((B_i x $(P/B)_i$) , respiration ($Resp_i$) and unassimilated food (UA_i) (see equation (2)):

(2) Consumption = Production + Respiration + Unassimilated food

(2) $Q_i = P_i + Resp_i + UA_i$

Ecosim is the dynamic component of EwE and allows the reproduction of past ecosystem dynamics and evolution or the simulation of future trends. The master equations of Ecosim are series of differential equations, derived from the Ecopath equation (1) and expressing changes in the biomass Bi of a functional group i during a time period dt (see equation (3)). These changes in biomass are calculated as the difference between the production of the group i during dt, immigration and losses of biomass (predation, fishing, natural mortality and emigrations).

(3) $\frac{dB\mathrm{i}}{dt} = \left(\frac{P}{Q}\right) i \times \sum_{j=1}^{N} Qji - \sum_{j=1}^{N} Qij + I_i - (\left(\frac{P}{B}\right) i\ (1- EE_i) + F_i + Ex_i)\ B_i$

where Ii represents immigrations and Fi is the fishing mortality rate of the group i. $\sum_{j=1}^{N} Qji$ is the total consumption by group i and $\sum_{j=1}^{N} Qij$ is the total predation on i. The estimations of consumption terms are based on “the foraging arena” theory (Ahrens et al. 2012) which assume that the biomass of each group i is divided into a vulnerable and an invulnerable compartment. The predator can only eat the vulnerable fraction. the invulnerable fraction is hiding when it is not feeding.

The impact of fishing and environment is modelled in Ecosim in the form of time-series related to fishing or environment. These forcing functions can drive the model during a hindcast period but also during the forecast period. Forcing functions related to fishing are either species fishing mortalities time series, effort time series by fleet or time series of catches by functional group. Forcing functions related to environment are time series of environmental or physical conditions. Functional groups could have a response function for certain environmental variables. When environmental conditions vary, consumption rates of the species that respond to these conditions are modified. Biomass or abundance indices time series are also included to drive the biomass of functional groups, so as to rebuild evolution trends in the ecosystem on the hindcast period. By fitting the model to these data, Ecosim can deduct biomasses and catches of functional groups for each year of the simulation.

Finally, Ecospace is the spatial component of EwE. This tool predicts the distribution of biomass of different functional groups in space over time on a spatial horizontal 2-D grid (Walters 1999, Pauly et al. 2000). Maps of local environmental and physical conditions are entered in Ecospace and functional responses of species to local conditions are defined. For each functional group and grid cell, a habitat foraging capacity is calculated as the product of functional responses resulting from local conditions. The habitat foraging capacity ranges from 0 to 1 and impacts the ability of a predator to feed in a grid cell, by affecting its consumption rate in this cell. These habitats foraging capacity maps can also be directly entered by the users. Moreover, in Ecospace, the Ecopath and Ecosim equations are applied to each grid cell. Functional groups in a grid cell can move into neighbouring cells (left, right, above and below). Movements are controlled by dispersal rates, which quantifies the ability of functional groups to disperse randomly over one time step and which is an input of the Ecospace model.

1.1.2. Application of the Ecopath model to the Celtic Sea

- *Study area*

The model of Hernvann *et al*. (2020) covers the continental shelf of the Celtic Sea (Divisions 27.7.e-h and 27.7.j2 according to the ICES classification), from the coastline to the 200m isobath (see *figure 1*). The total area is 232,360 km² (Moullec et al. 2017).

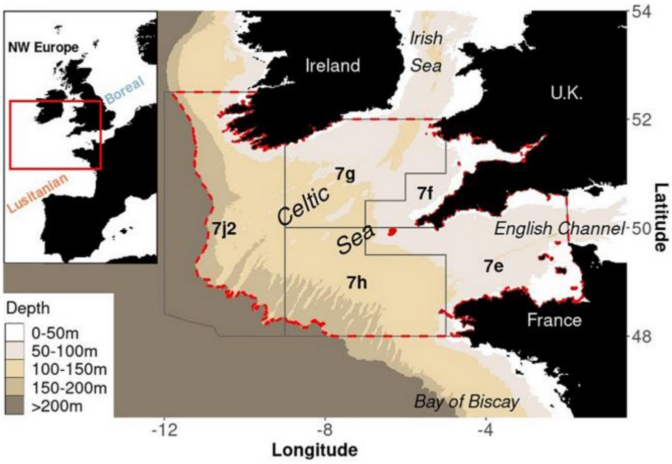

Figure 1.- General location of the Celtic Sea (top left corner) and delimitation of the study area regarding physical and management boundaries from Hernvann *et al*. (2020)

- ***The Ecopath model***

The model of Hernvann *et al.* (2020) is based on an Ecopath model describing year 1985. The Celtic Sea ecosystem is represented by 48 functional groups (monospecific or multi-specific, groups in *Appendix 1*). Three of the functional groups (the cod, hake and monkfish groups) are so-called "multi-stanzas": i.e., they are divided into a group for adult individuals and a group for juveniles. The model also includes 36 single-species fishing fleets, each targeting a different functional group, except for the cod, hake and anglerfish groups where juveniles and adults are targeted by the same fleet. Only 39 out of 48 functional groups are targeted by fisheries.

- ***The Ecosim model***

On this basis, Hernvann *et al*. (2020) develop an Ecosim model for the period 1985-2016. The Ecosim model was fitted to observed data: biomasses from ICES stock assessment, biomass indices from scientific surveys for fish (EVHOE, UK-WCGFS and CEFAS), biomass indices from the CPR (Continuous Plankton Recorder) survey for plankton, and catches for the period 1985-2016 from Statlant. Time series of catches and fishing mortality are used as forcing functions in the model. Catch forcing functions are used for multi-species groups for which no stock assessment outputs are available whereas fishing mortality forcing functions are used for monospecific groups for which stock assessment are available. Two forcing functions are also included to drive the production of phytoplankton compartments and the consumption of zooplankton compartments respectively. The phytoplankton forcing function is taken from a hydrodynamic biogeochemical model (NEMO-ERSEM) and from a vertical production model that relies on remote-sensed data of chlorophyll-a. The zooplankton forcing function comes from a suitable habitat model for zooplankton fitted to data of the CPR survey and to remote-sensed data of chlorophyll-a. Sea surface temperature and sea bottom temperature forcing functions, taken from biogeochemical models, are integrated into the model, and coupled with species response functions to temperature variations (*Appendix 2 and 3*), thus driving species consumption.

- ***The Ecospace model***

In the Ecospace module of EwE, Hernvann *et al*. (2020) uses the following method to extract averaged maps of biomass and catches by period: they extract an Ecopath model for a year in a chosen period of five years (for which a map is needed) and run Ecospace with the mean environmental conditions for the period. A primary production distribution map taken from the biogeochemical model POLSCOM-ERSEM, is entered in Ecospace to drive the plankton production and habitat capacity maps are entered for each functional group for the period in order to drive the distribution of functional groups for the period.

1.2. Modifications of the 1985-2016 EwE model

1.2.1. Time series and forcing functions

In order to simulate fisheries management scenarios with several future levels of fishing mortality (F), the forcing time series of the Ecosim model must be fishing mortality. However, for the multispecies groups in the model, the forcing time series were catches and the corresponding fishing mortalities were simulated by the Hernvann *et al*. model (2020) by the ratio of catches to biomasses. The Fs simulated by the Hernvann et al. 2020 over the period 1985-2016 are used as forcing time series in the new built model. The corresponding catches are now simulated by the new model.

1.2.2. Definition of the multi-specific fleets to be included in the Ecopath 1985 model

The Hernvann *et al*. (2020) model includes theoretical monospecific fleets, which are not representative of mixed fisheries in the Celtic Sea. The 1985 Ecopath model was modified to include multi-specific definition of fleets.

- ***Data mining***

The definition of the multi-specific fleets is based on the analysis of catches data (in tonnes) from the STECF Fisheries Dependent Information (FDI) database (STECF 2020). The data set includes the Celtic Sea landings and discards data (in tonnes) summed between 2015 and 2018, and aggregated according to different strata. For the "Country" stratum, 13 geographical units are represented: France, the UK geographical sub-units (England, Scotland, Northern Ireland, Guernsey, Jersey, Isle of Man), Ireland, Spain, Germany, Belgium, the Netherlands and Portugal. Landings and discards are also aggregated by gear type (31 different gears listed in *Appendix 4*) and by target species assemblage (12 different assemblages also listed in *Appendix 4*). Finally, the landings data are aggregated by ICES fishing area (27.7e-h and 27.7j). The discard data (in tonnes), which will be used in section 1.2.3, represent about 16% of Celtic Sea landings (13% of catches). It is assumed that some data are missing but that the loss of information is reasonable since in Kelleher *et al*. (2005) the proportion of global discards to catch is comparable (8% of catch).

From the raw data, the data set is reworked. The landings per species are aggregated by functional groups of the Ecopath model. FDI landings of taxa distributed over several functional groups are removed from the data set (this concerns 3.27% of total landings). For example, both “megrims” and "epibenthivorous demersal fish" functional groups contain megrims (*Appendix 1*). The category “megrims nei” of the FDI is thus removed from the data set. Unspecified gear or species assemblage were removed from the dataset, representing 3,14% of the total landings.

For consistency with the model spatial definition, the data to be selected are landings from areas 27.7.e-h and 27.7.j2 (j2), excluding area 27.7.j1 (j1). Within the FDI, landings data for areas j2 and j1 are aggregated. Official ICES landings data 2006-2018 (ICES 2020b) are used to calculate the proportion of landings *Pe* by species *e* that are caught in area j2 compared to the total area 7.j (j). This proportion *Pe* is the sum of landings of the species e in area j2 over 2015-2018, divided by the sum of landings of e in area j over the same period. In the case where the landings of a species are reported in « J_NK » in the ICES data set (« Not known » zone in area j), another calculation method is used. All species are classified into different groups: "demersal fish", "small pelagic fish", "large pelagic fish", "bivalves and gastropods", "cephalopods", and finally "crustaceans". For each of these groups, an average proportion of landings in j2 is calculated with species for which data are available. This average proportion is assigned to all species for which all landings are reported in "J_NK".

After an exploratory analysis of the data (not shown), some gears, countries and target species assemblages are grouped together (*Table 1*). For countries, the geographical sub-units of the United Kingdom are grouped under the same modality and all countries that make less than 5% of total landings are grouped together. Gears that account for less than 5% of total landings over 2015-2018 are grouped in a “other gears” group. Then, similar gear types are grouped together. Finally, target species assemblages that account for less than 5% of landings and that can be ecologically grouped with other assemblage categories are grouped.

Table 1.-Details of the different modalities chosen for each variable and the groupings implied. Countries and species codes are in *Appendix 4*.

Variables	**List of modalities by variable**		**Grouping for each modality**
Countries	UK	United-Kingdom	ENG, GBG, GBJ, IOM, NIR, SCO
	ESP	Spain	ESP
	FRA	France	FRA
	IRL	Ireland	IRL
	OTH	Other countries	NLD, BEL, DEU, PRT
Gears	DRA	Dredges	DRB, DRH
	FPO	Pots and traps	FPO
	GNT	Gill netters	GNS, GNC, GND
	OTB	Bottom otter trawls	OTB
	OTT	Otter twin trawls	OTT
	PTR	Pair trawls	PTM, PTB
	OTM	Midwater otter trawls	OTM
	TBB	Beam trawls	TBB
	LON	Longlines	LHP, LHM, LNB, LTL, LLD, LLS
	SEN	Danish and Scottish seines	SDN, SSC
	PS	Purse seines	PS
	OTH	Other gears	FYK, GEF, GTN, GTR, HMD, SB, SPR
Target species assemblage	DEF	Demersal fish	DEF, FIF, MCD
	CRU	Crustaceans	CRU
	MOL	Molluscs	MOL, CEP
	SPF	Small pelagic fish	SPF
	LPF	Large pelagic fish	LPF, MPD
	DWS	Deep water species	DWS
	FWS	Fresh water species	CAT, GLE

In the rest of the study, landings data by functional groups summed over 2015-2018 according to different levels of aggregation are manipulated. The different ways of aggregating landings will be termed "fishing sequence". For example, a type of fishing sequence may correspond to landings by functional groups that were made by a specific country and gear. Similarly, groups of vessels in the Ecopath model will be referred to as 'fleets', although these groups may not fit the strict definition of a fleet given in Ulrich *et al*. (2011).

- ***Statistical method to define multi-specific fleets***

In this study, the fishing sequence « Gear x Target species assemblage » that have similar landing profiles were grouped in order to define the fleets/métiers of the Ecopath 1985 model. Based on preliminary trials, the choice is made to disregards countries and aggregate the landings data according to the strata "Gear" and "Target species assemblage», which turn out to be the most structuring variables for the constitution of fleets/métiers. This is achieved by performing a weighted Principal Component Analysis (PCA) followed by a Hierarchical Ascendancy Classification (HAC) as in Pelletier & Ferraris (2000) and Deporte *et al.* (2012), where this method is used to respectively define métiers for an artisanal Senegalese fishery and for international otter trawl fisheries in the North Sea. The 38 fishing sequences created are our statistical individuals for the PCA. For each of these sequences, the proportions of landings for each of the 36 exploited EwE functional groups are calculated in relation to the total landings of the fishing sequence and constitute the quantitative variables of the PCA. In the PCA, individuals are weighted by their total landings over 2015-2018 so that fishing sequences with unusual landing profiles but very small landings are not given as much weight as other individuals. According to Cattell's criterion (or Scree test; Cattell 1966), the first dimensions of the PCA that concentrate the information of the data set are selected and then an HAC is conducted. The number of clusters in the HAC is determined by studying the loss of inertia by successive aggregation of clusters.

1.2.3. Inclusion of the detailed representation of the fishing fleets in the Ecopath model

The landings and discards in the 1985 Ecopath model must be distributed among the different multi-specific fleets. Thus, the amount of landings and discards of the 1985 Ecopath model is kept and only the distribution between fleets changes. However, we do not have the distribution of landings and discards of each functional group between the fleets in 1985 because these data are only available since 2015. It was therefore assumed that the distribution between the fleets was the same in 1985 as in 2016. The distribution of inter-fleet landings and discards for each group is calculated using the FDI data according to the following equations (4) and (5):

$$(4)\ PL_{i,fl,1985} = PL_{i,fl,2016} = \frac{\sum_{t=2015}^{2018} L_{i,fl,t}}{\sum_{t=2015}^{2018} L_{i,t}}$$

$$(5)\ PD_{i,fl,1985} = PD_{i,fl,2016} = \frac{\sum_{t=2015}^{2018} D_{i,fl,t}}{\sum_{t=2015}^{2018} D_{i,t}}$$

where i is a functional group, fl a fishing fleet, t is a year, $PL_{i,fl}$ the proportion of landings of g attributed to fl, $PD_{i,fl}$ the proportion of discards of g attributed to fl. $L_{i,fl,t}$ and $D_{i,fl,t}$ are respectively landings and discards of g landed/discarded by fl during the year t.

For the functional groups for which discards are not included in the FDI database (shrimps, scavenging carnivores, surface filter feeders, medium pelagic fish and suprabenthivorous demersal fish), the distribution is different. For shrimps, it is assumed that the distribution of discards between fleets is the same as for Norway lobster. For the other groups, it is assumed that the distribution is at a constant rate, uniform across fleets. In addition, as the FDI database does not separate the multi-stanza groups into adults and juveniles, it is assumed that the distribution of landings and inter-fleet discards is the same for adults as for juveniles.

1.3. Assessing the impact of fleets on the ecosystem in 2016

In order to assess the impact of each multispecies fleets on the ecosystem in 2016, an Ecopath model for the year 2016 is extracted from the Ecosim simulation 1985-2016. The model is balanced and then studied using different indicators and post analysis:

- **The mixed trophic impacts analysis (MTI analysis*):*** is a routine available in Ecopath. It reveals the direct and indirect effects that a change in biomass of a functional group will have on the biomass of other functional groups of the model (Ulanowicz & Puccia 1990, Christensen & Walters 2004a). This routine involves the calculation of a mixed trophic impact (MTI) for each pair of functional groups, following equation (6):

  $$(6)\ MTI_{i,j} = DC_{i,j} - FC_{j,i}$$

  where i is an impacting functional group, j is an impacted one, $DC_{i,j}$ is the proportion of j in the diet of i and $FC_{j,i}$ is the proportion of predation that i represents among j predators. Fleets are considered as predators. Thus, for a fleet fl, $DC_{fl,j}$ is the proportion that j represents in the catches of fl and $FC_{j,fl}$ is the proportion of predation that fl represents among j predators and among fleets which fish j. The MTI analysis consists in adding the impacts of each fleet/trophic group on each other across all trophic paths (Christian & Luczkovich 1999). The output of this routine is a matrix impacting groups/fleets x impacted groups/fleets where the levels of impact are comparable between lines and columns. If the coefficient impact of i on j is negative, i has a negative impact on j because i reduces j population growth (through predation, competition...). If it is positive, i has a positive impact because i improves population growth (though predation of a j predator, consumption of i by j).

- **Fishing mortalities (F):** are studied to assess what is the mortality generated by each fleet on each fished stock. Fishing mortalities are a direct output of the Ecopath model and is calculated as the ratio of catches to biomasses.

- **Fishing loss (Floss):** are studied in order to determine the impact that a fleet has on a stock compared to the total production of that stock (Gascuel 2005; Prato et al. 2016). For example, a fleet may catch less sole than anglerfish but have a greater impact on the sole stock if the sole stock production is low. It is calculated for each fleet/functional group pair as the ratio of catches to stock production.

1.4. Temporal simulation of climate change and fishery management scenarios

From 2016, the EwE model is used to simulate future environmental changes is the Celtic Sea ecosystem and to evaluate different fishery management scenarios until 2099.

1.4.1. Climate change forcing functions

To represent the future changes in the Celtic Sea ecosystem due to climate change, temporal predictions of sea surface temperature (SST), sea bottom temperature (SBT) and primary production (PP) are made up to 2099 according to two scenarios of CO_2 emissions mitigation: the Representative Concentration Pathways (RCP) 4.5 and the RCP 8.5 (IPCC 2014). The RCP4.5 is an intermediate scenario of Greenhouse Gas (GHG) emissions and the RCP8.5 is a scenario with very high GHG emissions. These temporal predictions are taken for each RCP scenario from 2017-2099 in Hernvann (2020). That information come from the coupling of a physical ocean circulation model (POLCOMS-AMM v6.3) and an ecosystem model of biogeochemistry (ERSEM 15.06) made by the Plymouth Marine Laboratory (pml.ac.uk). A third scenario is chosen to be the « without climate change » scenario. It is calculated as the mean of the historical environmental conditions (SST, SBT and PP) over 2010-2016 (*figure 2*).

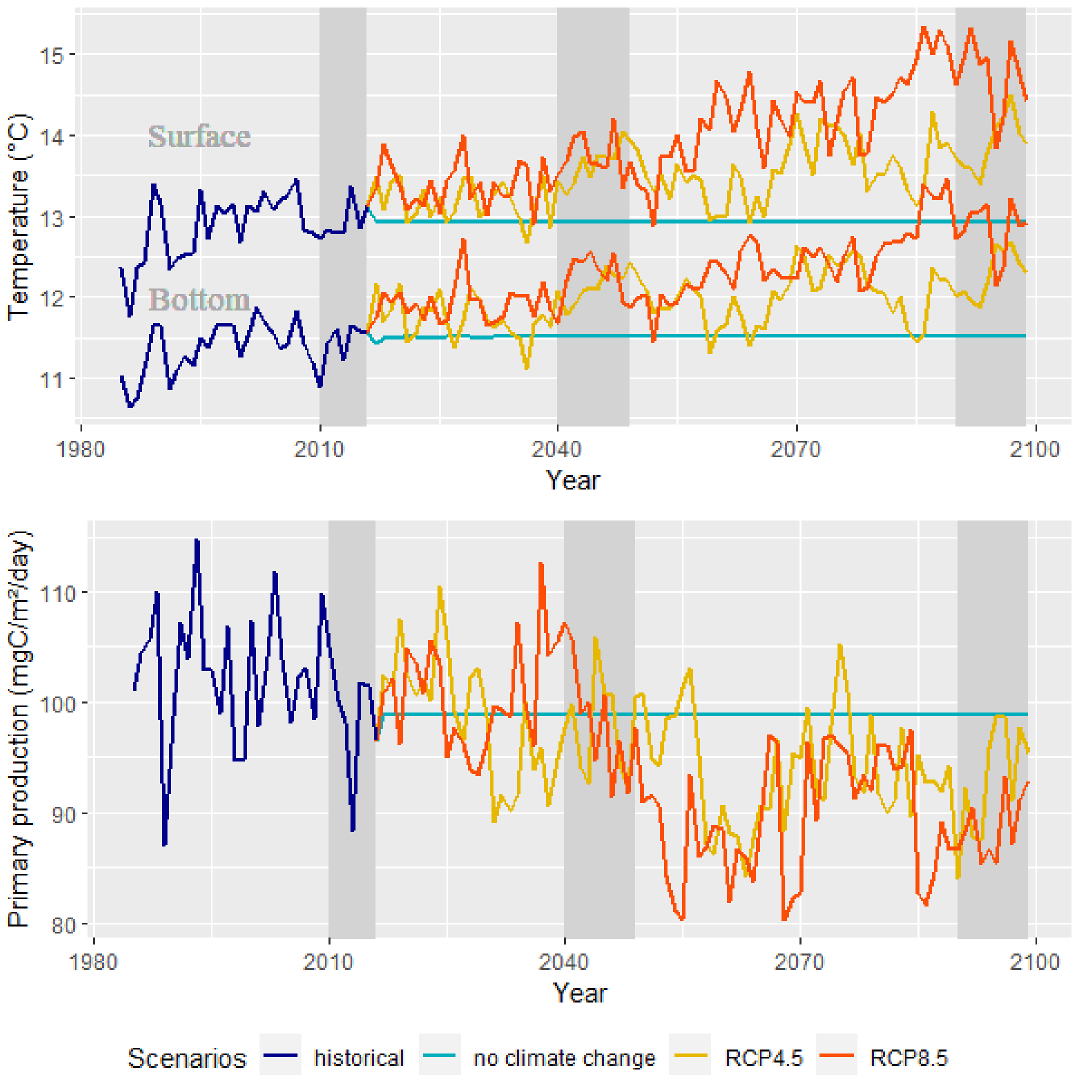

Figure 2.- Projected environmental changes in SST and SBT (top) and in PP (bottom)

1.4.2. Fisheries management scenarios

To simulate fisheries management scenarios in the Celtic Sea after 2016, different species fishing mortality time series over 2017-2099 are used as forcing function of the Ecosim model. Two groups of scenarios are adopted. On one hand, fishery management scenarios « by species » are designed, where a fishing mortality is fixed for each of the species. In scenarios by species, it is assumed that fleets are able to adapt their fishing effort to respect single-species fishing quotas, which is actually not fully the case in the context of mixed fisheries but which corresponds to the current European fisheries policy which correspond to a stock-based management. In reality, the adaptation of fleets is not total but still important.

The other group of scenarios is « by fleet ». The interest in running this family of scenarios is to assess the impact of a fleet-based management (rather than a stock-based management) that takes into account the fact that the catches of the species are dependent on each other, as it is thought in Gascuel *et al*. (2012). Within the model, as the forcing functions are fishing mortalities by species and not fishing effort by fleet, a back-calculation of species fishing mortalities is preliminary made. The distribution of species fishing mortalities among fleets in 2016 is taken as an output of Ecosim and "effort" multipliers are applied to some fishing mortalities by fleet according to the considered scenario. Then, for each species, the fishing mortalities due to each fleet are summed to have the total fishing mortality for each species. All the scenarios are presented below.

Scenarios by species:

- ***« Status quo » scenarios**:* exploited species fishing mortality over 2017-2099 is set constant and equal to the average fishing mortality over 2014-2016. In two other scenarios, species fishing mortality over 2017-2099 are decreased and increased by 20% compared to the status quo scenario: respectively the «0.8status quo» and «1.2status quo» scenarios.
- ***« Fmsy » scenarios:*** for species for which the maximum catch yield (MSY) is known, the fishing mortality over 2016-2099 is supposed to be equal to the fishing mortality at the MSY (Fmsy), for consistency with the current European Common Fisheries Policy (CFP) objectives. The Fmsy is taken from ICES single-species stock assessments. In two other scenarios («0.8Fmsy» and «1.2Fmsy»), fishing mortality on the species over 2017-2099 is decreased and increased by 20% compared to the « Fmsy scenario ».
- ***« Internal Fmsy » scenario***: the fishing mortality over 2017-2099 is supposed to be equal to the Fmsy estimated by the "MSY routine" of EwE (that are different from stock assessments' Fmsy) for functional groups which have a stock assessment's Fmsy, and species which have a fishing mortality at status quo greater than 0.1 (except cod and anglerfish juveniles). The interest of this scenario is to set Fmsys for species that do not have any in the stock assessments but which are quite exploited, and to have Fmsys derived from the multispecies approach, in accordance with the way the functional groups are set up and parameterized in the model.
- ***« Balanced harvest » scenario**:* is consistent with the concept of balanced harvest where it is assumed that more productive stocks can withstand higher fishing mortalities than other less productive stocks (Zhou et al. 2010). In the concept of « balanced harvesting », fishing mortality for each compartment of the ecosystem is set at the natural mortality rates of stocks (Zhou et al. 2010, Law et al. 2015), i.e. in accordance to the productivity of species. Fixing species fishing mortality according to the balanced harvest could help adopt sustainable fisheries more than increasing gear selectivity for species (Zhou et al. 2010) and could help maintain a relative size and composition in the ecosystem (Garcia et al. 2012) according to some scientific articles.

  In the balanced harvest scenario, for each exploited compartment (mean fishing mortality over 2014-2016 > 0.1), fishing mortality for each species is set at the natural mortality rate, calculated using the following formula (equation (7)):

  $$(7)\ M_i = Mpred_i + Mothers_i + \frac{Bacc}{B}_i$$

  where i is a species, M the natural mortality, Mpred the mortality due to predation, Mothers the mortality due to other causes (old age), $\frac{Bacc}{B}$ the biomass accumulation rate (which is part of the stock productivity).

Scenarios by fleet:

- ***« Active vs Passive gears » scenarios**:* are made to assess the impact of active gears and passive gears respectively. To this aim, the effort of fleets using active gears is successively decreased or increased by 50% as well as the effort of fleets using passive gears, which gives a total of 4 scenarios.
- ***« High TL vs low TL » scenarios:*** are made to assess the impact of fleets which catch high trophic level (TL) species and fleets which catch low TL species. The effort of fleets with an average TL of catches higher than 3.25 (limit that separate top predators and other species of the ecosystem), is successively decreased or increased by 50%. Idem for fleets with an average TL of catches lower than 3.25.
- ***« Brexit » scenarios:*** are made to assess the possible impact of Brexit on the ecosystem. In a first scenario, it is assumed that Brexit causes a closure of the United Kingdom's Exclusive Economic Zone (EEZ), without redistribution of fishing effort. 50% of the 27.7.e and 27.7.h, 40% of the 27.7.g and the

overall of the 27.7.f ICES divisions are supposed to be in the United Kingdom's EEZ (*figure 3*). Since the distribution of fishing effort by fleet and by area is available via the FDI database, the effort of European fleets is reduced in these areas by the percentages given above.

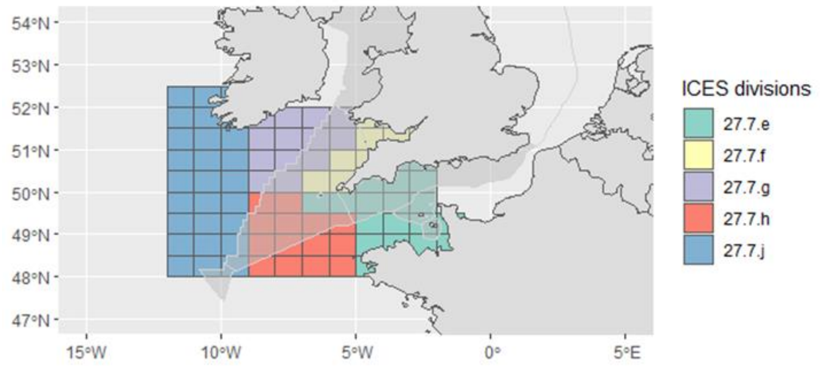

Figure 3.- Cartography of the Celtic Sea, representing ICES divisions superposed to the United Kingdom's EEZ

In a second « Brexit scenario », it is assumed that Brexit causes a closure of the United Kingdom's Exclusive Economic Zone (EEZ) with redistribution of fishing effort. The effort of United Kingdom's fleet is supposed to increase by 20%.

– ***« Seabass scenarios »:*** are made to assess the impact that a change in the gear used has on catches and biomasses of other species. The fishing mortality over 2016-2099 of a chosen species is maintained but the proportion of effort corresponding to passive and active gears is changed. Thus, the effort of fleets targeting a species varies as well as the fishing mortality of other species also caught by those fleets. The chosen species is the seabass, because it is an exploited species, for which we have identifiable targeting fleets using passive gears (longlines and gillnets) and identifiable targeting fleets using active gears (mainly trawls). Catches of targeting fleets come at 46% from active gears and at 53% from passive gears. In a first scenario, the seabass is targeted at 30% by passive gears and at 70% by active gears. In a second one, this is the other way round.

1.4.3. Tools and method to compare scenarios

Different indicators are chosen to study the changes in the Celtic Sea due to climate change and fisheries management:

(a) Catch-based indicators are chosen to study how climate change and management measures will affect the catches made by fisheries:

- **Total catch**: made by the fleets in t/km². This indicator is calculated using catches from the Ecosim model.
- **Trophic level (TL) of the catch**: corresponds to the average of the trophic level of the caught species weighted by the catches. TL of caught species and catches are given by the Ecosim model.

(b) Indicators of ecosystem health are chosen to study how climate change and management measures will affect the ecosystem:

- **Biomass of predators and trophic level of predators**: are calculated assuming that an ecosystem in good health is an ecosystem where predators are numerous and have a high TL. TL of predators is calculated as an average of the TL of species whose TL is higher than 3.25, weighted by biomasses.

- **Shannon-Wiener diversity index H'** (Shannon & Weaver 1949, Heip et al. 1998): is an indicator of ecosystem diversity and an indicator of both richness and evenness. The calculation of this indicator is done by Ecosim for each year of the simulation (Zhai & Pauly, 2020), as following (equation (8)):

$$(8)\ H' = -\sum p_i \ln(p_i)$$

where i are functional groups and p_i is the proportion of functional group i in the communities of the ecosystem. It ranges from 0 to 5 (Türkmen & Kazanci 2010). A high value of this indicator means a high diversity in the ecosystem. Usually, it is compared to species richness but in this study, richness is not varying as the model always have the same number of functional groups. Thus, it is presented here as an indicator of evenness that can be compared between scenarios.

– **Biomass ratio of demersal fish and chondrichthyans/ pelagic fish**: is an indicator calculated in Shannon *et al*. (2009) and aims at capturing global changes in the ecosystem structure in terms of distribution between demersal and pelagic compartments. It expresses the ratio between benthic and pelagic pathways and between top-down and bottom-up controls within the ecosystem. This indicator is expected to drop with an increased fishing pressure.

The indicators are calculated and averaged over two decades, chosen to compare scenarios. The elected decades are 2040s and 2090s because they are spaced in time, correspond to periods where the climate change scenarios are distinct and because they are similar the one chosen by Hernvann (2020). To compare scenarios and indicators value, a reference is chosen. For each indicator, the reference corresponds to the average of this indicator over 2010-2016 using the status quo scenario without climate change. All the indicators of all scenarios are compared to the reference. For trophic level indicators (TL of the catch and TL of predators), a difference between the TL and the TL of reference is calculated. For the other indicators, a ratio between the metric and the reference is calculated.

1.5. Spatial simulation of climate change and fishery management scenarios

Three scenarios are chosen to simulate spatial changes in the Celtic Sea ecosystem due to CC and fishing. The « status quo without CC » scenario and the « status quo RCP8.5 » are elected to study the spatial impact of climate on the food web and the "0.8Fmsy" scenario with a RCP8.5 climate change scenario is chosen to study spatial changes in the ecosystem if a fishery management scenario with less impact than the status quo RCP8.5 was adopted. The three scenarios are compared with each other for the decade 2090s, where it is supposed that simulations are stabilized. They are also compared with the reference period: 2010-2016.

To this aim, using the « Ecopath model from Ecosim » routine (Steenbeek et al. 2016), three yearly Ecopath models are extracted and balanced for the year 2095, for each scenario. One yearly model is also extracted and balanced for the year 2013. Then, spatial versions of these Ecopath models are built using the Ecospace module of EwE.

The Ecospace models are fed with primary production distribution for the period 2010-2016 and for 2090s (*Appendix 5*) which will drive the phytoplankton production. These PP distributions are predictions from the biogeochemical model POLSCOM-ERSEM. However, as 2010-2016 predictions are not available via POLSCOM-ERSEM which provides an historical run until 2005, it is considered that 2010-2016 predictions would be quite similar to those of 2000-2005.

The Ecospace models are also fed with habitat capacity maps for each functional group, calculated by Hernvann (2020) using the mean environmental conditions for 2010-2016 and 2090s and using fitted environmental responses of species to these variables. The habitat capacity maps are used to predict the functional groups' habitats in 2010-2016 and in 2090s.

Ecospace models were run on a spin-up period of 100 years. The following output of Ecospace models are saved for each scenario and for the historical period (2010-2016): predator biomass distribution maps, total catches distribution maps and effort multiplier maps for each fleet. Effort multipliers are calculated by fleet's cluster pro rata to the mean period catches by fleet within the cluster.

2. Results

2.1. Definition of the Celtic Sea fishing fleets

PCA reveals some functional group clustering over the first three axes (*Appendix 6*). The first 6 dimensions of the PCA, explaining 86.7% of the variance in the data set, were retained for the HAC. Each of the 6 dimensions are highly correlated to some functional group variables (*Appendix 7*). This shows that some landings proportions of functional groups are very correlated because they are caught together. This is the case for anglerfish, cod, whiting, haddock, and other demersal fish or elasmobranch that are targeted by mixed demersal fisheries. This is also the case for mackerel, horse mackerel, herring and for hake, piscivorous demersal fish.

7 clusters, describing 7 groups (groups of fishing sequences gear x target assemblage) having similar landings profiles, were selected, which explained 98.4% of the variance in the classification (*Appendix 8 and 9*). First cluster have high landings proportion for hake and piscivorous demersal fish, cluster 3 high landings proportion of mackerel and horse mackerel, cluster 4 high landings proportion of sardine, cluster 5 high landings proportion of commercial large crustaceans, cluster 6 high landings proportion of scavengers and cluster 7 high landings proportion of commercial bivalves. Cluster 2 was heterogeneous and it was empirically divided into 4 clusters (clusters 2, 8, 9,10) giving a total of 10 clusters (*figure 4*).

Results shows that the variables "target species assemblage" is very structuring in the constitution of the fleets. In fact, within those 10 clusters, 2 fleet's clusters only target crustaceans (clusters 5 and 8), 3 only target mollusks (clusters 2, 6 and 7), 2 target demersal fish (clusters 1 and 10), 2 target small pelagic fish (clusters 3 and 4) and 1 other fleet's clusters target large pelagic fish (cluster 9). The "Gear" variable seems also to be structuring. In each fleet, there are often no more than two predominant gears, except in fleet 10. The fleets targeting demersal species are separated into active gear (fleet 10) and passive gear (fleet 1). Fleets targeting small pelagics are separated by gear between purse seines (fleet 4) and pelagic trawls (fleet 3). Those targeting molluscs are separated between trawlers (fleet 2), fishing pots and traps (fleet 6) and dredgers (fleet 7). Finally, the fleets targeting crustaceans are well separated between dredgers (fleet 5) and trawlers (fleet 8), while the fleets targeting large pelagic fish with lines or twin trawls (fleet 9). In each of the clusters there are vessels of all sizes, and there is no particular pattern in the size distribution between the clusters, except in fleet 3 which concentrates vessels over 40m. In terms of countries, the UK and France are in all fleets. Ireland is present in 8 fleets but has significant tonnages in the trawler fleets (fleet 3 and 8). Similarly, the countries grouped under "Other countries" are mainly involved in fleets 3 and 8. Spain is represented in the fleet targeting large pelagic fish (fleet 9) and in the fleets targeting demersal species (fleet 1 and 10).

Each of the 10 fleets is characterized by high proportions of landings for one or more functional groups (*Table 2*).

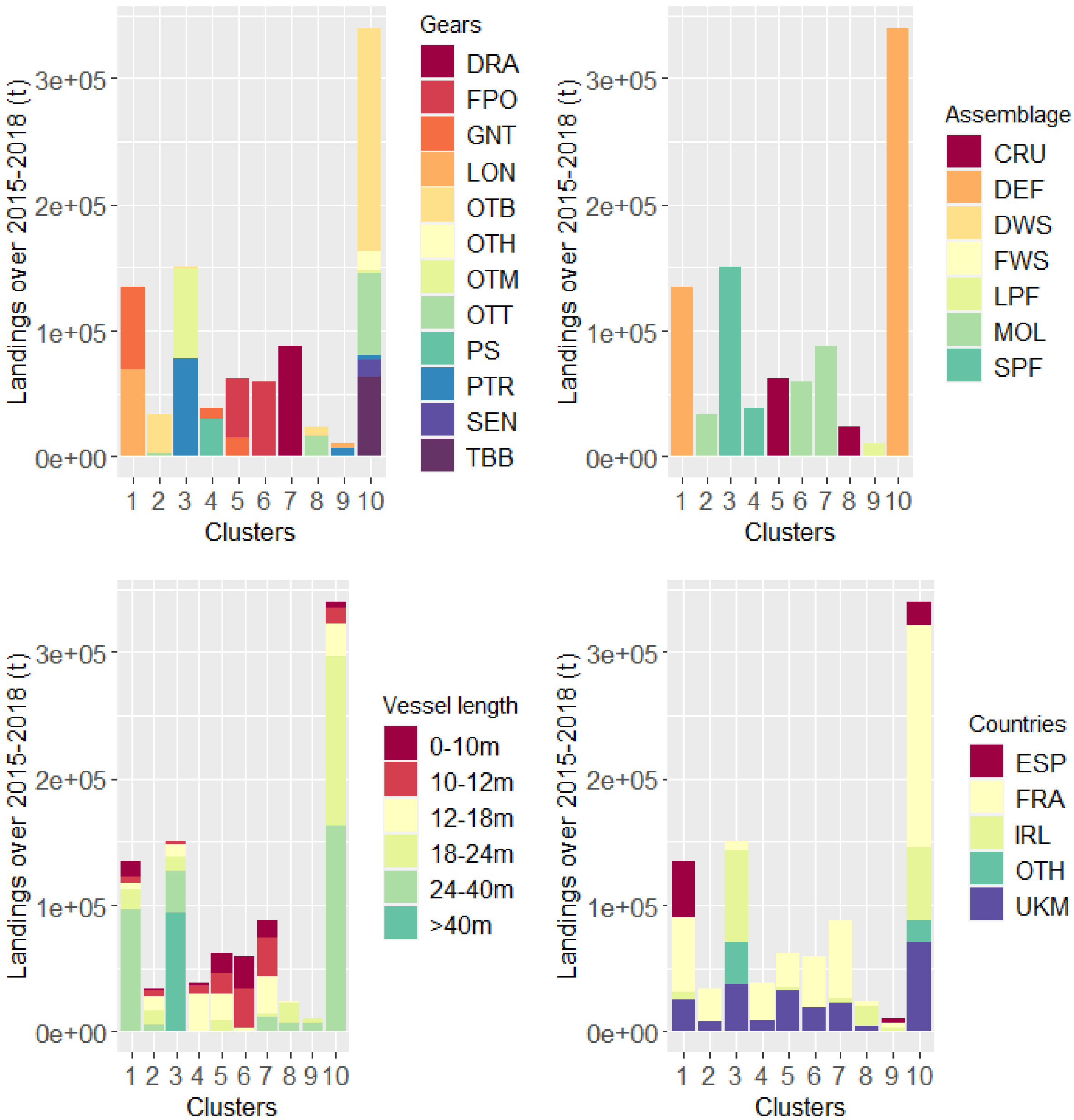

Figure 4.- Description of the 10 clusters in terms of gear (top left), target species assemblage (top right), vessel size (bottom left) and country (bottom right)

Table 2.- Characterization of clusters in terms of landings profiles of EwE functional groups

Cluster	Mainly landed group(s)
1	Hake and piscivorous demersal fish
2	Benthic cephalopods and squids
3	Mackerel
4	Sardine
5	Commercial large crustaceans
6	Necrophagous carnivores
7	Commercial bivalves
8	Norway lobster
9	Large pelagic fish
10	Piscivorous and epibenthivorous demersal fish, benthivorous demersal elasmobranch, whiting and anglerfish

For the purpose of fisheries management scenarios, it was decided to split the 10 clusters per country leading to 34 fleets (description of fleets in *Table 3*).

Table 3.- Description of the 34 fleets derived from the 10 HAC clusters

HAC clusters	Fleet code	Country	Mainly exploited functional groups	Target species assemblages	Main fishing gears
1	ESP DEF lines	Spain	Hake	Demersal fish	Lines
	FRA DEF dorm	France	Hake, piscivorous demersal fish, seabass, anglerfish, benthivorous demersal fish		Passive fishing gears: lines and nets
	IRL DEF GNT	Ireland	Piscivorous demersal fish and hake		Nets
	UKM DEF dorm	UK	Piscivorous demersal fish, hake, mackerel		Passive fishing gears: lines, nets
2	FRA MOL OTB	France	Commercial bivalves, Benthic cephalopods, squids, benthivorous demersal elasmobranch and piscivorous demersal fish	Mollusks	Bottom otter trawl
	UKM MOL OTB/OTT	UK	Benthic cephalopods		Bottom otter trawl, otter twin trawl
3	FRA SPF OTM	France	Horse mackerel, mackerel, herring	Small Pelagic fish	Midwater otter trawl
	IRL SPF PTR/OTM	Ireland	Herring, mackerel, horse mackerel, sprat		Midwater otter trawl, pair trawls
	OTH SPF OTM	Others	Horse mackerel		Midwater otter trawl
	UKM SPF PTR/OTM	UK	Mackerel, horse mackerel, sprat		Midwater otter trawl, pair trawls
4	FRA SPF PS	France	Sardine, herring	Small pelagic fish	Purse seine
	UKM SPF GNT	UK	Sardine		Gillnets
5	FRA CRU GNT/FPO	France	Commercial large crustaceans	Crustaceans	Nets, pots and traps
	IRL CRU FPO	Ireland			Pots, traps
	OTH CRU FPO	Others			Pots, traps
	UKM CRU FPO	UK			Pots, traps
6	FRA MOL FPO	France	Necrophagous carnivores	Mollusks	Pots, traps
	UKM MOL FPO	UK	Necrophagous carnivores, SSDF*		Pots, traps
7	FRA MOL DRA	France	Commercial bivalves	Mollusks	Dredges
	IRL MOL DRA	Ireland			Dredges
	UKM MOL DRA	UK			Dredges
8	FRA CRU OTT	France	Megrim and norway lobster	Crustaceans	Otter twin trawl
	IRL CRU tr	Ireland	Norway lobster, cod		Active arts: seines and trawls

	UKM CRU OTB/OTT	UK	Norway lobster, cod		Otter twin trawl and bottom otter trawl
9	ESP LPF lines	Spain	Large pelagic fish, pelagic sharks	Large pelagic fish	Lines
	FRA LPF PTR	France	Large pelagic fish		Pair trawls
	IRL LPF PTR	Ireland	Large pelagic fish		Pair trawls
	OTH LPF SEN	Others	Large pelagic fish, mackerel, horse mackerel		Seines
	UKM LPF lines	UK	Large pelagic fish		Lines
10	ESP DEF OTB	Spain	Anglerfish, piscivorous demersal elasmobranch, benthivorous demersal elasmobranch, hake, squids	Demersal fish	Bottom otter trawl
	FRA DEF tr	France	Megrim, Anglerfish, piscivorous demersal elasmobranch, benthivorous demersal elasmobranch, piscivorous demersal fish, blue whiting, cod		Active arts: seines and trawls
	IRL DEF tr	Ireland	Whiting, cod, piscivorous demersal fish, endobenthivorous demersal fish, anglerfish		Active arts: seines and trawls
	OTH DEF TBB	Others	Sole, plaice, benthivorous demersal elasmobranch, piscivorous demersal fish		Bottom beam trawl
	UKM DEF tr	UK	Sole, plaice, benthivorous demersal elasmobranch, anglerfish, piscivorous demersal fish, endobenthivorous demersal fish		Active arts: seines and trawls

*SSDF= « Surface deposit feeders »

2.2. Impact of fishing fleets on the Celtic Sea ecosystem in 2016

2.2.1. Impact of each fleet on the ecosystem through fishing mortalities and fishing losses on each functional group

Some Celtic Sea fleets have important impacts on the ecosystem in terms of fishing mortality (*figure 5*, detailed results in *Appendix 10*) and fishing losses on functional groups (*figure 6*; detailed results in *Appendix 11*).

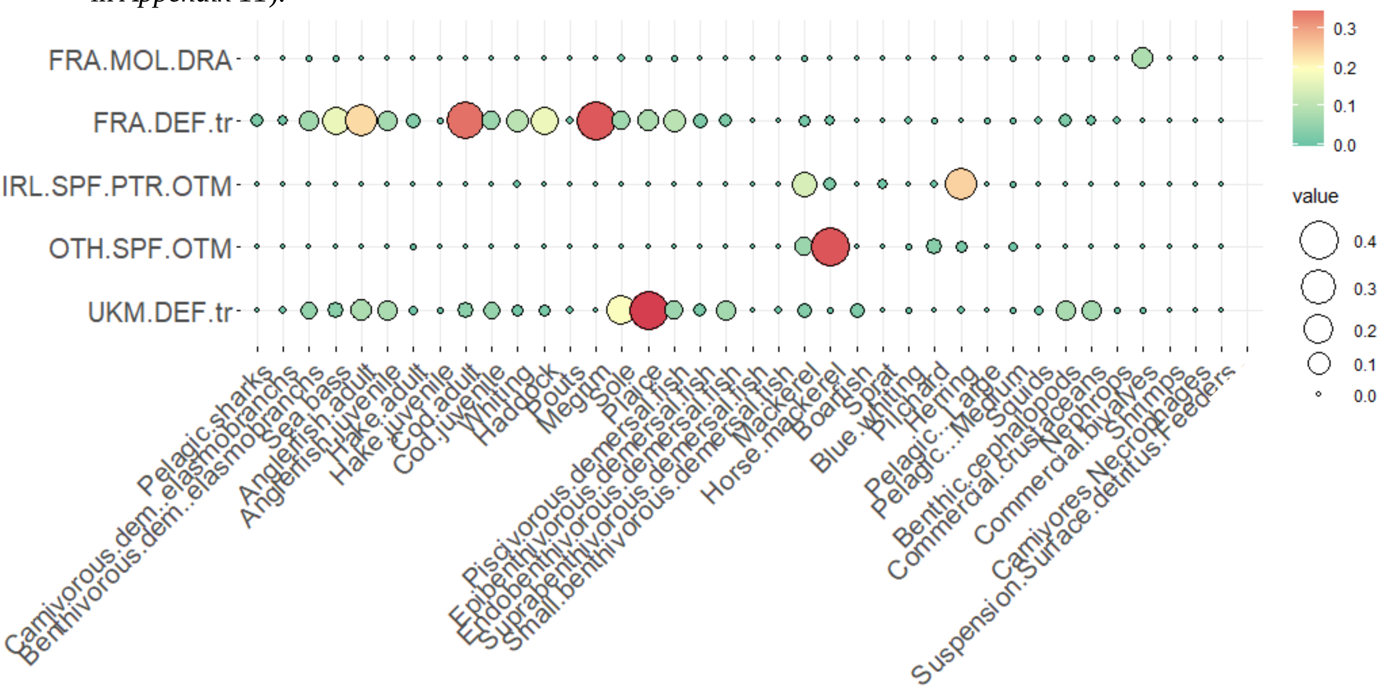

Figure 5.- Fishing mortalities in 2016 of five elected fleets

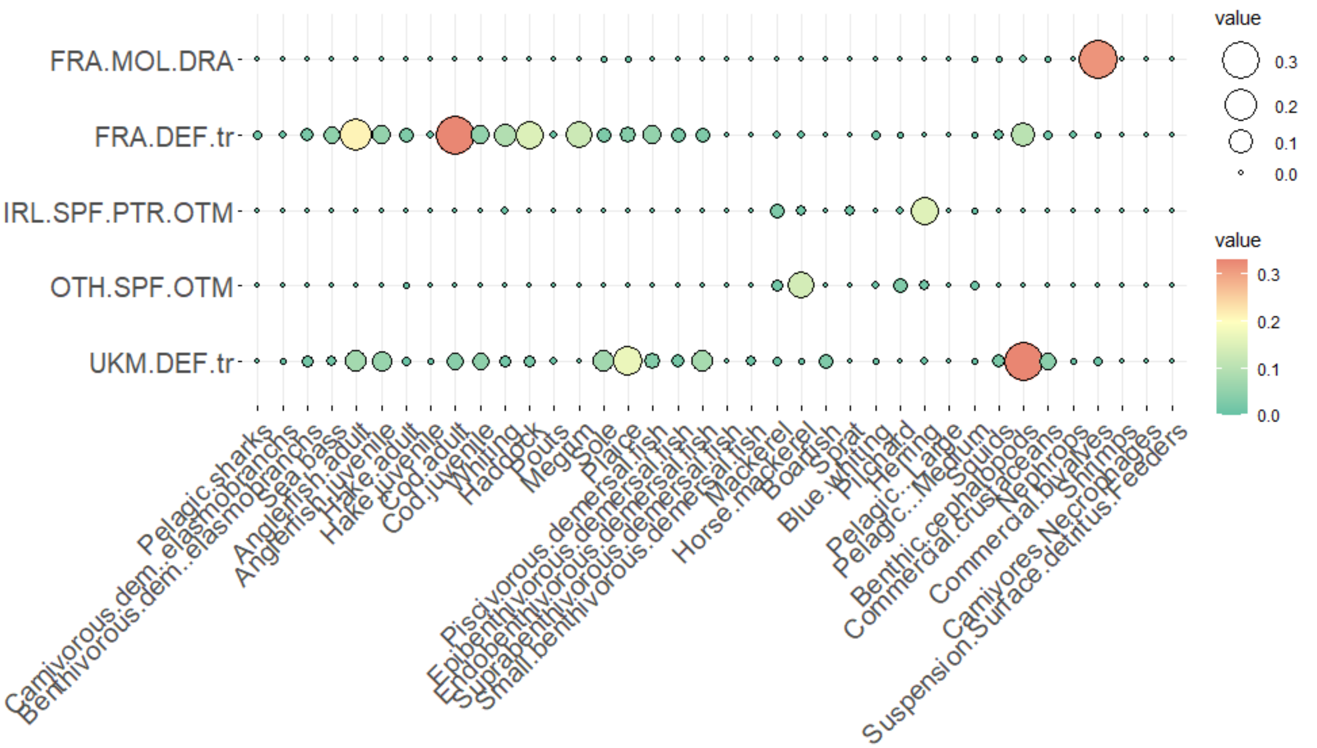

Figure 6.- Fishing losses in 2016 of five elected fleets

Two fleets induce high fishing mortalities for several functional groups: the French demersal trawl fleet and the United-Kingdom demersal trawl fleet which target demersal species with active gears (« FRA DEF tr » and « UKM DEF tr »). « FRA DEF tr » causes fishing mortalities close to 0.3 for cod (or 52% of the total fishing mortality for the stock), and close to 0.2 for anglerfish and haddock (or respectively 51% and 71% of the total fishing mortality for the stock) that are all species of high trophic level (trophic level between 4 and 5 except for haddock). « UKM DEF tr » causes fishing mortalities close to 0.3 for benthic cephalopods (44% of the total fishing mortality for the stock) and close to 0.2 for plaice (71% of the total fishing mortality for the stock). « FRA DEF tr » and « UKM DEF tr » have the highest overall group mortality (24 and 18% of the total mortality caused by the fleets). Those fleets also stand out from the point of view of fishing losses. FRA DEF tr generates large fishing losses, concentrated on high trophic levels (TLs > 4). It takes a large portion of the catch in relation to the production of megrim and cod (loss per fishery of 40% compared to the stock's production) and anglerfish (loss per fishery of 24% of the stock production). UKM DEF tr catches a lot of plaice and sole compared to the production of these two stocks (losses close to 40% and 20% respectively).

Other fleets have an important impact on species: « FRA MOL DRA », « IRL SPF PTR/OTM » and « OTH SPF OTM ». « FRA MOL DRA » concentrates its fishing mortality on commercial bivalves (mortality around 0.3 or 64% of the stock's total fishing mortality). This fleet do not appear to be catching much in terms of the production of the stocks fished. Two fleets targeting small pelagic fish generate high fishing losses but not high fishing mortalities: OTH SPF OTM which generate a high fishing loss of horse mackerel (close to 40%) and IRL SPF PTR/OTM which provoke a high fishing loss of herring (30%). Generally, the fleets with the highest impact in terms of removals relative to stock biomass are all active gear fleets (seines, trawls and dredges) and two of the fleets target demersal species.

2.2.2. Impact of fleets on functional groups and interactions between fleets through mixed trophic impacts analysis

The analysis of mixed trophic impacts shows that the impacts of each fleet on the functional groups are mostly direct and negative (*Appendix 12*). In fact, the MTI matrix is full of negative (or negligeable) values and the most visible negative values are logically at the intersection between a fleet and species that are directly targeted by this fleet. The same information is given as by the analysis of fishing mortality. On the other hand, the trophic impacts show that some fleets interact (*Appendix 13*). Main interactions (mixed trophic impact < -0.13) are detailed *table 4*.

Table 4.- Main interactions between fleets via the food web through mixed trophic impacts analysis

Impacting fleets	**Impacted fleets**	**Type of effect (direct/indirect)**	**Interpretation**
FRA SPF PS	UKM SPF GNT	direct	competition of fleets for sardine
FRA DEF tr	FRA CRU OTT/OTB	direct	competition of fleets for megrim
FRA MOL DRA	IRL MOL DRA, UKM MOL DRA	direct	competition of fleets for commercial bivalves
IRL CRU tr	UKM CRU OTT/OTB	direct	competition of fleets for nephrops
OTH SPF OTM	OTH LPF SEN FRA SPF OTM UKM SPF PTR/OTM	direct	competition of fleets for mackerel and horse mackerel
FRA DEF dorm FRA DEF tr UKM DEF dorm	UKM LPF lines	indirect	Impacting fleets catch large pelagic fish's preys (epibenthivorous and endobenthivorous demersal fish, benthic cephalopods and squids) and the impacted fleet catches large pelagic fish.

Main interactions between fleets in the Celtic Sea are due to direct competition for the species catch. The fleets of some countries may affect the fleets of other countries that target the same species, with the same type of gear or not. However, some fleets do have an impact on fleets from their own country. There is only one indirect interaction between fleets through the food web that is predominant: some fleets targeting demersal species have a negative impact on UKM LPF lines. This is due to the fact that these fleets fish the demersal and benthic preys of large pelagics, which are themselves fished by the UKM LPF lines fleet.

2.3. Temporal changes in the Celtic Sea ecosystem due to climate change and fishing management scenarios

2.3.1. The impact of climate change on the Celtic Sea

The status quo fishing scenario was combined with the three climatic scenarios to explore the effect of climate change on catches and on the ecosystem in the Celtic Sea (*figure 7*).

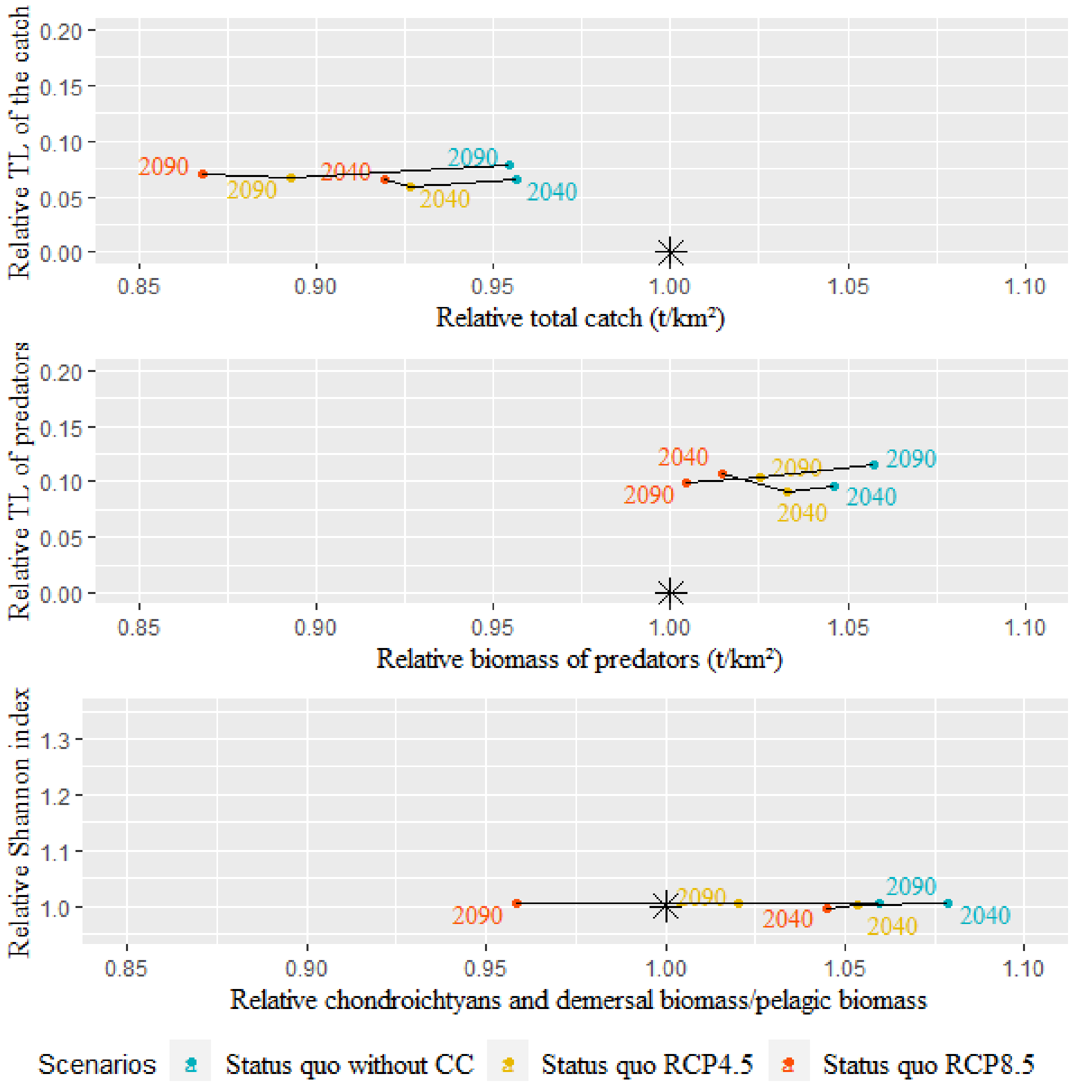

Figure 7.- Effect of climate change on: (top) catches and their TL; (middle) predator biomass and their TL; (bottom) Shannon diversity index and on the ratio of chondrichthyans and demersal biomass to pelagic. **Points labelled "2040" correspond to the 2040s. Idem for 2090. Points of different scenarios are linked by decade. The star-shaped point corresponds to the reference point (status quo without CC scenario over 2010-2016) for the indicators shown. The reference scenario for 2040s and 2090s corresponds to turquoise points.*

The first result to note is that even if nothing changes (status quo without CC) the ecosystem will continue to evolve, with decreasing catches (by about 5%) and increasing biomass (+5 %), while the mean trophic levels will increase. This results from the internal dynamic of the system, reaching slowly an equilibrium.

For a given decade (2040s or 2090s), CC leads to a decrease in total catch and biomass of predators compared to a scenario without CC. This decrease is even greater as climate change is accentuated (RCP8.5

scenario). The decrease in total catches is estimated around 4% for the 2040s and 8% for the 2090s. The main concerned functional groups are the following: medium pelagic fish, cod, plaice, shrimps and endobenthivorous demersal fish. This suggests that CC will have an impact on some fleets targeting those species. For example, the decrease in cod and endobenthivorous demersal fish catches will have an impact on demersal trawlers fleets (FRA DEF tr, IRL DEF tr and UKM DEF tr) and the drop of plaice catches will have an impact on UKM DEF dorm and demersal trawlers fleets which target those species. In the same way the decrease in medium pelagic fish catches will have an impact concentrated on FRA SPF PS which target sardine but catch medium pelagics.

The decrease in the biomass of predators is estimated at 3% for the 2040s and 5% for the 2090s. The main concerned functional groups are the following: plaice, cod, carnivorous demersal elasmobranch, sprat, large pelagic fish and endobenthivorous demersal fish. Climate change does not seem to have an effect on the TL of catches and predators nor on evenness but seems to cause a drop in the biomass ratio of chondrichthyans and demersal over pelagics (3% for the 2040s and 10% for the 2090s).

2.3.2. The impact of fishing management scenarios by species on the Celtic Sea ecosystem in the context of CC

Simulations outputs of some scenarios by species exhibit distinct global patterns (*figure 8*, detailed species fishing mortalities in *Appendix 14*, detailed results in *Appendix 15*). All the shown scenarios are combined with a RCP8.5 scenario except the reference scenario which is without climate change.

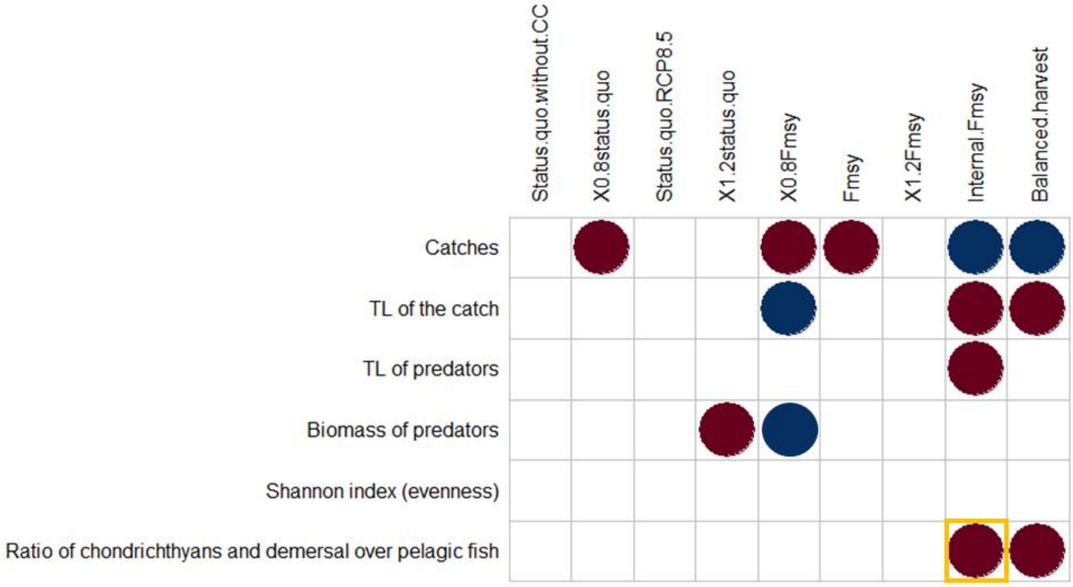

Figure 8.- Summary of simulations of scenarios by species **Indicators are in rows and scenarios by species in columns. A point indicates a positive (blue)/ negative (red) and significant (>10% or >0.05 TL unit) variation of the indicator compared to the status quo with climate change. A yellow border indicates that the indicator's value is significantly different (variation >10% or >0.03 TL unit) between 2040s and 2090s.*

The different fisheries management scenarios have different impacts on catches and their trophic level. The Fmsy scenarios induce small variations in the trophic level of catches compared to the status quo with climate change (RCP8.5). This suggests Fmsy target is not so far from the status quo situation except for some groups. In both Fmsy and status quo scenarios families, catches decrease compared to the status quo RCP8.5 except for the « 1.2xstatus quo» scenario. They decrease more for the Fmsy scenarios than for the status quo scenarios. The scenario with the greatest decline in catches is the « 0.8xFmsy » scenario, which leads to a decline in catches of around 20% compared to a status quo with climate change. The « internal Fmsy » and « balanced harvest » scenarios are very different from the others: they lead to an increase in catches (around 25% for internal Fmsy and 45% for balanced harvest compared to the status quo RCP8.5) and a decrease in their trophic level (a decrease of around 0.08 for the internal Fmsy scenarios and 0.3 for the balanced harvest compared to the status quo RCP8.5), which represents a significant decrease in the trophic level of catches.

At the same time, several scenarios allow for a small increase in predator biomass compared to the status quo with CC for 2040s and 2090s: all the scenarios except the « 1.2status quo » scenario allow for an increase in predator biomass, but only « 0.8Fmsy », « 0.8status quo » scenarios lead to a higher predator TL for 2040s and 2090s. “0.8Fmsy” scenario is the only scenario by species which represent a significant increase in the predator biomass (10% compared to the status quo with CC) due to the decrease in the fishing pressure. None of the scenarios represent a significant increase on the predator’s TL.

In terms of biodiversity, variations of the Shannon diversity index between scenarios are really small. The « 0.8Fmsy » and « Fmsy » scenarios are those that allow the Shannon index to increase or remain constant whatever the decade (2040s or 2090s) compared to the status quo with CC. The « 0.8Fmsy » scenario remain the best scenario in term of evenness in the ecosystem, and allow for an increase by 0.5% in diversity for 2040s and by 0.9% in diversity for 2090s compared to the status quo with CC. The « Fmsy » scenario does not allow for an increase in evenness for 2040s and 2090s compared to the status quo RCP8.5. Other scenarios are quite similar in terms of evenness in the ecosystem.

The value of the ratio of chondrichthyans and demersal biomass to pelagic biomass is generally lower for the « balanced harvest » and « internal Fmsy » scenarios, and are the only one which represent a decrease of the ratio compared to the status quo with CC, whatever the decade. They imply a significant variation of the biomass ratio. For the “internal Fmsy” scenario, this decrease is due to a drop in the hake biomass due to an increased fishing pressure on hake (fishing pressure in *Appendix 14*) and an increase in horse mackerel and mackerel biomasses due to a decreased fishing pressure compared to the status quo. For the “balanced harvest” scenario, the biomass ratio is lower than for the status quo because the fishing pressure on mackerel is drastically decreased

For some scenarios, indicators’ value differs between 2040s and 2090s. It is particularly the case for the « internal Fmsy » scenario where there is a decrease in the biomass ratio between 2040s and 2090s due to high fluctuations of some species (e.g., boarfish).

Thus, climate change causes a decrease in the predator biomass. The « 0.8Fmsy » management scenario in the context of climate change would allow for a significant increase in biomass of predators, increase that could compensate CC’s effects. It would also allow for a non-significant increase in the predator’s TL and in the biomass ratio even if CC do not seem to have an effect on these indicators.

2.3.3. The impact of fishing management scenarios by fleets on the Celtic Sea ecosystem in the context of CC

Simulations outputs of some scenarios by species exhibit distinct global patterns (*figure 9*, detailed species fishing mortalities in *Appendix 16*, detailed results in *Appendix 17*). All the shown scenarios are combined with a RCP8.5 scenario except the reference scenario which is without climate change.

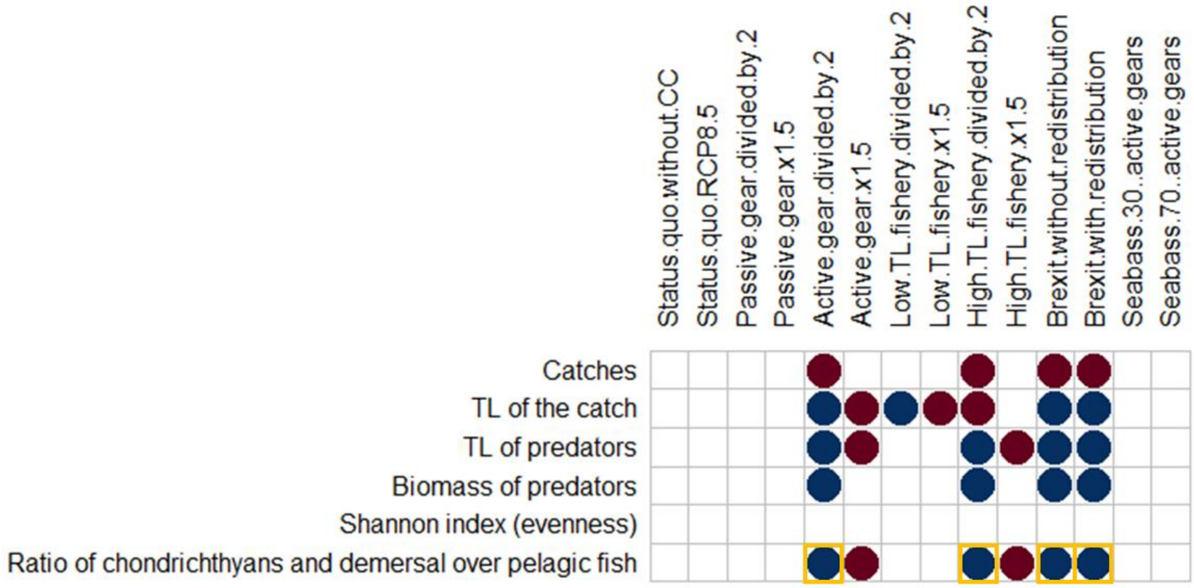

Figure 9.- Summary of simulations of scenarios by fleets **Indicators are in rows and scenarios by species in columns. A point indicates a positive (blue)/ negative (red) and significant (>20% or >0.05 TL unit) variation of the indicator compared to the status quo with climate change. A yellow border indicates that the indicator's value is significantly different (variation >10% or >0.03 TL unit) between 2040s and 2090s.*

The different fisheries management scenarios by fleet also have different impacts on catches and their trophic level. Some scenarios lead to strong variations in the trophic level of catches compared to the status quo with CC scenario. The mean TL of catch increases notably for the two « Brexit » scenarios where there is a closure of the British EEZ with or without effort redistribution. This suggests catches loss in the UK EEZ globally come from lower TL species (such as sardine, commercial bivalves and crustaceans). This is also the case for the scenario where the fishing effort of the fleets targeting low trophic levels is reduced (due to a decrease of catches of sardine, commercial bivalves, large crustaceans or horse mackerel) and for the scenario where the fishing effort of the active gear fleets is reduced (due to a decrease of catches of species of low trophic level partly targeted by active gears: sardine, nephrops, medium pelagic fish, herring and commercial bivalves). The other scenarios are quite similar to the status quo RCP8.5 scenario in terms of TL of the catch. In terms of total catches, the scenarios that stand out are the « Brexit » scenarios (decrease in catches of around 35 and 30% compared to the status quo RCP8.5 for 2040s and 2090s), « High TL fisheries /2 » and « Active gears /2 » (decrease in catches of around 30% compared to the status quo RCP8.5 for 2040s and 2090s). The other scenarios range from a 20% decrease in catches to a 10% increase compared to the status quo with CC.

At the same time, some scenarios allow for an increase in predator biomass due to the decrease in fishing mortality: the two « Brexit » scenarios (increase of 20% to 30% depending on the decade), the « high TL fisheries /2 » scenario (increase of around 17% for 2040s and 2090s) and the « active gears /2 » scenario (increase of around 15% for 2040s and 2090s). The scenarios where the effort of fleets targeting high trophic levels and the effort of the active gear's fleets are multiplied cause a decrease in the biomass of predators compared to the status quo with CC (decrease of about 15% for 2040s and 2090s for both scenarios). These scenarios, which stand out in terms of predator biomass, also stand out in terms of predator TL compared to the status quo with CC. The two « Brexit » scenarios, the « high TL fisheries /2 » scenario and the « active gears /2 » scenario result in an increase of between 0.08 and 0.10 TL units depending on the decade, and the « high TL fisheries x1.5 » and « active gears x 1.5 » scenarios result in a decrease of between 0.05 and 0.08 TL units depending on the decade and the scenario.

Finally, in terms of Shannon diversity index, variations between scenarios are again very small. Four scenarios are above the status quo RCP8.5 for both 2040s and 2090s: « Brexit » without redistribution, « Brexit » with redistribution, «High TL fisheries /2», «Active gears /2». The worst scenarios in terms of evenness for 2040s and 2090s are the two high catch scenarios: « high TL fisheries x1.5 » and « active gears x 1.5 » scenarios.

The value of the ratio of chondrichthyans and demersal biomass to pelagic biomass is similarly very different for the four low catch scenarios (value between 25 and 35% below the status quo scenario under the status quo RCP8.5 scenario) and for the two high catch scenarios (between 2 and 10% above the status quo RCP8.5 scenario). This suggest that these scenarios where the fishing pressure is reduced, allow for a biomass increase for certain demersal species (e.g., cod, sole and plaice biomasses for the four low catch scenarios)

For some scenarios, indicators' value differs between 2040s and 2090s. It is particularly the case for the « Brexit » scenarios, « high trophic level fishery /2 » and « Active gear fishery /2» scenarios where there is a decrease of the biomass ratio of chondrichthyans and demersal over pelagics between 2040s and 2090s due to some species fluctuation.

Thus, climate change causes a decrease in the predator biomass. Four management scenarios simulated would allow for a significant increase in biomass of predators in the context of climate change, increase that could compensate CC's effects: « Brexit » scenarios, « Active gears /2 » and « High trophic level fisheries /2 » scenarios.

Finally, results show that the effect of many fishing management scenarios (by species or by fleets) on the elected indicators is more important than the effect of climate change.

2.4. Spatial changes in the Celtic Sea ecosystem due to climate change and fishing management scenarios

2.4.1. Predicted predator biomass spatial changes in the Celtic Sea

Predator biomass distributions predicted by Ecospace models are shown *figure 10*.

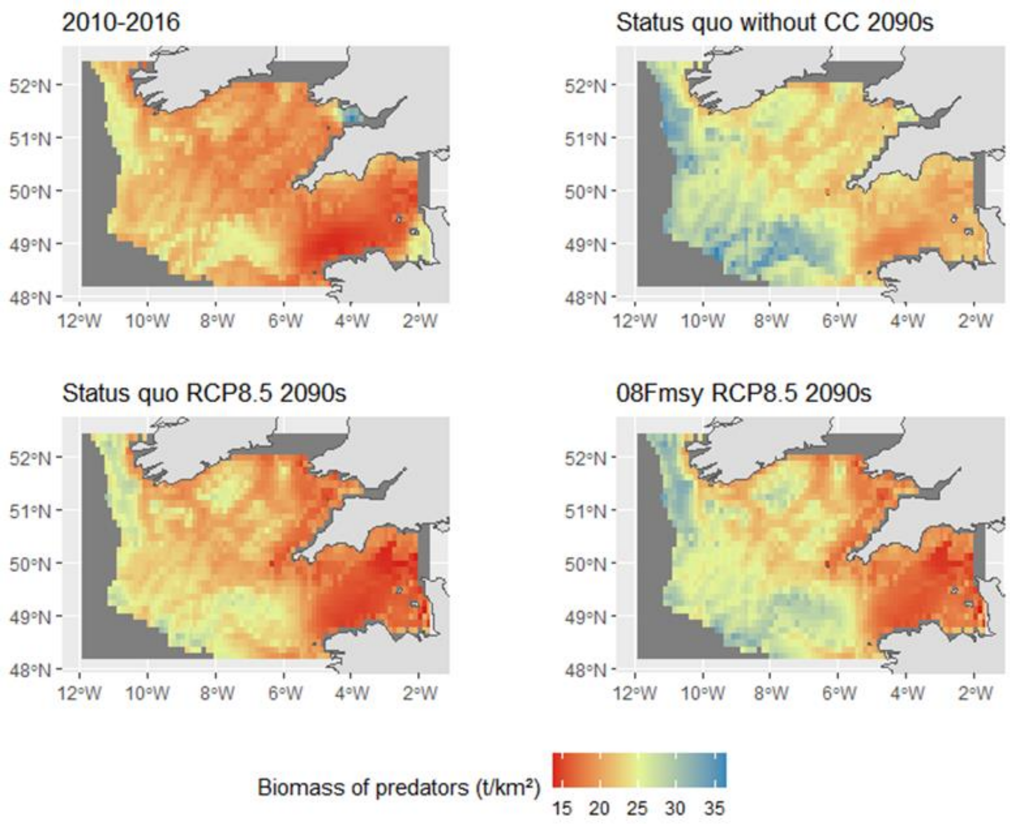

Figure 10.- Predicted predator biomass distributions

In the Celtic Sea, the predator biomass is heterogeneously distributed in space. There is a relatively low predator biomass especially in the Western Channel (area 7e) and the Bristol Channel (area 7f), although parts of these areas have a locally high predator biomass. The offshore areas close to the continental slope (areas 7h and 7j2) are more populated with predators. In a scenario with no change in climate and fisheries management, there is a general increase in biomass for 2090s, which is rather uniform across the Celtic Sea. The addition of a climate change effect (status quo scenario RCP8.5) seems to erase this visible increase between 2010-2016 and 2090s to restore a situation quite similar to that of the 2010-2016 period. The distribution of predators is slightly different, however, as some areas are slightly richer in biomass, such as the Southwest of Ireland and the Celtic South (zone 7h). Others seem to be poorer in predator biomass: the east of Bristol Channel and the east of Western English Channel, both of which were previously very rich in predator biomass. The adoption of fisheries management of 0.8Fmsy fishing mortality (0.8Fmsy RCP8.5 scenario) allow for a CC mitigation: there is a clear improvement in predator biomass in areas previously quite rich, but the increase is very slight in areas with low biomass such as the Western Channel and Bristol Channel which remain deficient compared to the status quo without CC for 2090s. Part of the biomass is restored but not all of it.

2.4.2. Predicted catches distribution in the Celtic Sea

Catches distributions predicted by Ecospace models are shown *figure 11*.

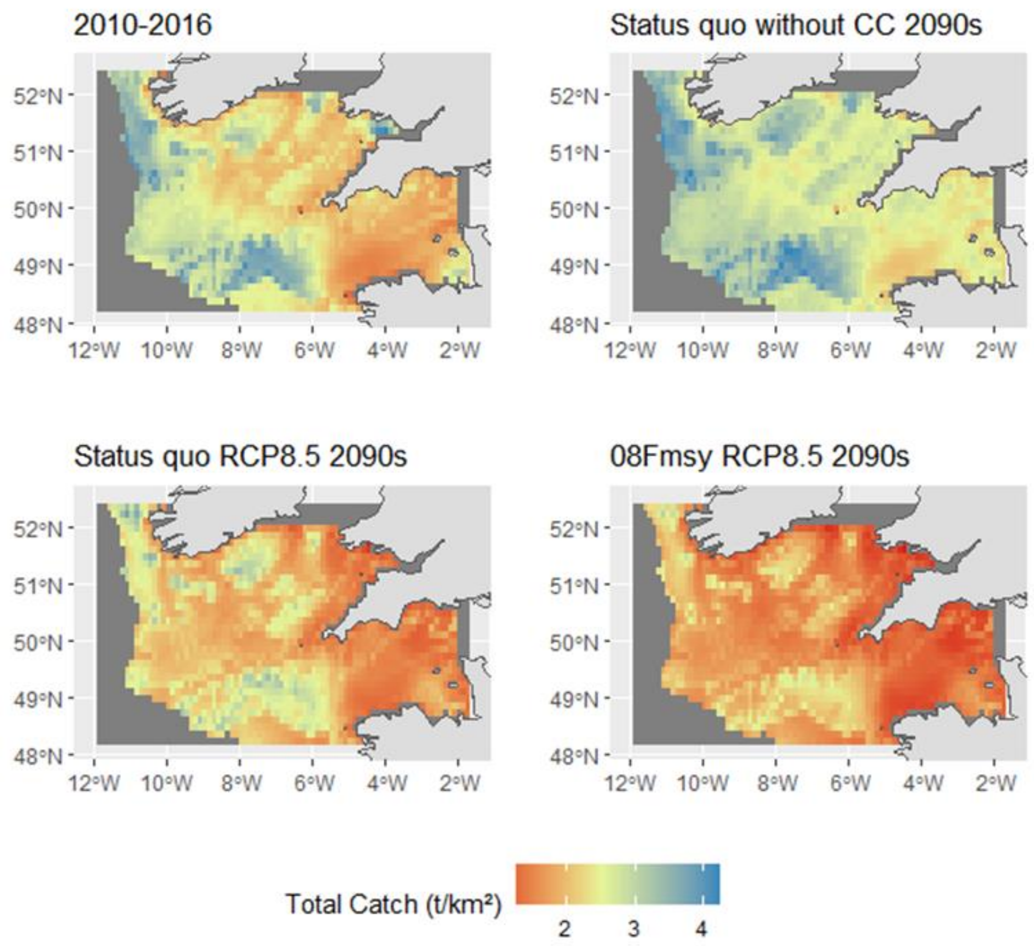

Figure 11.- Predicted catches distributions

In general, the distribution of catches seems to follow the distribution patterns of predator biomass. For the reference period, predator-rich areas have the highest catches in t/km². There is a general increase in total catches between 2010-2016 and 2090s, when average catches are quite high throughout the area. The addition of the CC causes a drastic decrease in catches across the whole area with the lowest catches in the Bristol Channel and the Western Channel. The adoption of a "0.8Fmsy" management measure appears to reduce total catches in addition to the effect of CC on catches.

3. Discussion

3.1. Definition of Celtic Sea fleets

3.1.1. Justification of the new approach

Usually, in Ecopath models, the definition of fleets is based on the aggregation of vessels considering several recurring variables: the country, the fishing gear, the type of fishery (demersal/pelagic) and sometimes the species harvested. For example, in Halouani *et al*. (2020), where an Ecopath model for the Bay of Seine is described, the 6 fleets are classified based on the fishing gear, the species and the targeted assemblage. In Bauer *et al.* (2018, 2019), where an Ecopath model for the Baltic Sea is defined, the 10 fleets are conventionally selected according to gear type (active demersal, passive demersal, pelagic) and vessel size. In the Celtic Sea models, theoretical single-specific fleets were considered in Moullec *et al*. (2017) or in Hernvann et al. (2020) while in Lauria et al. (2016) fleets where separated by country and gear . These choices do not fully capture the mixed fisheries of the Celtic Sea. In fact, if fisheries are to be managed not by monospecific quotas but by fleet so as to take into account the mixed fisheries issues (dependence between species catches) as it is thought in Gascuel *et al*. (2012), the fleets involved must have similar landing profiles. This justifies the new approach and the redefinition of fleets in the Ecopath model.

Typologies of fleets that are based on landing profiles already exist for the Celtic Sea, notably in Mateo *et al*. (2017) and Moore *et al*. (2019). However, these works have not been used because they are not based on data for all countries or species, which is essential for our study which concerns all Celtic Sea fisheries. In fact, Mateo *et al*. only concentrate on French landings data and Moore *et al.* only takes into account data on demersal species landings. Moreover, in both studies data are spatialized, which is not intended in this study.

In the end, the method has limitations since some classes are heterogeneous and these classes have large tonnages (e.g., cluster 10 of the HAC).

3.1.2. Quality of the clustering

The data used in the study are already an aggregation of many fishing operations, based on the species targeted which identification is not clearly defined. As the aim is to group vessels that have the same landings profiles, it would have been preferable for the clustering to work with a data set including fishing trip landings, that are more disaggregated, but such data are not publicly available at international level. The consequence of using such a dataset is that not groups of vessels but groups of fishing operations are used. Thus, the same fishing boat can be included in two different fleets if it practices two different métiers during the year, which is quite common. In the study it is assumed that fisheries management can act at the level of métiers rather than groups of vessels, whereas the current management is not by métier. Thus, the model does not seem to be adapted to a current fishing management by fleet where a certain fishing permit could be granted for each vessel.

The division of the 7 clusters into 10 clusters seems relevant as the cephalopod (cluster 2), Norway lobster (cluster 8), large pelagic (cluster 9) and mixed demersal trawl fisheries (cluster 10) are identified separately in the literature (Mateo et al. 2017, Moore et al. 2019) and as the grouping does not really make sense according to expert knowledge.

After the HAC, the 10 clusters obtained were redivided by creating sub-classes for each country. This empirical clustering by country is not justifiable from a statistical point of view (the country does not structure landing profiles enough) but it is done here because it is intended to run simulations of different fisheries management scenarios and that the country is an important management unit. This classification leads to have fleets that represent small landings. It is questionable whether it is appropriate to keep these fleets or whether it makes sense to group these fleets with others when they have few landings. However, these fleets are often targeting large pelagic fish, as large pelagic fisheries are not widespread in the Celtic Sea. Therefore, they cannot be removed from the model and grouping them with others would not necessarily make sense in term of fishery management.

3.1.3. Consistency of identified Celtic Sea fleets compared to previous studies

Our study reveals the complexity of highly mixed Celtic Sea fisheries and thus, the difficulty to manage fisheries in this area due to multiple gear types, countries and target species assemblages and due to the dependance between the catches of different species in the context of mixed fisheries. Like in other scientific work on the typology of fleets in the Celtic Sea (Mateo et al. 2017, Moore et al. 2019) working on landings data, it can be seen that certain variables are very structuring, particularly target species assemblage (Moore et al. 2019). Other variables have been used in those studies of typology, which are not taken into account in this study. Some of these variables were tested and found to be non-structuring with the dataset used. This is the case, for example, of the "vessel size" variable. Other variables were not included and were not tested because they were not thought to be structuring or considered redundant with the targeted-species criteria. This is the case of the “mesh size” variable, for example.

Compared to the typology of French Celtic Sea fleets carried out by Mateo *et al*. (2017) and to the typology of Celtic Sea fleets conducted by Moore *et al*. (2019), some fleets are clearly identified. The set net fishery cluster of Moore *et al*. is really similar to our first cluster of the HAC. There are both English and French fisheries targeting hake (FRA DEF dorm and UKM DEF dorm) and a mixture of demersal species of all kinds. The Irish mixed demersal Set Net fishery moreover corresponds to our IRL DEF GNT fleet. However, the Spanish fleet « ESP DEF lines » is not represented because Spanish data are not used in Moore *et al*. Within the bottom trawl fishing fleets, some resemblances are noticeable. Some similarities can be seen in the French and Irish fleets targeting Norway lobsters (the « FRA CRU OTT » and « IRL CRU tr » fleets from the 8th cluster): in both studies, nephrops directed fisheries are also identified as being mixed demersal fisheries because they also fish demersal species like megrim or cod. FRA CRU OTT also corresponds to one of Mateo *et al*. clusters. Among other bottom trawl fishing activities, French and English mollusk and cephalopod fisheries (FRA MOL OTB and UKM MOL OTB/OTT), the Irish whiting directed fishery (IRL DEF tr), the English flatfish fishery (UKM DEF tr) and the numerous mixed demersal fisheries are consistent with Moore *et al*. study.

However, compared to Mateo *et al.* study, large and small pelagic fisheries are more numerous and this difference is due to the difference in the dataset used. For example, FRA SPF OTM is also identified in Mateo *et al*. but sardine seine fisheries (cluster 4 of our HAC) are not. Moreover, some of the fleets in our study seem to combine several fleets into one. As an example, English pollack directed set net fishery and English hake directed set net fisheries of Moore *et al*. are grouped in the FRA DEF dorm fleet. This may be because the landing profiles used to define the fleets are those of the functional groups and not those of the species and also because data are not as precise as in Moore *et al* that only takes into account demersal fisheries. As a consequence, the study method leads to a more detailed view of small and large pelagic and shellfish fisheries, whereas demersal fisheries are by far the most important in the Celtic Sea in terms of landings. This explains why some fleets targeting demersal species concentrate a large tonnage in terms of landings (particularly FRA DEF tr and UKM DEF tr).

3.2. Quality and consistency of temporal simulations

3.2.1. Predictive capacity of the model

A critical analysis of the predictive capacity of the model has been done by Hernvann *et al* (2020) and there is nothing to complement this work in this study. More information on the model's predictive capacity can thus be found in Hernvann *et al*.

The simulations carried out allow a number of indicators to be predicted for each scenario. The estimation of these indicators should be viewed with caution because the model takes time to stabilize. In fact, fishing pressure is applied from 2016 onwards and the estimate of the indicators is not immediately stabilized. The evolution of indicators over time (*Appendix 18 and 19*) for some scenarios shows that for both catches and predator biomass, for each of the scenarios, the model is not stabilized before 2040, but it does reach stabilization by this time for all scenarios. Thus, no temporal evolution of the indicators can be analyzed between 2016 and 2040. From a fisheries management perspective, this means that the model does not allow for testing potential management measures in the short term but rather in the long term, while current fisheries management policies are more short term than long term.

In this study, the introduction of new species due to climate change is not taken into account as in Hernvann (2020). It could be interesting to modify the model to integrate this issue in the study.

3.2.2. Scenario definition

The scenarios carried out in the study are more or less realistic. For example, the consistency of the Fmsy scenario (with “external Fmsy” that are from stock assessments) should be discussed because Fmsy is not applied to functional groups that are quite exploited and for the conservation of those species can also imply other management policies. This is the case for piscivorous demersal fish (e.g., ling, conger eel, pollack...) which are exploited at a fishing mortality of 0.21 at status quo. Among all the exploited groups, only 14 groups have stock assessment's Fmsy, and so have a management rule applied in our external "Fmsy" scenario. Although it is not a high ratio, these external Fmsy scenarios still correspond to a management reality since we are not going to manage species with Fmsy which cannot be estimated. It is also questionable whether it is appropriate to include stock assessment's Fmsy, since the latter use single-species models and in which the working assumptions are quite different. It can also be noticed that scientific advices are currently provided and TACs are implemented for some of the non-assessed species considered in the model, especially based on data-limited rules defined by ICES. Such types of management were not considered in our simulations.

This supports the inclusion of an "internal Fmsy" scenario that uses Fmsy estimated by the ecosystem model and includes Fmsy for all the functional groups that are significantly exploited (fishing mortality > 0.1 at status quo).

Concerning the consistency of the Brexit scenarios, they are first of all very theoretical, since agreements are currently planned so that European vessels can continue fishing in the British EEZ. These scenarios are therefore extreme, as are the other scenarios by fleet. Furthermore, the rule used to reduce the effort of the European fleets in the area could be improved by spatializing the effort of the fleets. For example, for some fleets that are highly impacted by the Brexit, such as FRA MOL FPO (reduced effort proportion in *Appendix 20*), the vessels are mainly small (size < 12m; *Appendix 21*) and will not be able to cross the Channel to fish in the United Kingdom EEZ. A finer rule should therefore be applied to these fleets.

On the other hand, both families of scenarios have flaws. The scenarios by species are not completely realistic in the sense that the fleets will not totally adapt to the establishment of a fishing pressure by species and will inevitably make some additional discards due to mixed fisheries. On the other hand, the scenarios by fleet are more realistic in theory, because they allow taking into account this dependence between the catches of the species fished within the same mixed fishery, while in practice they do no relate to the current management tools used in the frame of the Common Fisheries Policy. In addition, they do not allow the optimization of an ecosystem parameter (e.g., biodiversity, stock recovery). This could be done by using the "Fishing policy optimization" routine of the EwE software used for example in Christensen & Walters (2004) for the Gulf of Thailand area or in Natugonza *et al*. (2020) for Lake Victoria. Finally, the way the model is built does not allow for scenarios by fleet where we can more fully explore the impact of these scenarios on the catches by fleet because the model is currently forced with fishing mortalities applied to the functional groups, and not with fishing efforts by fleet. Moving to fleet effort forcing would allow to go further in our approach but requires to modify the Ecosim model and to recalibrate the model.

3.2.3. Consistency and robustness of results

Analyzing the results of simulations for the three climatic scenarios combined with the status quo fishing management scenario, it can be seen that results are consistent with the literature. In Hernvann *et al*. (2020), where status quo scenarios are combined with the RCP4.5 and RCP8.5 scenarios, climate change causes a diminution of catches (if we compare the RCP4.5 and the RCP8.5 scenarios) and a decrease in the predator biomass with TLs greater or equal to 4, included in the indicator « biomass of predators with TL >3.25 ». Our study reveals the same changes in the ecosystem but as the elected indicators are different from the ones of Hernvann *et al.*, there is no further possible comparison between both studies.

Analyzing the results of simulations for the fishing management scenarios by species, we can see that Fmsy scenarios allow to maintain a quite healthy ecosystem in terms of biodiversity (evenness), biomass and trophic level of predators and relative composition of the ecosystem (ratio of chondrichthyans and demersal over pelagic fish). Decreasing the fishing mortality by 20% compared to the Fmsy («0.8Fmsy») and the status quo («0.8Status quo») and the adoption of the Fmsy for exploited species («Fmsy» scenario) are the best options among scenarios by species. On the contrary, the « Internal Fmsy » and the « balanced harvest » scenarios have a huge (negative) impact on some indicators of good health (Shannon index and ratio of chondrichthyans and demersal biomass over pelagic biomass) whereas « balanced harvest » strategy is considered as being a good strategy that allow for conserving size-structure and composition in the ecosystem (Garcia et al. 2012; Law et al. 2015). This theory is yet not unanimously supported as Froese *et al*. (2016) suggest that empirical evidence of the efficiency of the balanced harvest strategy is lacking and that exploiting resilient species with moderation is still the better solution. Moreover, Froese *et al*. suggest that the « balanced harvest » strategy is not possible because human will never develop large zooplankton fisheries.

In addition, « Internal Fmsy » scenario has a huge impact on the ecosystem health because values of internal Fmsy are questionable. Some Fmsy are of the same order of magnitude as the stock assessment's Fmsy (e.g., sole, plaice or cod) but others are very high. For example, the Fmsy estimated by the routine for whiting is 1.99 and that of monkfish is 1.46. Those high values and unrealistic of Fmsy reveals structural or parametrization issues of certain groups within the model. In fact, a group which has a high Fmsy in the routine, is a more productive group than it actually is, so a group that may have high natural or predation mortality. For example, in the case of whiting, the predation mortality is 0.75, which is too high for a species that is not a forage species. These problems of high mortalities could come from a misestimations in the diet matrix. In the case of whiting, this flaw could be solved by creating a multi-stanza group for the species because adults are not too predated generally whereas juveniles are more predated and "forage". Separating adults and juveniles could allow to have two different parametrizations for two groups that have different biological properties (diets, productivity, predation...). The software routine is sometimes used in rare papers (e.g., with the EwE model for the Irish Sea: Bentley et al. 2020) but in general, few publications are interested in it. Perhaps it is simply not possible to use this type of model to estimate Fmsy because it is not designed for this purpose, and this routine should be a validation criterion of the model rather than an output. Perhaps, those high values of Fmsy reveals structural issues in the model.

Analyzing the results of simulations for the fishing management scenarios by fleets, four scenarios allow to maintain a healthy ecosystem in terms of biodiversity (evenness), biomass and trophic level of predators and relative composition of the ecosystem (ratio of chondrichthyans and demersal over pelagic fish) because they correspond to scenarios where fishing pressure is quite decreased compared to the status quo. It would appear that decreasing the fishing pressure on high trophic levels and decreasing the use of active gears would improve the ecosystem health. This is consistent with the expected result because active gears fleets are responsible of high catches and discards compared to passive ones in the model. In the literature, it is stated that active gears are in fact more impacting due to large discards (Davies et al. 2009, Zeller et al. 2018). This is consistent with our results but it is also said that active gears are quite impacting because of their impact on the seabed (Chuenpagdee et al. 2003, Collie et al. 2017), a process that is not considered in Ecopath. Moreover, high trophic level fisheries were also expected to be impacting because they are doing high catches because many fleets are targeting high trophic levels (25 fleets over 34) and because the fleets that have the highest catches target high trophic levels such as FRA DEF tr whose mean catch TL is around 4.1 or UKM DEF tr whose mean catch TL is around 3.8. In the literature, fishing top predators affect the ecosystem stability (Nye et al. 2013) by reducing the length of the trophic chain (Allesina & Tang 2012), and by removing the control by predators (top-down control), which is consistent with our results.

The results of scenarios by fleets seem to show that if catches are to be increased without too much impact on the ecosystem, the solution would be to increase catches of low trophic level species and decrease fishing pressure on high trophic levels. This is not the right solution according to our "balanced harvest" scenario that show a huge impact on health indicators. According to Smith *et al.* (2011) fishing low trophic levels and notably small pelagic fish could have a huge impact on the ecosystem depending on the abundance of those pelagic fish and according to their connectance (the proportion of connections that they represent in the food web). Yet, according to Merillet *et al*. (2021), some small pelagics (sprat, sardine, horse mackerel and herring) have a high connectance in the Celtic Sea and their removal could lead to “the lowest robustness” of the food web. Moreover, in Pikitch *et al*. (2014) and Wiley *et al*. (2013) it appears that many predators are strongly dependent on those pelagic fish, particularly seabirds. In the Celtic Sea, seabirds, some elasmobranch functional groups and some demersal groups are in fact quite dependent of pelagic fish due to their diet (they notably eat many mackerels and horse mackerels). If our study does not clearly reveal these impacts, this is due to the definition of “High VS low TL” scenarios where a high trophic level is greater than 3.25. Redefining the limit, we could probably capture this phenomenon. Nowadays, the convention TL which separate small pelagics to predators is 3.5 (it was 3.25 before). Separating at 3.5 will probably let some small pelagics in the group of predators (e.g., blue whiting: TL around 3.7) and setting the limit to 3.7 will let some predatory fish in the group of non-predators (e.g., sole and plaice: TL around 3.4). It is also possible that we capture this phenomenon less efficiently due to the poorer definition of the low trophic level groups in the model (which is characteristic of ecosystem models).

Concerning other scenarios, it is clear that a United Kingdom’s EEZ closure would imply a huge decrease in catches and thus, an ecosystem in better health. By varying the proportion of active gears targeting a species, at equal fishing pressure, it would appear that there are only slight differences in the ecosystem macro indicators. However, due to mixed fisheries, varying this proportion imply variations in biomass of other species. For example, in “seabass” scenarios, dropping active gears compared to passive ones leads to a slight decrease of diversity and relative composition of the ecosystem (biomass ratio of chondrichthyans and demersal over pelagic fish; *Appendix 17*) but leads to a huge decrease of both plaice and cod biomass and catches (*Appendix 22 and 23*) due to demersal mixed fisheries caused by trawlers (“FRA DEF tr” and “UKM DEF tr”).

In the frame of an important CC (RCP8.5) for 2090s, a loss of 8% of catches and a loss of 5% of predator biomass is intended compared to a situation without CC. Among scenarios by species, Fmsy scenario represent an additional moderate catch loss compared to the status quo with CC (below 10%) but allow to increase the biomass of predators by 8% compared to the status quo with CC. Thus, it would allow to have a moderate catch loss, to compensate the loss of predator biomass and to maintain a relatively good ecosystem health in terms of evenness and structure. Nevertheless, the 0.8 Fmsy scenario would be more appropriate for the ecological maintenance of the ecosystem and a predator biomass recovery. Among scenarios by fleet, results show that the management lever to keep a certain ecosystem health and to increase the predator biomass to compensate CC’s effects are fleets which fish with active gears and fleets which target high trophic levels. The scenarios elected that reduce fishing effort of those fleets are too extreme and cause a severe loss of catches (-25% of catches). A solution to preserve ecosystem health while maintaining catches would be an intermediate fishing effort for those two fleet’s types, lower than currently but not divided by two as it is shown in the study.

3.2.4. Relevance of the elected indicators

The elected indicators allow us to have an idea of the consequences of each adopted fishing measure and each climate change scenario on catches and on the ecosystem. If we compare the choice of these indicators with the indicators of the European Marine Strategy Framework Directive (MSFD; 2008/56/EC), which defines indicators for a "Good Ecosystem Status" of marine ecosystems, indicators are found that go in the same direction. Large fish (top predators) are clearly an issue in the MSFD following the descriptor number 4 (D4) of a good ecosystem status: “All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity”. Predator biomass can be linked with the criterion 3 (C3) of D4: “Abundance trends of functionally important selected group/species”.

In the frame of the IndiSeas scientific working group, which aim at selecting different indicators to evaluate the impact of fishing on marine ecosystems’ health and functioning, those indicators of ecosystem predator's health are also ubiquitous even if predator's biomass is rather viewed in a relative way to the rest of the ecosystem (Shin & Shannon 2010, Coll et al. 2016). According to the selection criteria of a good indicator defined by Shin and Shannon (2010) and Rice and Rochet (2005), TL of predators and predator's biomass are good indicators: they are sensitive to fishing, measurable, understandable (to raise public awareness) and have an ecological significance.

Concerning the Shannon diversity index, it echoes the descriptor number 1 (D1) of the MSFD which states: « Biological diversity is conserved. The quality and number of habitats and the distribution and abundance of species are adapted to the existing physiographic, geographic and climatic conditions ». The interest of this indicator is that it does not only concern top predators but also other important elements in the ecosystem such as small pelagics or invertebrates. It is also the case for the biomass ratio of chondrichthyans and demersal over pelagic fish, which is interesting because it is an indicator of a certain balance preserved in the ecosystem. These indicators are perhaps less understandable from the perspective of the "public awareness" criterion of Rice and Rochet (2005) and Shin and Shannon (2010). Shannon index does not appear to be very sensitive to fishing in the study considering the small changes in the indicator. This issue is also mentioned in Shin and Shannon (2010). Additionally, it is difficult to analyze changes in this indicator. However, this issue is common for indicators of this type. Shannon is elected here because it is easy to calculate in Ecosim but we could also have chosen indicators of diversity and conservation selected by Shin *et al*. such as the intrinsic vulnerability of functional groups. Nevertheless, it would have been biased due to the structure in functional groups.

3.3. Quality and consistency of spatial simulations

3.3.1. Heterogeneity of predator biomass distribution in space and between scenarios

Simulated predator biomass appears low in several areas including the Western Channel (7e) and the Bristol Channel (7f), which are coastal areas of depth between 50 and 100 m (Celtic Sea map, *figure 1*). Predicted biomass of predators are higher in the Southwest Ireland (7j2) and in the Celtic South (7h), which are in contrast deeper areas closer to the continental slope than areas 7f and 7e. These areas are also areas where primary production is lower (*Appendix 5*).

Results also show that areas of low predator biomass seem to be more impacted by CC because the decrease in biomass in these zones is slightly larger. Although the adoption of a "0.8Fmsy" fishery management would partially restore the biomass of predators in some part of the Celtic Sea (7j2 and 7h in particular), such a management rule would not compensate for the effects of climate change in the Western Channel and the Bristol Channel. Two main processes can explain this loss of predator biomass due to CC:

- Firstly, some species drop off a lot on the coast and little near the continental slope and these coastal species are responsible for large changes in biomass. This decrease is due either to a more important decrease in food availability to the coast or to a more important increase in temperature to the coast (Hernvann 2020) that affect habitat capacity of species. For example, a functional group that is responsible for predator biomass decrease near the coast is the group of "epibenthivorous demersal fish" (such as gurnards or mullets; group distributions in *Appendix 24*). This functional group mainly feed on "carnivores and necrophages", on the "suprabenthos" and on the "large mesozooplankton". However, there is no drastic decrease in the biomass of those prey groups due to CC (distributions of group's preys in *Appendix 25*) while coastal habitat capacity of epibenthivorous demersal fish show a lower habitat capacity with CC than without CC (group's habitat capacities in *Appendix 26*). Moreover, habitat capacity maps are built thanks to generalized habitat models (GAM; Hernvann et al. 2020) and the sea bottom temperature variable is included to build the model. So, in the case of epibenthivorous demersals, the decrease is due to a more important decrease in coastal sea bottom temperature (SBT). It is actually the same case for endobenthivorous demersal fish, another functional group that is decreasing due to CC near the coast. Those two functional groups' response function (functional responses in *Appendix 2 and 3*) show in fact a decrease in density in response to the decrease in sea bottom temperature from 12°C (mean SBT without CC) TO 13°C (mean SBT with a RCP8.5 CC scenario). Those species are thus boreal species, that prefer cold waters (Dinter 2001, Hernvann et al. 2020).

– Secondly, some species biomass are increasing near the continental slope, in deeper areas. This increase allows to compensate biomass loss near the continental slope but not near the coast. This is the case of boarfish for example (boarfish distributions in *Appendix 27*). In the case of boarfish, this increase is due to an increase in the food availability of the preys, as boarfish mainly feed on "Large mesozooplankton" (66% of the boarfish diet) and that large mesozooplankton biomass increase (mesozooplankton distributions in *Appendix 28*)

3.3.2. Investigating the realism of effort and catches distribution predictions in Ecospace

It is necessary to question the realism of the distribution of effort by Ecospace. To investigate this realism, effort multiplier maps by fleet cluster provided by EwE over 2010-2016 are shown in *Appendix 29* and FDI database catches by cluster and statistical rectangle (over 2015-2016) are shown in *Appendix 30*. The comparison between maps is difficult since the resolution and the variable are not the same: Ecospace has a better definition than FDI data which are at the statistical rectangle scale and Ecospace allow to build fleet effort maps rather than catches maps by fleet. However, these maps allow for a preliminary comparison.

It appears that spatialized catches of the FDI database and Ecospace effort distribution by fleet can be very different for some clusters. Only effort distribution of cluster 8 seems to be very similar to the distribution of catches of the FDI data base. This unrealistic distribution of efforts by Ecospace can be due to two facts. Firstly, in Ecospace, efforts by fleet are distributed following a gravity model (Walters 1999, Romagnoni et al. 2015): for each Ecospace cell the gravity model calculates an attractiveness of the cell for a fleet depending on several parameters. These parameters include: biomass of species fished, partial fishing mortality by fleet and species and fishing costs. However, depending on how the model is set up (here, all Ecospace fleet parameters are set to default), the attractiveness of cells is just a linear combination of the level of biomass of caught species and the associated fishing mortality. Thus, the effort distribution of a fleet is determined by the biomass distribution of the main fished species, whereas in the reality other parameters can influence fishing effort. For example, fishing costs are quite important because they determine the fleet's profit and the perception of profit can also vary according the fisherman and influence the effort distribution. However, those parameters are not taken into account. It is said in Romagnoni *et al*. (2015) that the model sensitivity to the profit perception of fishermen can be high, and that this parameter is often a parameter "neglected" by Ecospace modelers. Considering this parameter and spatialized sailing costs would certainly improve the realism of the effort distribution and thus catch distribution (as effort distribution by fleet determine catches distribution).

The other element that could lead to an unrealistic Ecospace distribution of the effort is the generalized additive models (GAM) used to calculate species habitat capacity (predicted habitat) and thus the species distribution. In fact, as effort distribution is led by biomass distribution of the main species fished, if the predictive capacity of the generalized species habitat model is moderate, the effort distribution quality will also be moderate. Thus, both GAM models and the gravity model can affect the realism of fleet effort distribution by Ecospace.

Cluster 8 (nephrops fisheries) seem to be the only one that present low differences between FDI catches distribution and Ecospace effort distribution. The model thus has a good capacity to predict effort distribution of cluster 8. Moreover, the effort distribution of the cluster 8 is also consistent with catches distribution of Mateo et al. (2017). Some clusters are probably concerned by the quality of GAM models because GAM models' predictive capacity is lower when the functional group is composed of different species and because the main groups fished by those clusters are multispecies functional groups: it implies clusters 2, 5, 6, 7, 10. However, habitat capacities of those groups (habitat capacities of main fished functional groups by cluster in *Appendix 31*) seem to be quite realistic and consistent with the literature. For example, cluster 2 is mainly composed of *Sepia officinalis* and this species live between 0 and 200m and cluster 6 is mainly composed of lobsters and the habitat capacity of lobsters of cluster 8 is really similar to that of cluster 6. For cluster 5, there is maybe a more important issue due to GAM models because the main species fished are commercial crustaceans but within this group the main species is *Cancer pagurus* and this species is supposed to live mainly between 6 and 40m (FAO). However, the habitat capacity calculated is greater in zones deeper than 100m (*Appendix 31*). Cluster 9 is certainly the best example of group that is not well distributed (biomass distributions of main fished species by cluster in *Appendix 32*): large pelagic fish, the main group fished, have the highest biomasses in two coastal areas whereas they are not supposed to be so numerous near the coast. This is due to the fact there is no habitat capacity entered in Ecospace for the group because large pelagics frequent the area only very temporarily, so it is difficult to calculate a habitat capacity for this group due to low occurrences.

For some clusters the simple gravity model we uses appears not sufficient to explain the distribution of fishing effort. This is clearly the case for clusters 3, 5 and 10 where FDI catches are greater at the coast than near the biomass peaks, revealing the failing to take into account sailing costs. For example, high biomasses of mackerel are situated in the Celtic South (zone 7.h), off shore near Ireland (in the north of the 7.j zone) while high FDI catches are situated at the coast of those places because sailing costs are lower there. For some other clusters, such as clusters 2, 4, 6, and 7, the quality of the gravity model outputs are not so good because clusters are composed of French and United Kingdom fleets (and sometimes Irish fleets), each fishing near their own coast, also revealing the failure to take into account fishing costs. For example, cluster 7 is composed of a French (FRA MOL DRA), an Irish fleet (IRL MOL DRA) and a United Kingdom's fleet (UKM MOL DRA) which are fishing near their coast because sailing costs are greater off shore.

Cluster 1 is quite different than the others because GAM model do not appear to be the main problem even if the distribution of the hake's (the main species fished) biomass seems to be coastal, whereas hake is not a particularly coastal species (habitat capacities in *Appendix 31*). In fact, this could reveal a problem in the diet matrix where hake is eating sprats, a coastal species whereas hake is not coastal at all. This induces a change in hake biomass distribution compared to hake's habitat capacity (correctly predicted by the GAM model).

The following table tries to summarize the main modeling issues in Ecospace for each cluster.

Table 5.- Main modeling issues in Ecospace by clusters

Clusters	**Main fished group**	**Low/ High differences between FDI catches and Ecospace effort distributions**	**Main issue**
1	Hake	High	Diet matrix
2	Benthic cephalopods	High	Gravity model due to the failure to take into account fishing costs and due to the fleet's constitution
3	Mackerel	High	Gravity model due to the failure to take into account fishing costs
4	Sardine	High	Gravity model due to the failure to take into account fishing costs and due to the fleet's constitution
5	Commercial crustaceans	High	Gravity model due to the failure to take into account fishing costs

6	Carnivores and scavengers	High	Gravity model due to the failure to take into account fishing costs and due to the fleet's constitution
7	Commercial bivalves	High	Gravity model due to the failure to take into account fishing costs and due to the fleet's constitution, GAM
8	Norway lobster	Low	/
9	Large pelagics	High	GAM
10	Piscivorous demersal fish	High	Gravity model due to the failure to take into account fishing costs

3.3.2. Quality of the method for the extraction of average indicator maps

Compared to Ecosim, the method used with Ecospace seems to predict different indicator's values. In fact, when indicators' value by cells are averaged, the global indicator values are not exactly the same as predicted in Ecosim, even if the order of magnitude remains the same. This method used to produce average indicators by cell for a given period is the same as that used in Hernvann (2020). This method is biased as it requires several Ecopath models to be extracted for different time periods, and each of them to be balanced. Nevertheless, the bias is moderate and likely the same for all models, as the models have been balanced in the same way as much as possible.

A spin up period of 100 years was chosen to run the Ecospace models. At the beginning of the Ecospace simulations, as in Ecosim, the model takes some time to react to the forcing data (relative biomass curves simulated by Ecospace in *Appendix 33*). The model seems to start being quite stable after about 65 years, so after 100 years it really seems to be stabilized. We could decrease this spin-up period by adapting Ecospace parameters set to default regulating the speed of convergence but those parameters were not explored in the study.

3.3.3. Data quality

The mean environmental conditions used for each period are predictions from the POLSCOM-ERSEM model. However, as the POLSCOM-ERSEM model does not provide predictions for the period 2010-2016, the average conditions were assumed to be similar to the 2000-2005 predictions available from the POLSCOM-ERSEM model. Satellite primary production distribution data for 2010-2016 could have been used, thus providing observed data and not predictions. However, using observed data for 2010-2016 and using predictions for 2090s would have caused a bias as there is a gap between these two types of data for the historical period. Thus, it was decided to keep predictions of POLSCOM-ERSEM for each period.

Conclusion

Using multivariate statistical analysis followed by clustering (HAC and empirical clustering) based on international landings data (FDI data base), this study enabled the establishment of fairly representative fleets of the Celtic Sea fisheries, in order to improve a pre-existing Ecopath with Ecosim model. Even if the method is uncommon in Ecopath modeling, and that it leads to heterogeneous fleets with very large tonnages (which has an impact on the study's results), it enables the definition of fleets having the same landings profiles and thus a reflection on fisheries management by fleet within the framework of Celtic Sea mixed fisheries. It especially helps to identify fleets that have a particularly high impact on exploited resources and the ecosystem (French and UK active gear fleets targeting demersal species).

With the resulting modified model, it was possible to run various simulations of CC and fisheries management scenarios and thus to explore the impact of Celtic Sea mixed fisheries on the ecosystem under climate change by calculating catch-based or ecosystem indicators. The results show that while climate change is expected to have negative effects on predator biomass and catches in the Celtic Sea, fisheries management can induce greater changes in the ecosystem. The study shows that if stock-based management are maintained, ecosystem health can take different trajectories. The "balanced harvest" target, by increasing catches and decreasing their trophic level, would result in a worsening of several ecosystem indicators (significant worsening for the biomass ratio). On the contrary, the "Fmsy" and "0.8Fmsy" targets would appear to be better targets, as they would allow an improvement in the health of the ecosystem, although these two scenarios would lead to a fairly strong decrease in catches in the Celtic Sea. The "0.8Fmsy" strategy could be a strategy to compensate for the effects of climate change on predator biomass, although it would not restore the status quo biomass level without climate change in all areas of the Celtic Sea.

However, as single species quotas are not in accordance with a more ecosystem-based approach to fisheries, the study focuses on alternative management of fisheries based on fleets, which would be more appropriate due to the dependence between catches of the species fished. It reveals that certain fleets (fleets targeting high trophic levels and active gear fleets) could be a lever for management. However, these results are very dependent on the ecosystem indicators chosen and could be different if other indicators were considered.

Finally, this study reveals some structural problems within the model (e.g., related to the establishment of diet matrices, the internal Fmsy estimates, or the construction of habitat models for functional groups, etc.) but also some possible improvements to increase the predictive capacity of the model (improvement of the parameters concerning the fleets in Ecospace, etc.). Finally, this study provides an initial insight into the impact of Celtic Sea mixed fisheries fleets on the ecosystem in the context of climate change. In a next step, reanalyzing the above-mentioned points and including fishing effort series in the model, instead of forcing fishing mortality series by species, it will be possible to go further and to simulate more realistic fleet-based management scenarios, as a key tools to make operational an ecosystem approach of fisheries management in the context of climate change.

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Annexes

Appendix 1.- Composition of functional groups of the 1985 Ecopath model of Hernvann *et al*. (2020)

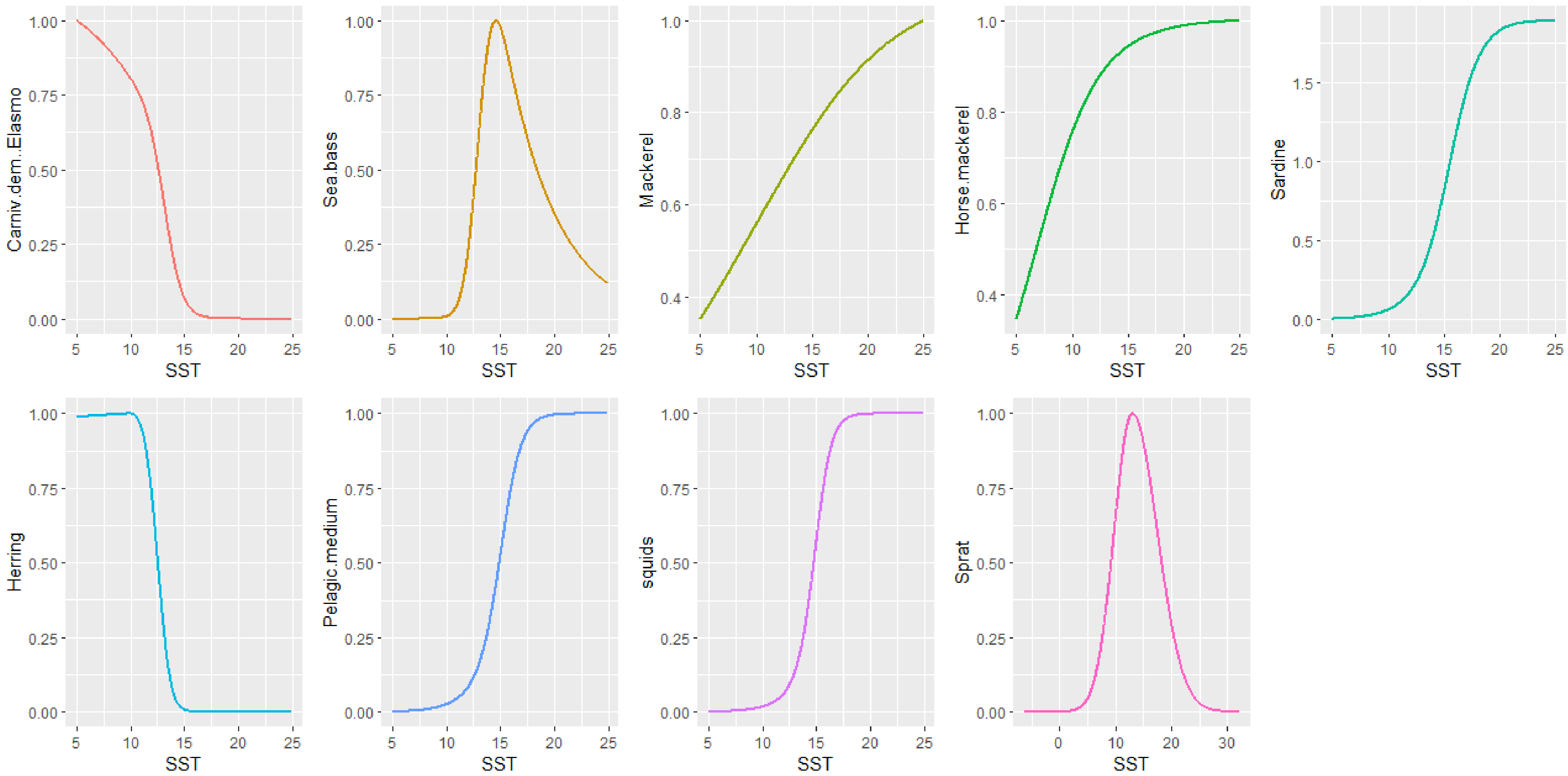
Common name	***Latin name***	**Ecopath group**
Northern gannet	*Sula bassana*	Plunge and pursuit divers seabirds
Common murre	*Uria aalge*	
Razorbills	*Alca torda*	
Atlantic puffin	*Fratercula arctica*	
Herring gull	*Larus argentatus*	Surface feeders seabirds
Yellow-legged gull	*Larus michachellis*	
Lesser black-backed gull	*Larus fuscus*	
great black-backed gull	*Larus maritimus*	
Kittiwakes	*Rissa tridactyla*	
Minke whale	*Balaenoptera acutorostrata*	Baleen whales
Humpback whale	*Megaptera novaengliae*	
Sei whale	*Balaenoptera borealis*	
Fin whale	*Balaenoptera physalus*	
Blue whale	*Balaenoptera musculus*	
Harbour porpoise	*Phocoena phocoena*	Toothed whales and Seals
Common dolphin	*Delphinus delphis*	
Striped dolphin	*Stenella coeruleoalba*	
Bottlenose dolphin	*Tursiops truncates*	
Risso's dolphin	*Grampus griseus*	
White-beaked dolphin	*Lagenorhynchus albirostris*	
Atlantic White-sided dolphin	*Lagenorhynchus acutus*	
False Killer Whale	*Pseudorca crassidens*	
Long-finned Pilot Whale	*Globicephala melas*	
Short-finned Pilot Whale	*Globicephala macrorhynchus*	
Killer Whale (Orca)	*Orcinus orca*	
Halichoerus grypus	*Grey seal*	
Phoca vitulina	*Harbour seal*	
Gervais beaked whale	*Mesoplodon europaeus*	
True's beaked whale	*Mesoplodon mirus*	
pygmy sperm whale	*Kogia breviceps*	
dwarf sperm whale	*Kogia simus*	
Thresher	*Alopias vulpinus*	Pelagic sharks
Bluntnose sixgill shark	*Hexanchus griseus*	
Shortfin mako	*Isurus oxyrinchus*	
Porbeagle	*Lamna nasus*	
Blue shark	*Prionace glauca*	
Tope shark	*Galeorhinus galeus*	
Shagreen ray	*Leucoraja fullonica*	Piscivorous demersal elasmobranchs
Blue skate	*Raja batis*	
White skate	*Raja alba*	
Angelshark	*Squatina squatina*	
Longnose spurdog	*Squalus blainville*	
Marbled electric ray	*Torpedo marmorata*	
Picked dogfish	*Squalus acanthias*	
Starry smooth-hound	*Mustelus asterias*	Benthivorous demersal elasmobrancs
Cuckoo ray	*Leucoraja naevus*	
Smooth-hound	*Mustelus mustelus*	
Blonde ray	*Raja brachyura*	
Spotted ray	*Raja montagui*	
Thornback ray	*Raja clavata*	
Blackmouth catshark	*Galeus melastomus*	
Common stingray	*Dasyatis pastinaca*	
Common eagle ray	*Myliobatis aquila*	
Sandy ray	*Raja circularis*	

Longnosed skate	*Raja oxyrinchus*	
Undulate ray	*Raja undulata*	
Small-spotted catshark	*Scyliorhinus canicula*	
Nursehound	*Scyliorhinus stellaris*	
Small-eyed ray	*Raja microocellata*	
Blackbellied angler	*Lophius budegassa*	Anglerfish
Angler(=Monk)	*Lophius piscatorius*	
European seabass	*Dicentrarchus labrax*	Sea bass
European hake	*Merluccius merluccius*	Hake
Atlantic cod	*Gadus morhua*	Cod
Haddock	*Melanogrammus aeglefinus*	Haddock
Whiting	*Merlangius merlangus*	Whiting
Megrim	*Lepidorhombus whiffiagonis*	Megrim
Norway pout	*Trisopterus esmarkii*	Pouts
Pouting(=Bib)	*Trisopterus luscus*	
Poor cod	*Trisopterus minutus*	
European plaice	*Pleuronectes platessa*	Plaice
Common sole	*Solea solea*	Sole
European conger	*Conger conger*	Piscivorous demersal fish
Pollack	*Pollachius pollachius*	
Turbot	*Psetta maxima*	
Brill	*Scophthalmus rhombus*	
Ling	*Molva molva*	
John dory	*Zeus faber*	
Common lingue	*Molva macrophthalma*	
Common dentex	*Dentex dentex*	
Meagre	*Argyrosomus regius*	
Saithe(=Pollock)	*Pollachius virens*	
Atlantic halibut	*Hippoglossus hippoglossus*	
Silver scabbardfish	*Lepidopus caudatus*	
Blackbelly rosefish	*Helicolenus dactylopterus*	
Wreckfish	*Polyprion americanus*	
European eel	*Anguilla anguilla*	
Atlantic salmon	*Salmo salar*	
Sea trout	*Salmo trutta*	
Black Sea brill	*Psetta maeotica*	
Atlantic thornyhead	*Trachyscorpia cristulata*	
Barracudas nei	*Sphyraena spp*	
Spotted seabass	*Dicentrarchus punctatus*	
Four-spot megrim	*Lepidorhombus boscii*	Epibenthivorous demersal fish
Greater forkbeard	*Phycis blennoides*	
Fourbeard rockling	*Enchelyopus cimbrius*	
Red gurnard	*Chelidonichthys cuculus*	
Surmullet	*Mullus surmuletus*	
Blackspot seabream	*Pagellus bogaraveo*	
Argentine	*Argentina sphyraena*	
Three-bearded rocling	*Gaidropsarus vulgaris*	
Tub gurnard	*Chelidonichthys lucerna*	
Grey gurnard	*Eutrigla gurnardus*	
Red scorpionfish	*Scorpaena scrofa*	
Black scorpionfish	*Scorpaena porcus*	
Comber	*Serranus cabrilla*	
Greater weever	*Trachinus draco*	
Atlantic wolffish	*Anarhichas lupus*	
Gilthead seabream	*Sparus aurata*	
Streaked gurnard	*Chelidonichthys lastoviza*	

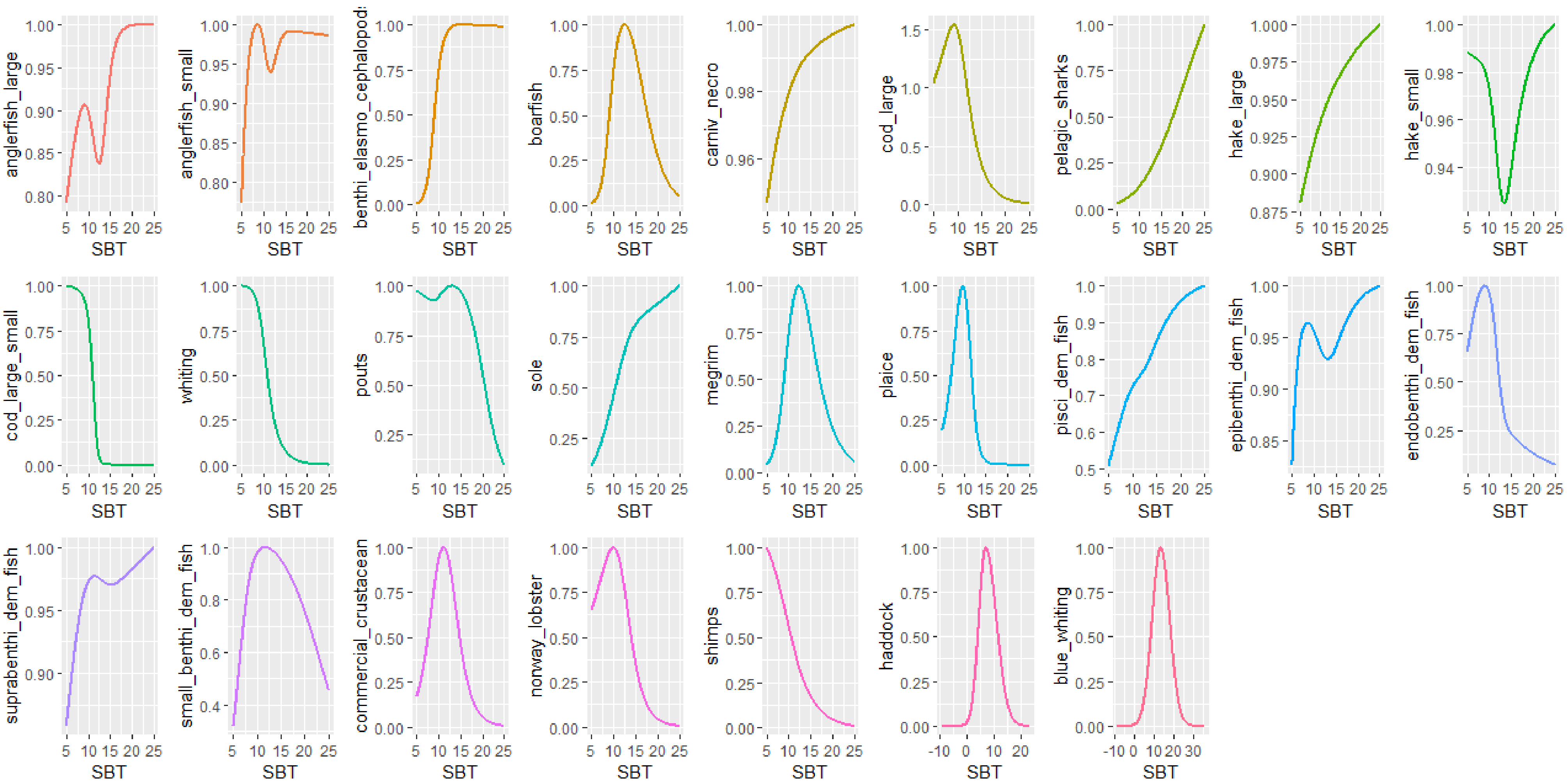
Thicklip grey mullet	*Chelon labrosus*	
Ballan wrasse	*Labrus bergylta*	
Axillary seabream	*Pagellus acarne*	
Common pandora	*Pagellus erythrinus*	
Black seabream	*Spondyliosoma cantharus*	
Golden grey mullet	*Liza aurata*	
Thinlip grey mullet	*Liza ramada*	
Flathead grey mullet	*Mugil cephalus*	
Piper gurnard	*Eutrigla lyra*	
Lumpfish(=Lumpsucker)	*Cyclopterus lumpus*	
Grey triggerfish	*Balistes capriscus*	
Longfin gurnard	*Chelidonichthys obscurus*	
Lesser weever	*Echiichthys vipera*	
Lesser weever	*Labrus mixtus*	
Amer. Plaice	*Hippoglossoides platessoides*	
Cuckoo wrasse	*Pagrus pagrus*	
Common dab	*Limanda limanda*	Endobenthivorous demersal fish
Witch flounder	*Glyptocephalus cynoglossus*	
Lemon sole	*Microstomus kitt*	
Thickback sole	*Microchirus variegatus*	
Sand sole	*Solea lascaris*	
European flounder	*Platichthys flesus*	
Dragonet	*Callionymus lyra*	Small benthivorous demersal fish
Spotted ragonet	*Callionymus maculatus*	
Fivebeard rockling	*Ciliata mustela*	
Sand goby	*Pomatoschistus minutus*	
Butterfly blenny	*Blennius ocellaris*	
Imperial scaldfish	*Arnoglossus imperialis*	
Scale-rayed wrasse	*Acantholabrus palloni*	
Mediterranean scaldfish	*Arnoglossus laterna*	
Solenette	*Buglossidium luteum*	
Fries's goby	*Lesueurigobius friesii*	
Greater pipefish	*Syngnathus acus*	
Black goby	*Gobius niger*	
Norwegian topknot	*Phrynorhombus norvegicus*	
Lozano's goby	*Pomatoschistus lozanoi*	
Red bandfish	*Cepola macrophthalma*	Suprabenthivorous demersal fish
Silvery pout	*Gadiculus argenteus*	
Silvery lightfish	*Maurolicus muelleri*	
Bogue	*Boops boops*	
Greater argentine	*Argentina silus*	
Greater sand-eel	*Hyperoplus immaculatus*	
Great sandeel	*Hyperoplus lanceolatus*	
Small sandeel	*Ammodytes tobianus*	
Transparent goby	*Aphia minuta*	
Smooth sandeel	*Gymnammodytes semisquamatus*	
Longspine snipefish	*Macrorhamphosus scolopax*	
Blue whiting	*Micromesistius poutassou*	Blue whiting
Boarfish	*Capros aper*	Boarfish
Atlantic mackerel	*Scomber scombrus*	Mackerel
Atlantic horse mackerel	*Trachurus trachurus*	Horse mackerel
Atlantic herring	*Clupea harengus*	Herring
European sprat	*Sprattus sprattus*	Sprat
European pilchard	*Sardina pilchardus*	Sardine
Garfish	*Belone belone*	Large Pelagic fish
Atlantic bonito	*Sarda sarda*	

Golden redfish	*Sebastes marinus*	
Albacore	*Thunnus alalunga*	
Atlantic bluefin tuna	*Thunnus thynnus*	
Swordfish	*Xiphias gladius*	
Atlantic pomfret	*Brama brama*	
Little tunny	*Euthynnus alletteratus*	
Skipjack tuna	*Katsuwonus pelamis*	
Allis and twaite shads	*Alosa alosa, A. fallax*	Medium pelagic fish
European anchovy	*Engraulis encrasicolus*	
European smelt	*Osmerus eperlanus*	
Atlantic saury	*Scomberesox saurus*	
Sand smelt	*Atherina presbyter*	
Atlantic chub mackerel	*Scomber colias*	
Chub mackerel	*Scomber japonicus*	
Mediterranean horse mackerel	*Trachurus mediterraneus*	
Broadtail shortfin squid	*Illex coindetii*	Squids
Northern shortfin squid	*Illex illecebrosus*	
European squid	*Loligo vulgaris*	
European flying squid	*Todarodes sagittatus*	
European common squid	*Alloteuthis subulata*	
Veined squid	*Loligo forbesi*	
lesser flying squid	*Todaropsis eblanae*	
Common cuttlefish	*Sepia officinalis*	Benthic cephalopods
Pink cuttlefish	*Sepia orbignyana*	
Elegant cuttlefish	*Sepia elegans*	
Bobtail squid	*Sepiola sp*	
Horned octopus	*Eledone cirrhosa*	
Common octopus	*Octopus vulgaris*	
Stout bobtail	*Rossia macrosoma*	
Norway lobster	*Nephrops norvegicus*	Norway lobster
Edible crab	*Cancer pagurus*	Commercial large crustaceans
European lobster	*Homarus gammarus*	
Spinous spider crab	*Maja squinado/brachydactyla*	
Velvet swimcrab	*Necora puber*	
Common spiny lobster	*Palinurus elephas*	
Shrimps (Sh)		
Commercial bivalves (ComBiv)		
Suprabenthos (Supra)		
Suspension and surface deposit feeders (SSDF)		
Subsurface deposit feeders (SubSDF)		
Carnivores and necrophages (CarnNec)		
Benthic meiofauna (Meio)		
Macrozooplankton (MacroZ)		
Mesozooplankton - Large (MesoL)		
Mesozooplankton - Small (MesoS)		
Microzooplankton (MicroZ)		
Phytoplankton - Large (PhL)		
Phytoplankton - Small (PhS)		

Appendix 2.- Functional response of functional groups to sea surface temperature (SST) in Hernvann *et al*. (2020)



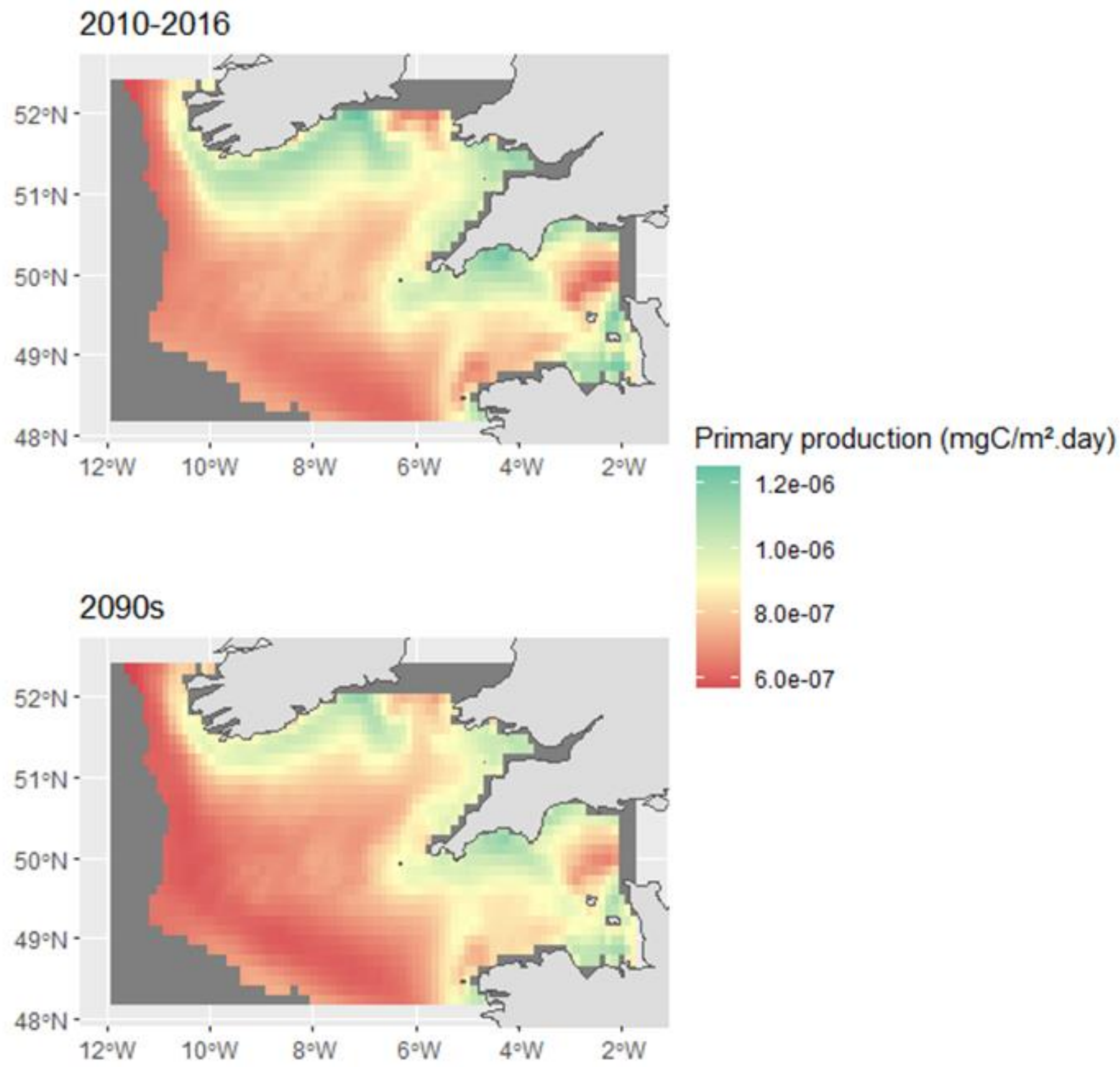
Appendix 3.- Functional response of functional groups to sea bottom temperature (SBT) in Hernvann *et al*. (2020)



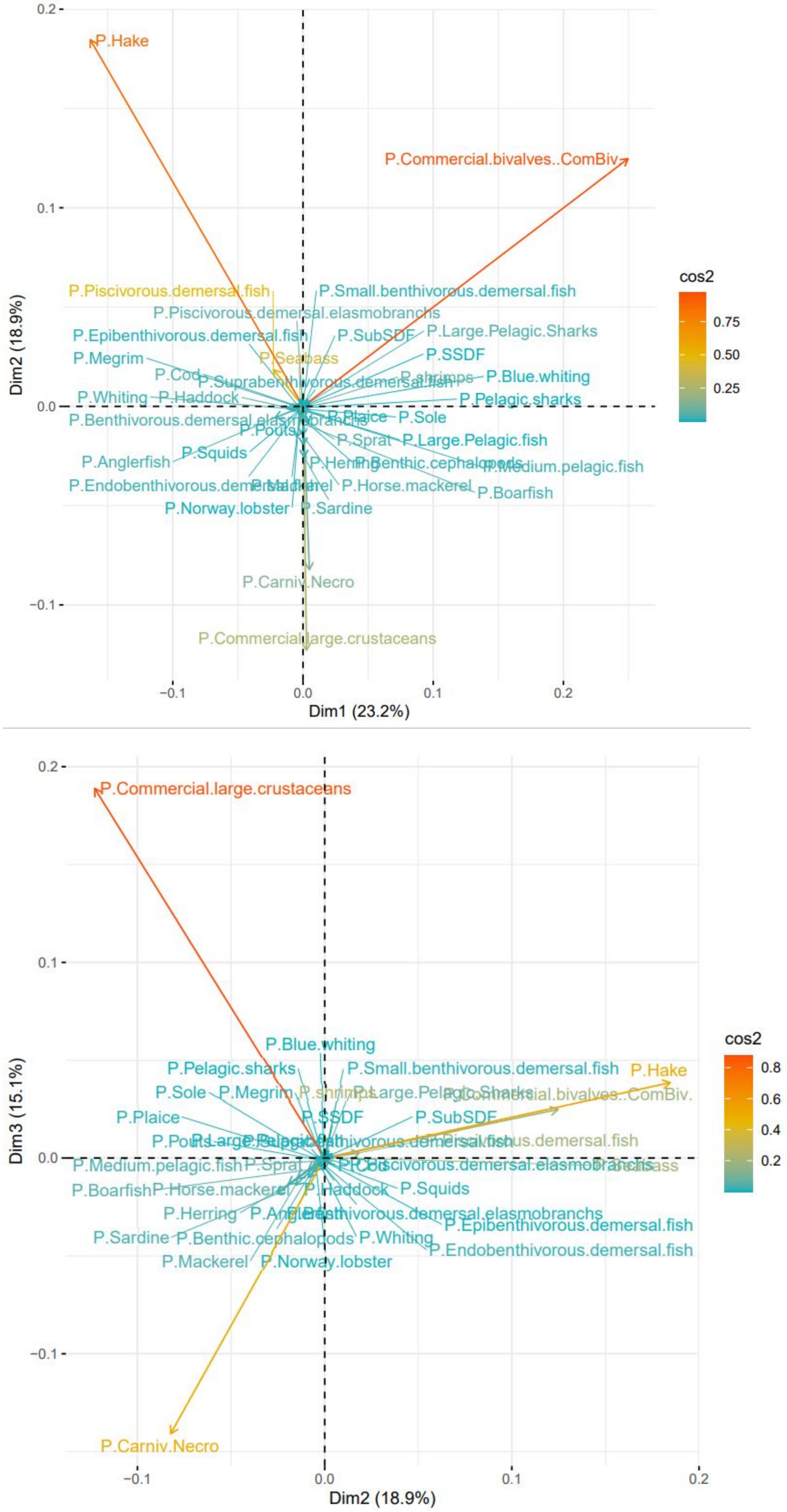
Appendix 4.- Variable's list, abbreviations and modalities of the data set

Variables	**Abbreviations of modalities**	**Meaning**
Countries	FRA	France
	ENG	England
	IRL	Ireland
	ESP	Spain
	SCO	Scotland
	DEU	Germany
	BEL	Belgium
	NLD	The Netherlands
	NIR	Northern Ireland
	GBG	Guernsey
	GBJ	Jersey
	IOM	Ile of Man
	PRT	Portugal
Gears	OTB	Bottom otter trawl
	FPO	Pots and Traps
	OTT	Otter twin trawl
	DRB	Boat dredges
	PTM	Pelagic pair trawl
	GNS	Set gillnets (anchored)
	OTM	Midwater otter trawl
	TBB	Beam trawl
	LLS	Set longlines
	PS	Purse seines
	GTR	Trammel nets
	SSC	Scottish seines
	GNC	Encircling gillnets
	LHP	Handlines and pole-lines (hand-operated)
	LLD	Drifting longlines
	SV	Boat seines
	LTL	Troll lines
	SDN	Danish seines
	NK	No specified gear
	NO	No gear
	HMD	Mechanised dredges including suction dredges
	GND	Driftnets
	LHM	Handlines and pole-lines (mechanised)
	GTN	Combined gillnets-trammel nets
	SB	Beach seine
	PTB	Bottom pair trawl
	LNB	Boat-operated lift nets
	GEF	Glass eel fishing
	SPR	Pair seines
	DRH	Hand dredges
	FYK	Fyke nets
Target species assemblage	DEF	Demersal fish
	SPF	Small pelagic fish
	MOL	Mollusks
	CRU	Crustaceans
	NK	Not known assemblage
	CEP	Cephalopods
	LPF	Large pelagic fish
	FIF	finfish
	MPD	Pelagic and demersal fish
	MCD	Crustaceans and demersal fish
	DWS	Deep water species
	GLE	Eels
	CAT	Catadromous fish

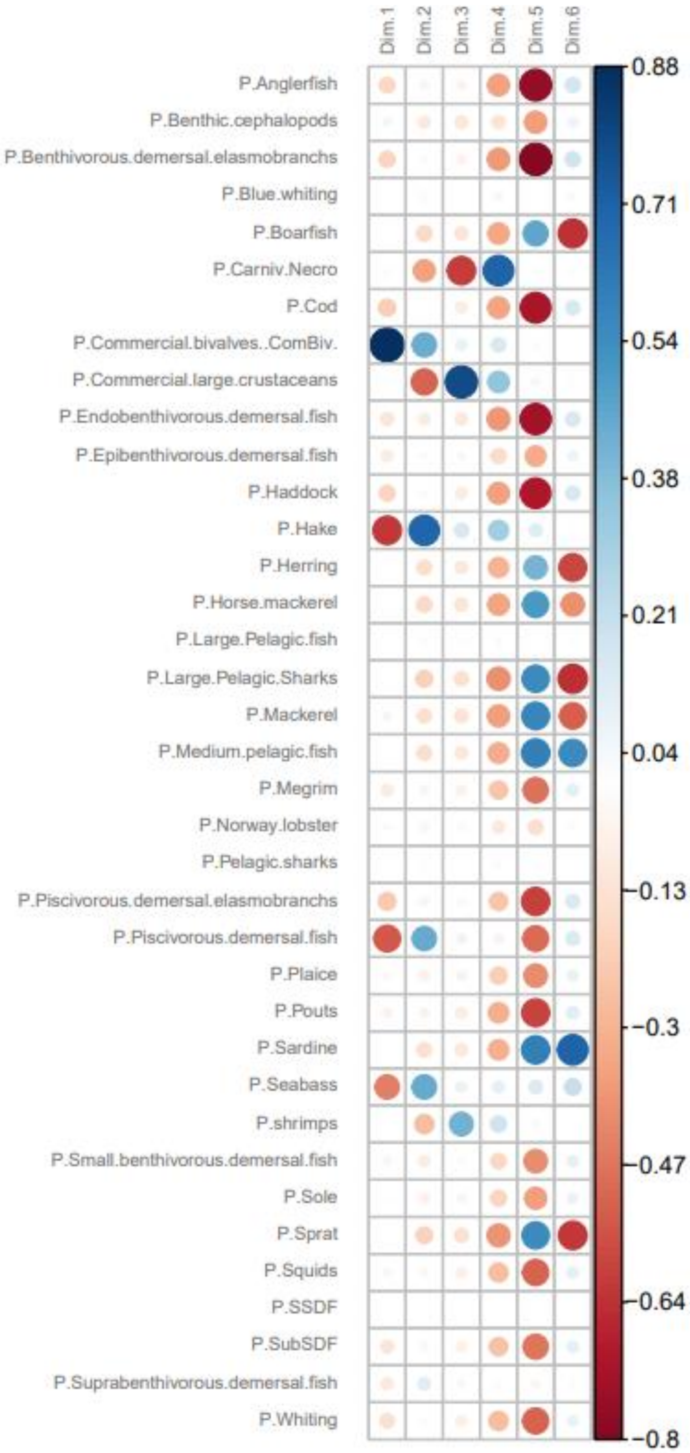
Appendix 5.- Predictions of PP distribution for 2010-2016 and for 2090s



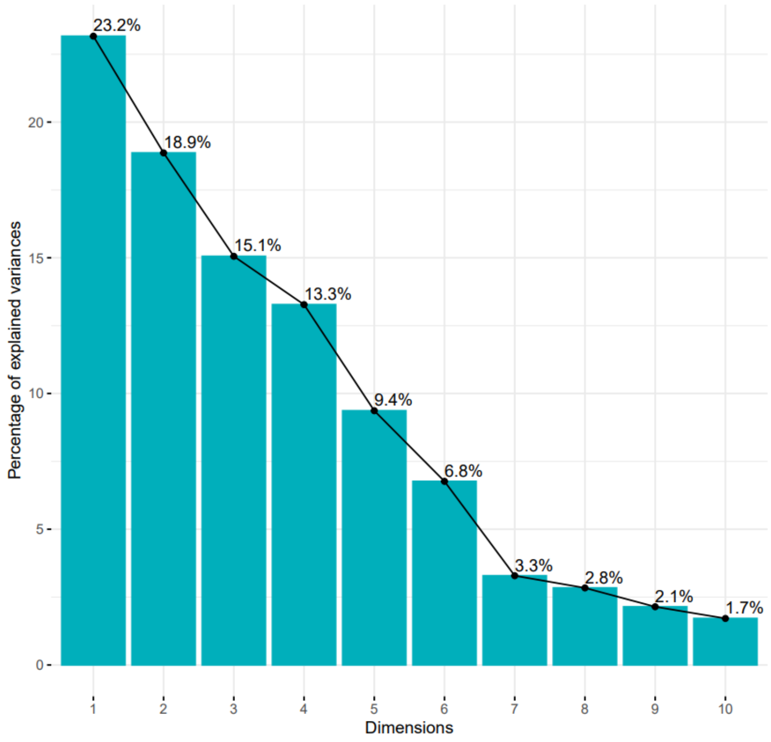
Appendix 6.- PCA projection of the functional groups on axes 1 and 2 (top) and 2 and 3 (bottom). The percentage numbers on the axes are the percentages of inertia explained by that axis. cos² is the quality of representation of variables.



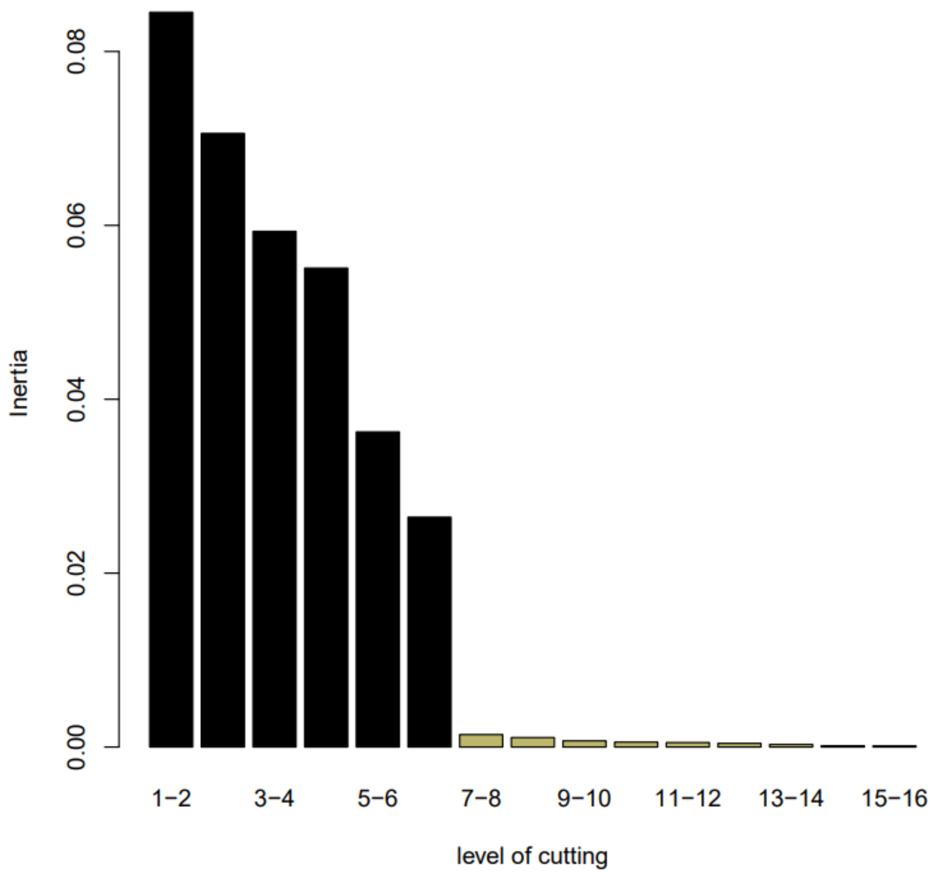
Appendix 7.- Correlation between PCA dimensions and variables



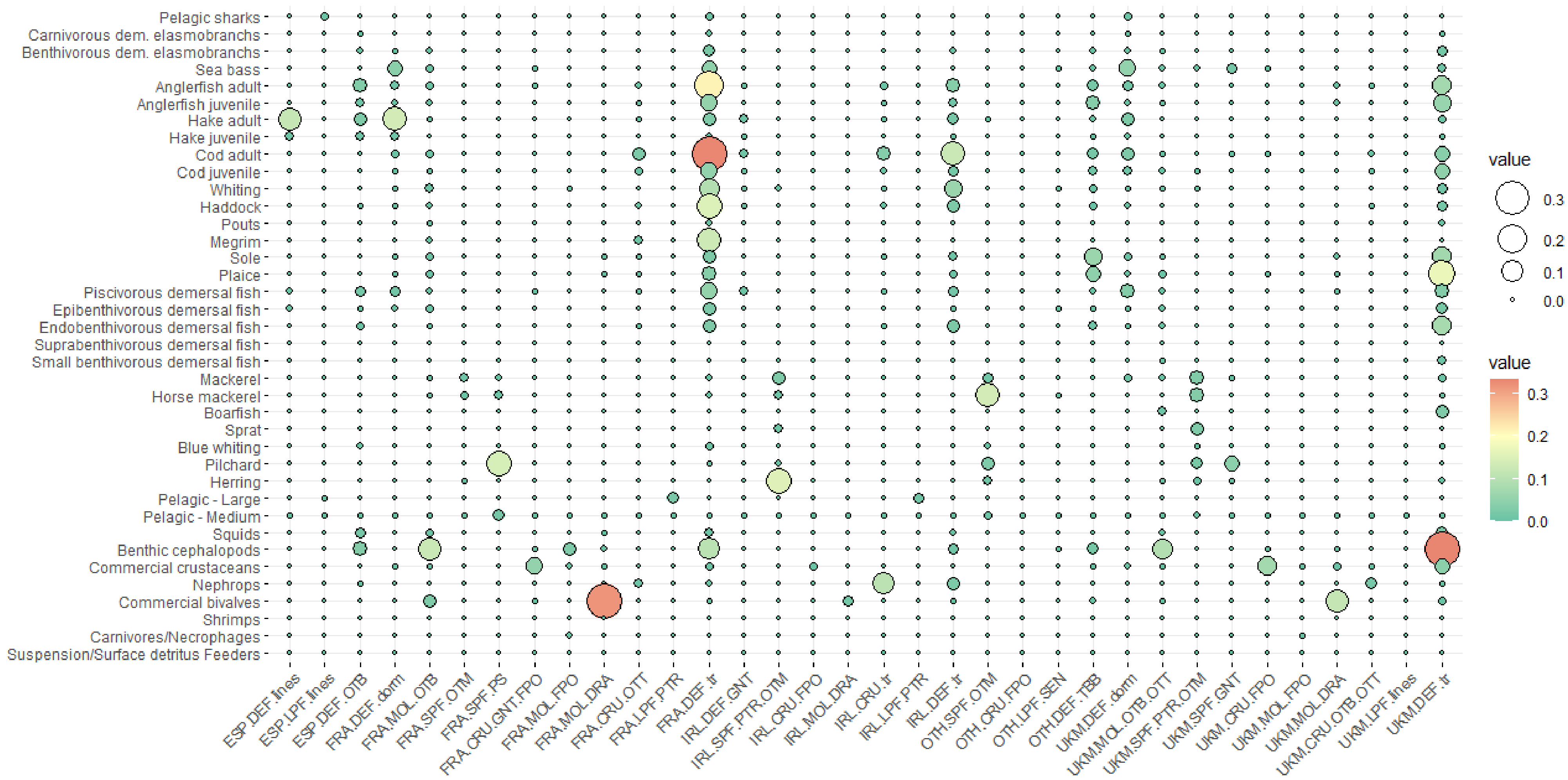
Appendix 8.- Scree plot of the PCA



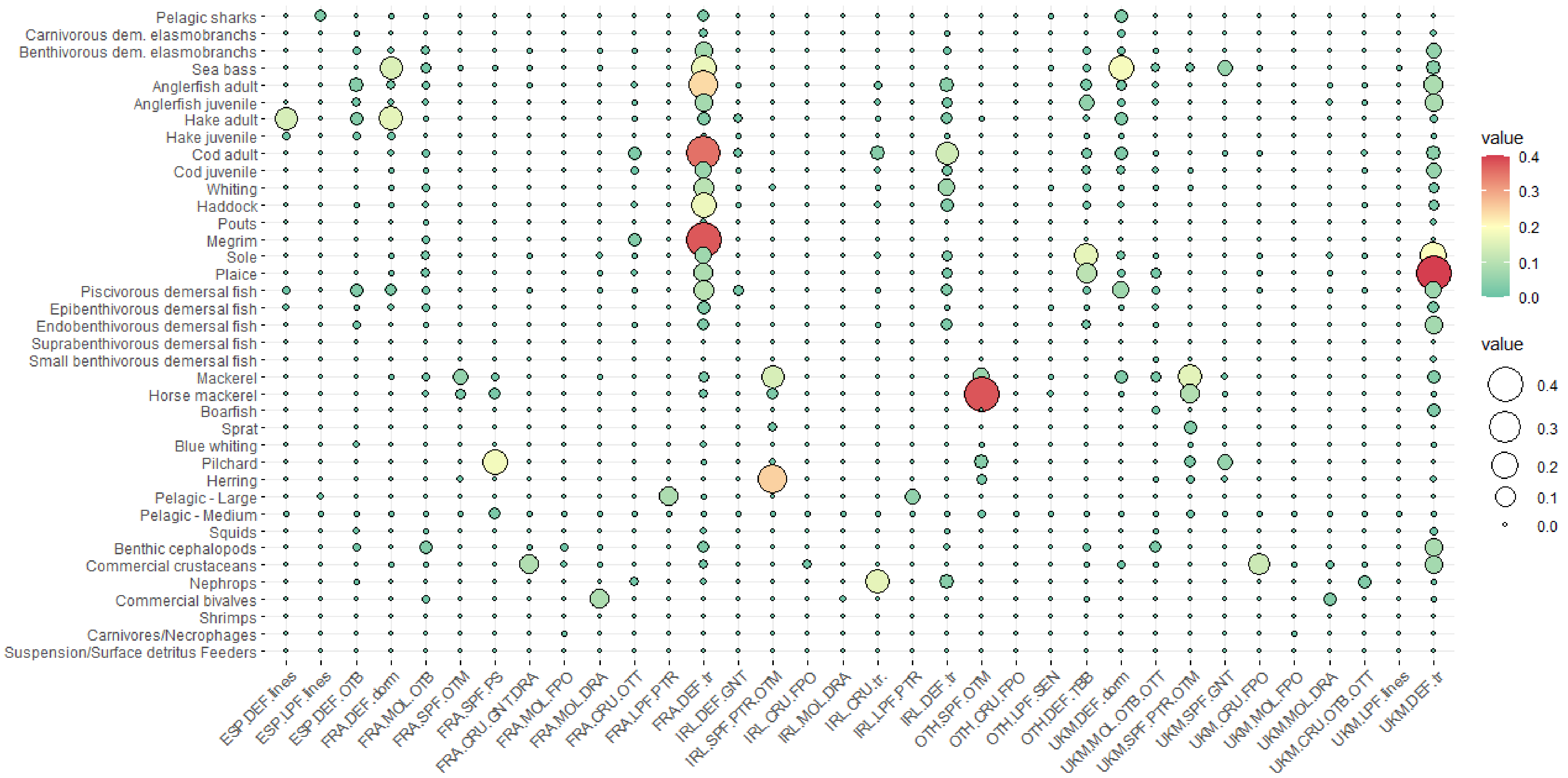
Appendix 9.- Inertia loss by successive aggregation of HAC cluster



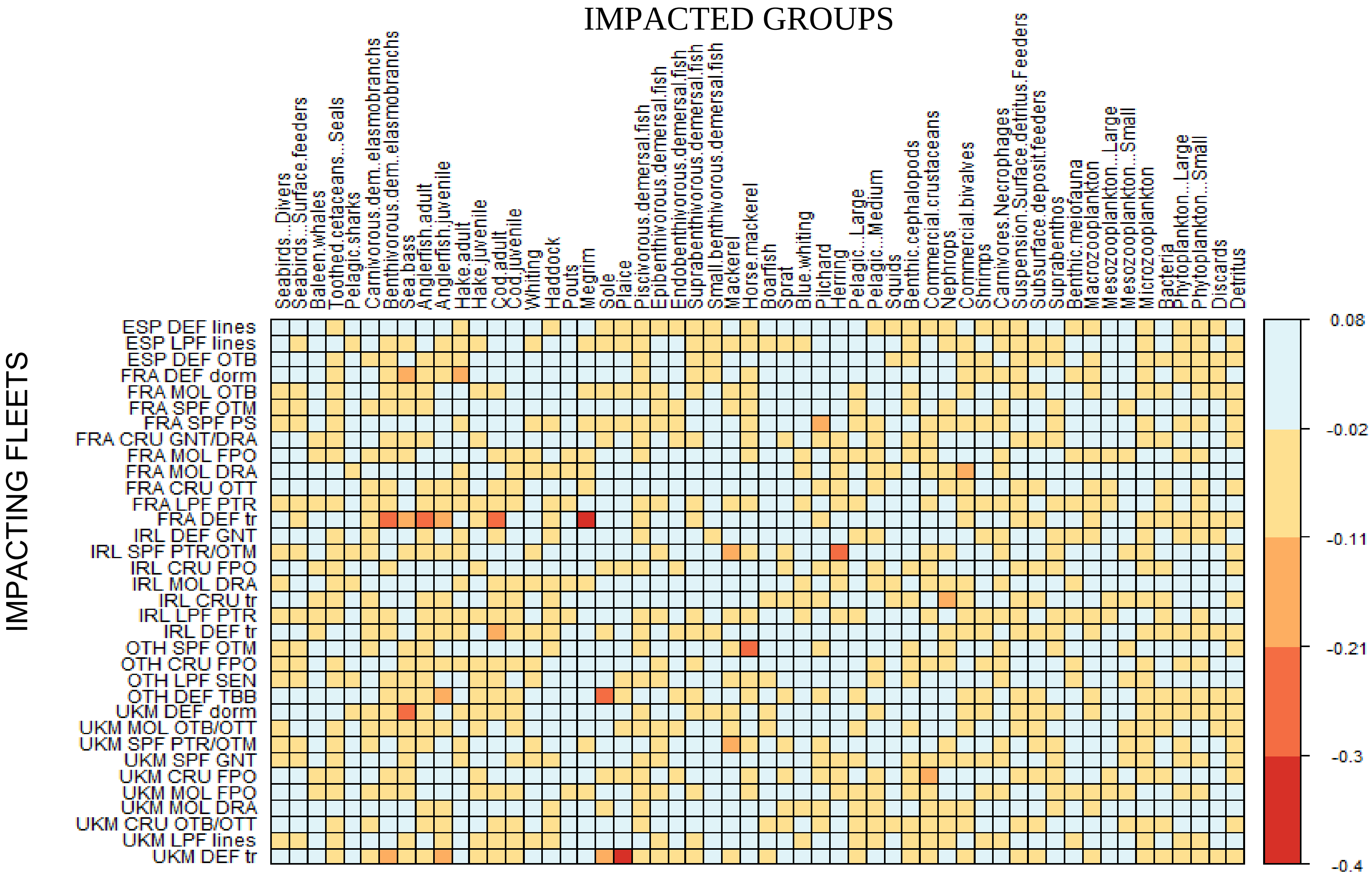
Appendix 10.- Partial fishing mortalities by fleet and functional group



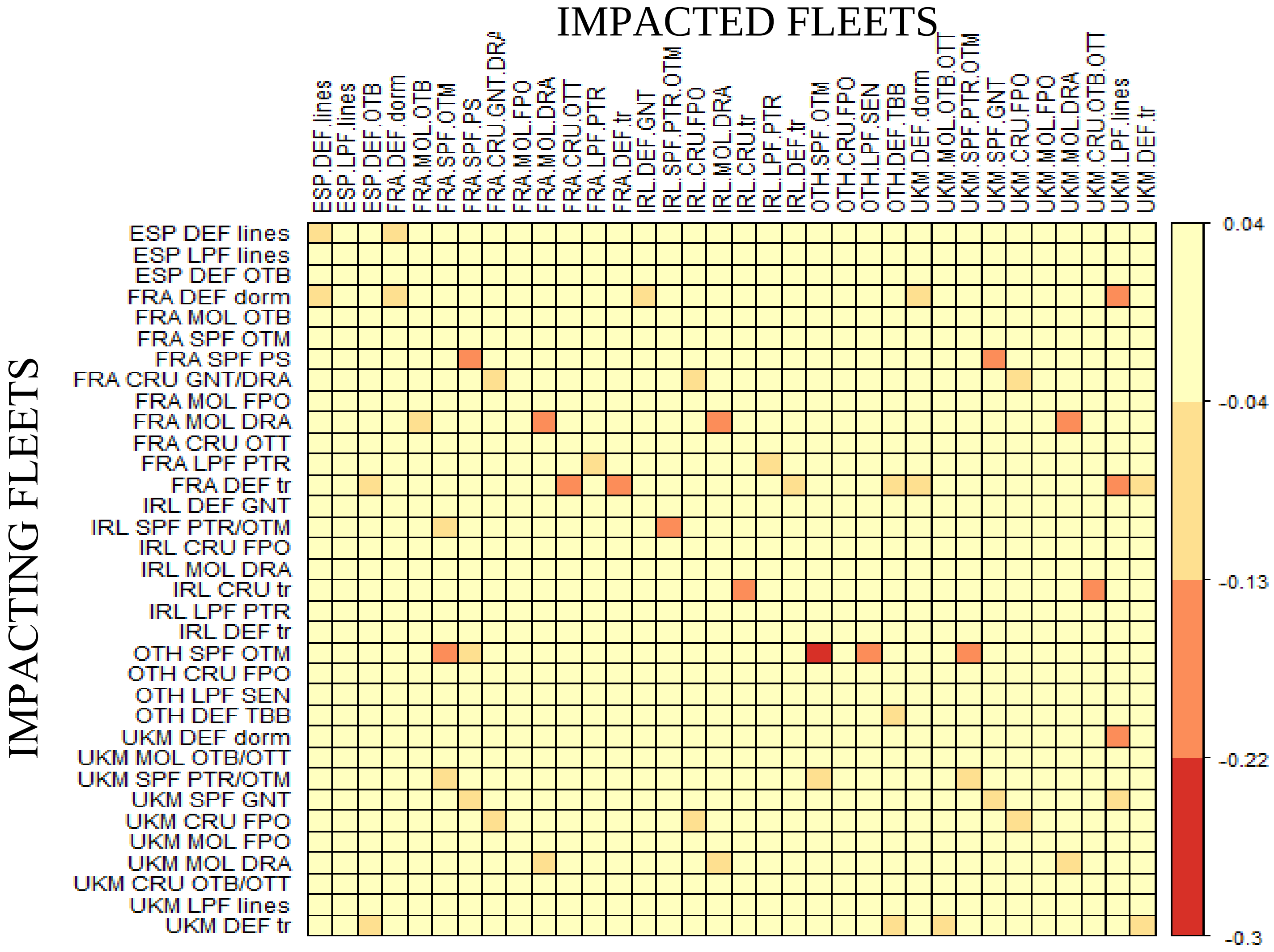
Appendix 11.- Fishing losses: ratio of catches to stock's production



Appendix 12.- Mixed trophic impacts analysis on fleets/groups. *Blue squares (between 0.08 and -0.02) are considered as negligible impacts*



Appendix 13.- Mixed trophic impacts analysis on fleets. *Light yellow squares (between -0.04 and 0.04) are considered as negligible impacts*

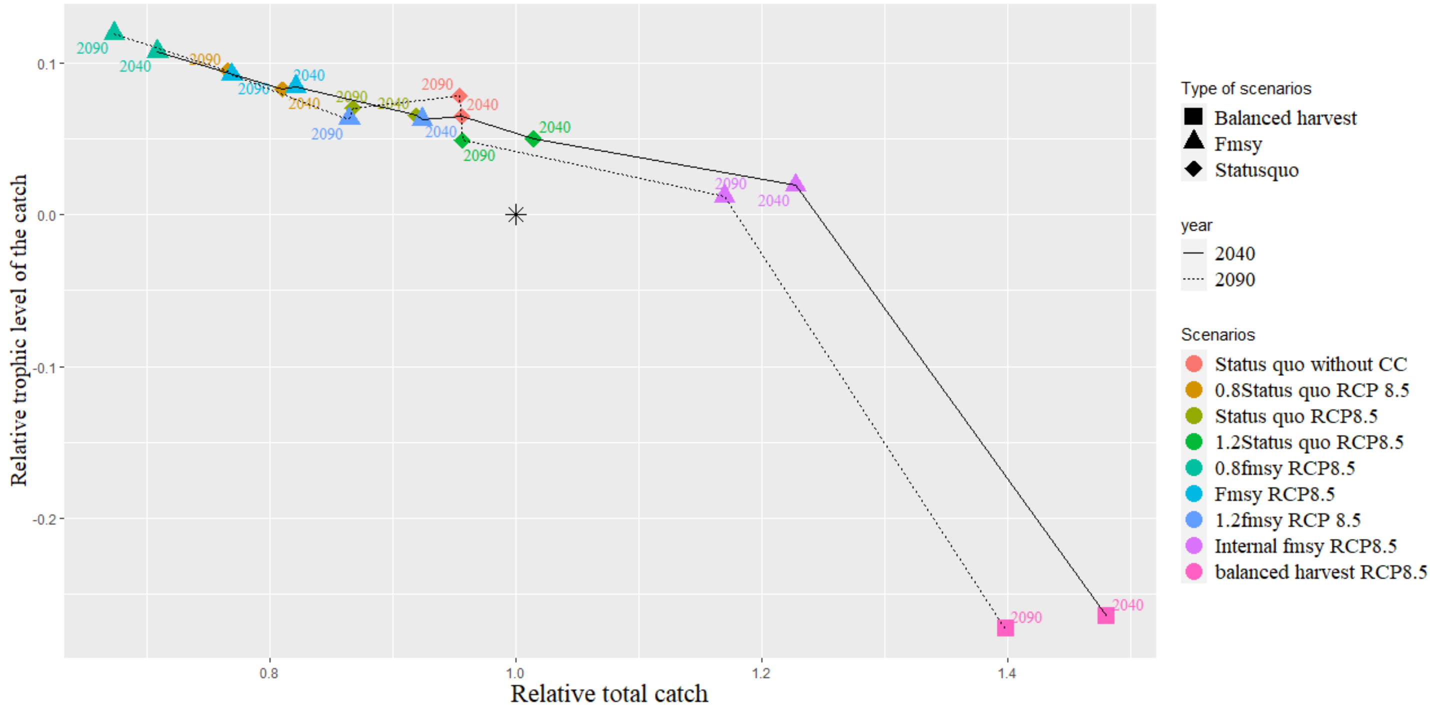


Appendix 14.- Functional group fishing mortalities applied over 2017-2099 in each of the scenarios by species

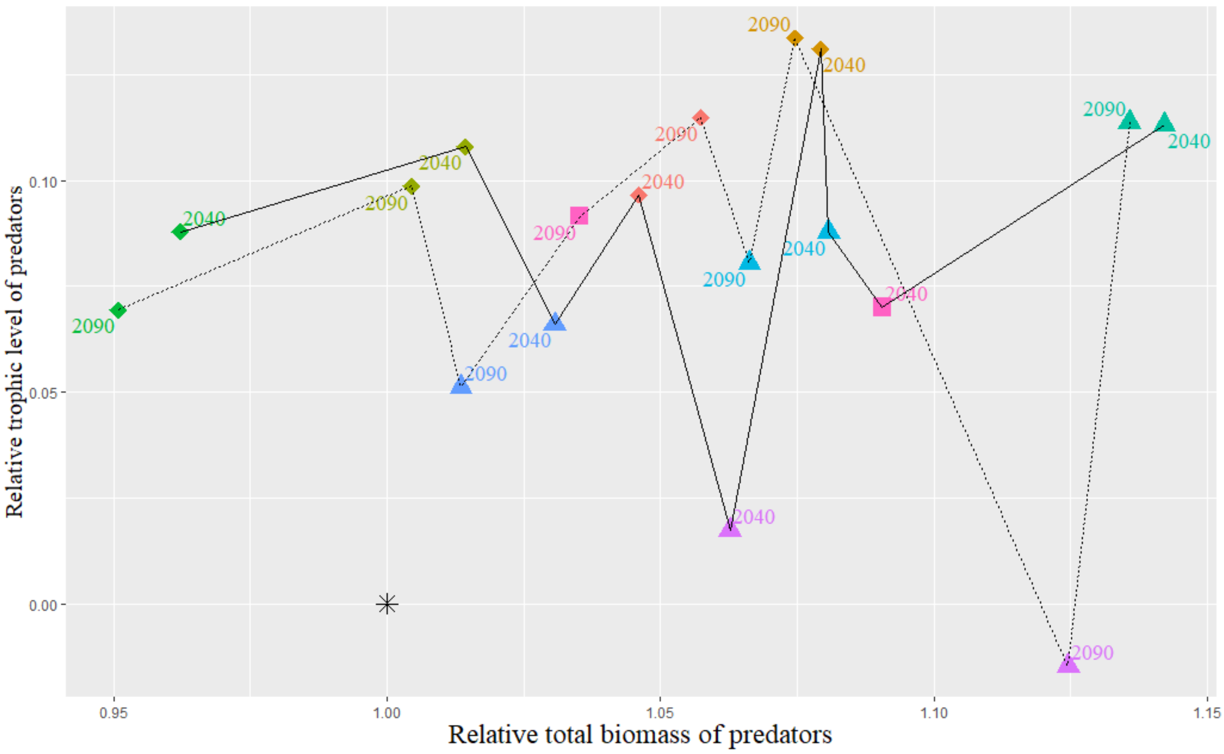
	0.8xstatus quo	Status quo	1.2xstatus quo	0.8xFmsy	Fmsy	1.2xFmsy	Internal Fmsy	balanced harvest
Pelagic sharks	0,0132	0,0164	0,0197	0,0132	0,0164	0,0197	0,0164	0,1867
Carnivorous dem, elasmobranchs	0,0062	0,0078	0,0094	0,0062	0,0078	0,0094	0,0078	0,2403
Benthivorous dem, elasmobranchs	0,0381	0,0477	0,0572	0,0381	0,0477	0,0572	0,0477	0,2417
Sea bass	0,1673	0,2091	0,2509	0,1891	0,2364	0,2837	0,6273	0,0980
Anglerfish adult	0,3195	0,3994	0,4792	0,2672	0,3340	0,4008	1,4657	0,4596
Anglerfish juvenile	0,1670	0,2087	0,2505	0,1670	0,2087	0,2505	0,2087	0,5378
Hake adult	0,3070	0,3838	0,4606	0,2921	0,3651	0,4381	0,4248	0,4887
Hake juvenile	0,0187	0,0233	0,0280	0,0187	0,0233	0,0280	0,0233	1,4821
Cod adult	0,4928	0,6160	0,7392	0,1499	0,1873	0,2248	0,2285	0,2690
Cod juvenile	0,1552	0,1940	0,2328	0,1552	0,1940	0,2328	0,1940	0,6633
Whiting	0,1361	0,1701	0,2041	0,0823	0,1029	0,1234	1,9937	0,7136
Haddock	0,1661	0,2076	0,2492	0,1345	0,1682	0,2018	1,3096	0,6500
Megrim	0,1380	0,1725	0,2071	0,0832	0,1040	0,1248	1,2256	0,1979
Sole	0,1612	0,2016	0,2419	0,2001	0,2501	0,3001	0,2197	0,1931
Plaice	0,2458	0,3073	0,3687	0,1732	0,2164	0,2597	0,2628	0,1509
Piscivorous demersal fish	0,1954	0,2442	0,2931	0,1954	0,2442	0,2931	1,7212	0,3266
Epibenthivorous demersal fish	0,0645	0,0807	0,0968	0,0645	0,0807	0,0968	0,0807	0,7880
Endobenthivorous demersal fish	0,1652	0,2065	0,2479	0,1652	0,2065	0,2479	0,5560	0,9128
Suprabenthivorous demersal fish	0,0006	0,0007	0,0009	0,0006	0,0007	0,0009	0,0007	1,8512
Mackerel	0,2231	0,2789	0,3347	0,0773	0,0966	0,1160	0,2013	0,0893
Horse mackerel	0,1592	0,1990	0,2388	0,1267	0,1583	0,1900	0,0359	0,1622
Boarfish	0,0507	0,0634	0,0761	0,0507	0,0634	0,0761	0,0634	0,9433
Sprat	0,0266	0,0332	0,0399	0,0266	0,0332	0,0399	0,0332	0,8000
Blue whiting	0,0079	0,0099	0,0119	0,0070	0,0088	0,0105	0,3295	1,3791
Pilchard	0,1162	0,1453	0,1743	0,1162	0,1453	0,1743	0,4298	0,5395
Herring	0,1166	0,1458	0,1749	0,0477	0,0596	0,0715	0,0223	0,4391
Pelagic - Large	0,0551	0,0689	0,0827	0,0551	0,0689	0,0827	0,0689	0,2159
Pelagic - Medium	0,0923	0,1154	0,1385	0,0923	0,1154	0,1385	0,0358	0,7577
Squids	0,0787	0,0984	0,1180	0,0787	0,0984	0,1180	0,0984	3,8125
Benthic cephalopods	0,6250	0,7813	0,9375	0,6250	0,7813	0,9375	1,5507	3,3029
Commercial crustaceans	0,1565	0,1956	0,2347	0,1565	0,1956	0,2347	0,2761	0,3855
Nephrops	0,1049	0,1312	0,1574	0,0474	0,0593	0,0712	0,2229	0,4829
Commercial bivalves	0,3640	0,4550	0,5460	0,3640	0,4550	0,5460	1,0388	3,1606
Shrimps	0,0025	0,0031	0,0037	0,0025	0,0031	0,0037	0,0031	2,7152
Carnivores/Necrophages	0,0042	0,0052	0,0063	0,0042	0,0052	0,0063	0,0052	1,8870
Suspension/Surface detritus Feeders	0,0001	0,0001	0,0001	0,0001	0,0001	0,0001	0,0001	2,7878

Appendix 15.- Reuslt of simulation with scenarios by species in terms of (a) catch and TL of the catch (b) biomass of predators and TL of predators and (c) Shannon diversity index and ratio of biomass of chondrichtyans and demersal over pelagic fish

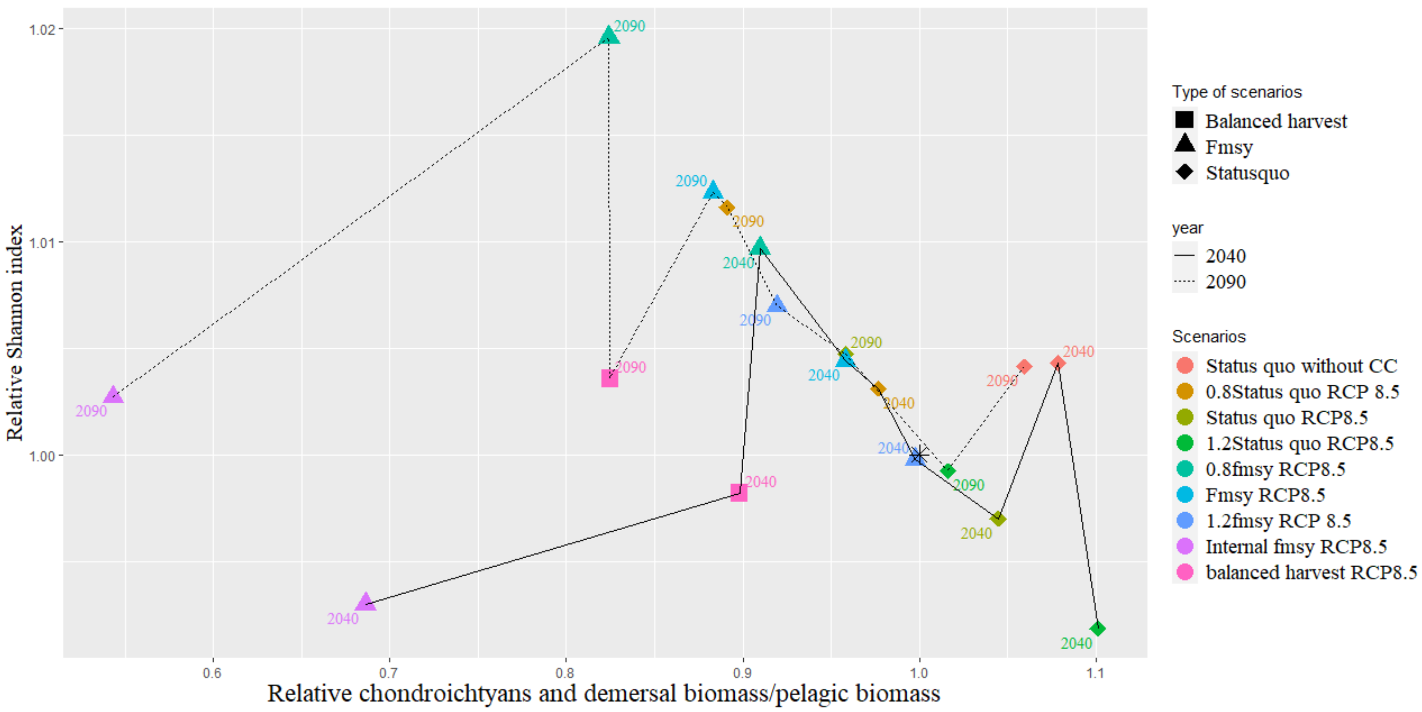
(a)



(b)



(c)



Relative Shannon index
1.02
1.01
1.00
0.6
0.7
0.8
0.9
1.0
1.1
Relative chondroichtyans and demersal biomass/pelagic biomass
Type of scenarios
Balanced harvest
Fmsy
Statusquo
year
2040
2090
Scenarios
Status quo without CC
0.8Status quo RCP 8.5
Status quo RCP8.5
1.2Status quo RCP8.5
0.8fmsy RCP8.5
Fmsy RCP8.5
1.2fmsy RCP 8.5
Internal fmsy RCP8.5
balanced harvest RCP8.5

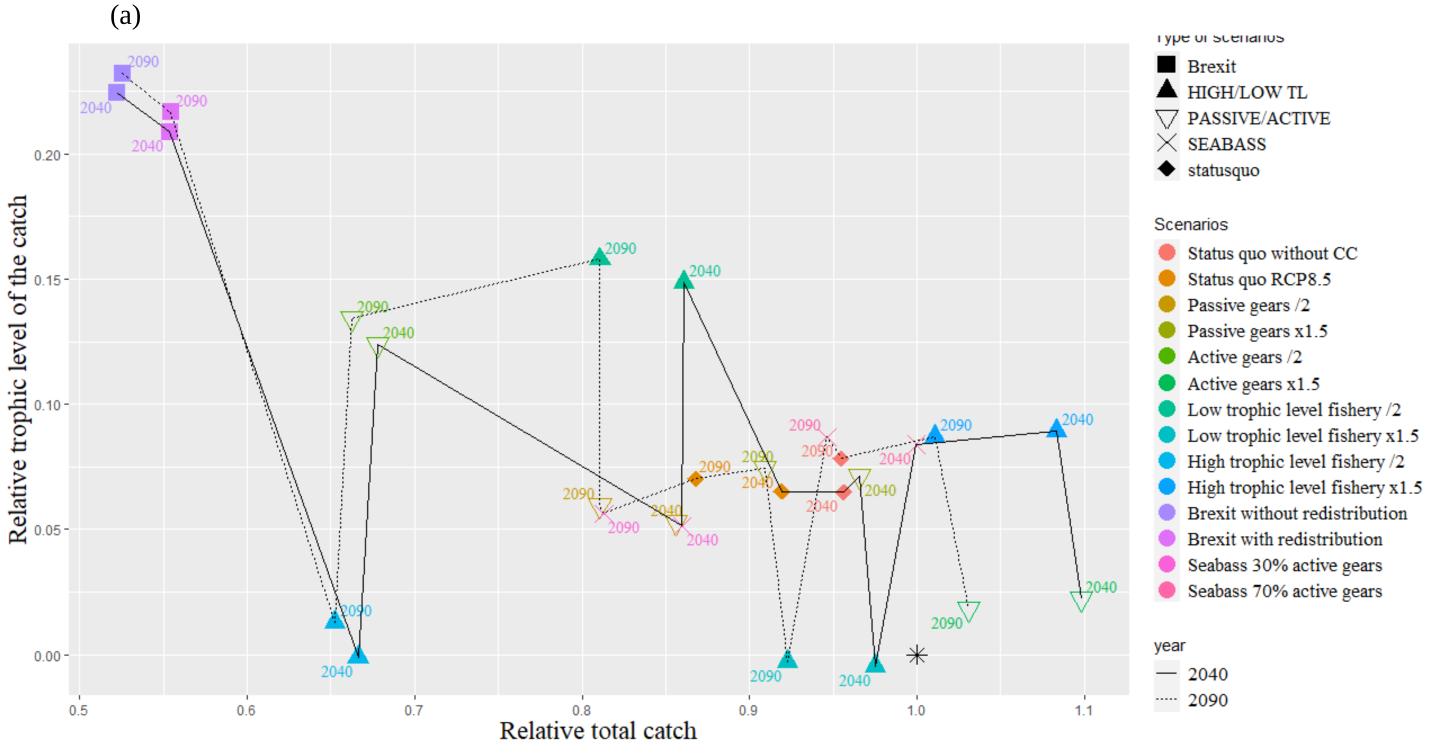
Appendix 16.- Functional group fishing mortalities applied over 2017-2099 in each of the scenarios by fleet

	Status quo	Passive gear /2	Passive gear x1,5	Active gear /2	Active gear x1,5	Low trophic level fishery /2	Low trophic level fishery x1,5	High trophic level fishery /2	High trophic level fishery x1,5	Brexit without redistribution	Brexit with redistribution	Seabass 30% active gears	Seabass 70% active gears
Pelagic sharks	0,0164	0,0108	0,0220	0,0138	0,0191	0,0164	0,0165	0,0082	0,0246	0,0105	0,0116	0,0165	0,0164
Carnivorous dem, elasmobranchs	0,0078	0,0069	0,0087	0,0048	0,0108	0,0078	0,0078	0,0039	0,0117	0,0036	0,0041	0,0065	0,0097
Benthivorous dem, elasmobranchs	0,0477	0,0459	0,0494	0,0256	0,0697	0,0476	0,0478	0,0239	0,0714	0,0169	0,0189	0,0360	0,0649
Sea bass	0,2091	0,1451	0,2730	0,1685	0,2496	0,1994	0,2188	0,1142	0,3039	0,1415	0,1592	0,2091	0,2091
Anglerfish adult	0,3994	0,3877	0,4111	0,2114	0,5873	0,3986	0,4002	0,2005	0,5982	0,1323	0,1422	0,3069	0,5363
Anglerfish juvenile	0,2087	0,2051	0,2124	0,1080	0,3094	0,2072	0,2103	0,1059	0,3115	0,0736	0,0817	0,1645	0,2742
Hake adult	0,3838	0,2361	0,5315	0,3396	0,4280	0,3838	0,3838	0,1919	0,5757	0,2992	0,3050	0,3796	0,3900
Hake juvenile	0,0233	0,0161	0,0306	0,0189	0,0278	0,0233	0,0233	0,0117	0,0350	0,0167	0,0170	0,0231	0,0237
Cod adult	0,6160	0,5964	0,6356	0,3276	0,9044	0,6158	0,6162	0,3082	0,9237	0,1868	0,1965	0,4960	0,7938
Cod juvenile	0,1940	0,1862	0,2018	0,1048	0,2833	0,1940	0,1940	0,0970	0,2910	0,0744	0,0839	0,1528	0,2550
Whiting	0,1701	0,1690	0,1712	0,0862	0,2540	0,1699	0,1703	0,0852	0,2550	0,0460	0,0474	0,1369	0,2193
Haddock	0,2076	0,2056	0,2096	0,1058	0,3094	0,2076	0,2076	0,1038	0,3114	0,0533	0,0554	0,1507	0,2920
Megrim	0,1725	0,1725	0,1726	0,0863	0,2588	0,1725	0,1725	0,0863	0,2588	0,0352	0,0352	0,1178	0,2536
Sole	0,2016	0,1986	0,2045	0,1037	0,2994	0,2001	0,2030	0,1022	0,3009	0,0709	0,0803	0,1651	0,2556
Plaice	0,3073	0,3050	0,3096	0,1559	0,4586	0,3067	0,3078	0,1542	0,4604	0,1255	0,1462	0,2279	0,4248
Piscivorous demersal fish	0,2442	0,2053	0,2831	0,1610	0,3275	0,2437	0,2448	0,1227	0,3658	0,1276	0,1415	0,2182	0,2828
Epibenthivorous demersal fish	0,0807	0,0779	0,0834	0,0431	0,1183	0,0805	0,0809	0,0406	0,1208	0,0276	0,0307	0,0594	0,1122
Endobenthivorous demersal fish	0,2065	0,2063	0,2068	0,1035	0,3096	0,2064	0,2067	0,1034	0,3097	0,0815	0,0926	0,1564	0,2808
Suprabenthivorous demersal fish	0,0007	0,0006	0,0008	0,0005	0,0009	0,0007	0,0007	0,0004	0,0010	0,0004	0,0004	0,0006	0,0008
Mackerel	0,2789	0,2705	0,2872	0,1478	0,4100	0,2759	0,2818	0,1424	0,4154	0,1206	0,1349	0,2745	0,2854
Horse mackerel	0,1990	0,1988	0,1992	0,0997	0,2983	0,1953	0,2027	0,1032	0,2948	0,0632	0,0666	0,1978	0,2007
Boarfish	0,0634	0,0634	0,0634	0,0317	0,0951	0,0634	0,0634	0,0317	0,0951	0,0317	0,0380	0,0460	0,0892
Sprat	0,0332	0,0332	0,0333	0,0167	0,0498	0,0332	0,0333	0,0167	0,0498	0,0155	0,0180	0,0333	0,0332
Blue whiting	0,0099	0,0099	0,0099	0,0050	0,0149	0,0099	0,0099	0,0050	0,0149	0,0032	0,0033	0,0082	0,0125

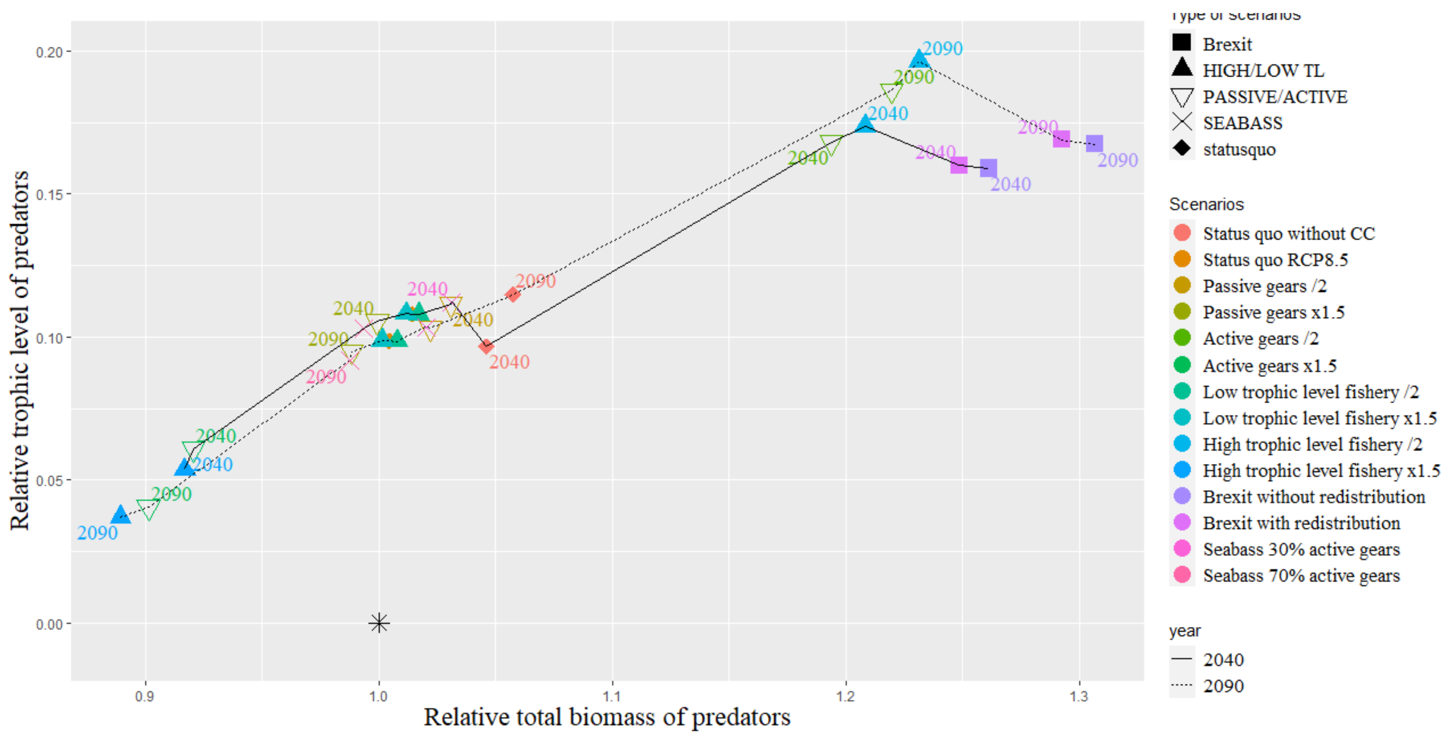
Pilchard	0,1453	0,1319	0,1587	0,0860	0,2045	0,0887	0,2018	0,1292	0,1614	0,0393	0,0459	0,1531	0,1337
Herring	0,1458	0,1452	0,1463	0,0734	0,2181	0,1453	0,1463	0,0734	0,2182	0,0531	0,0539	0,1454	0,1464
Pelagic - Large	0,0689	0,0681	0,0697	0,0352	0,1025	0,0689	0,0689	0,0345	0,1033	0,0343	0,0343	0,0688	0,0690
Pelagic - Medium	0,1154	0,1075	0,1234	0,0657	0,1652	0,0852	0,1456	0,0879	0,1429	0,0307	0,0337	0,1159	0,1148
Squids	0,0984	0,0983	0,0985	0,0493	0,1475	0,0981	0,0986	0,0495	0,1473	0,0384	0,0426	0,0806	0,1247
Benthic cephalopods	0,7813	0,7646	0,7979	0,4073	1,1552	0,7638	0,7987	0,4081	1,1544	0,2731	0,3175	0,6237	1,0146
Commercial crustaceans	0,1956	0,1255	0,2657	0,1679	0,2233	0,1922	0,1990	0,1012	0,2900	0,1142	0,1347	0,1797	0,2192
Nephrops	0,1312	0,1312	0,1312	0,0656	0,1968	0,1312	0,1312	0,0656	0,1968	0,0435	0,0452	0,1301	0,1327
Commercial bivalves	0,4550	0,4545	0,4555	0,2280	0,6820	0,2452	0,6648	0,4373	0,4727	0,0637	0,0752	0,4534	0,4574
Shrimps	0,0031	0,0021	0,0041	0,0026	0,0036	0,0031	0,0031	0,0016	0,0046	0,0018	0,0019	0,0031	0,0031
Carnivores/Necrophages	0,0052	0,0031	0,0074	0,0048	0,0057	0,0032	0,0073	0,0046	0,0058	0,0020	0,0023	0,0052	0,0053
Suspension/Surface detritus Feeders	0,0001	0,0001	0,0001	0,0000	0,0001	0,0001	0,0001	0,0000	0,0001	0,0000	0,0000	0,0001	0,0001

Appendix 17.- Results of simulation with scenarios by fleets in terms of (a) catch and TL of the catch (b) biomass of predators and TL of predators and (c) Shannon diversity index and ratio of biomass of chondrichthyans and demersal over pelagic fish

(a)

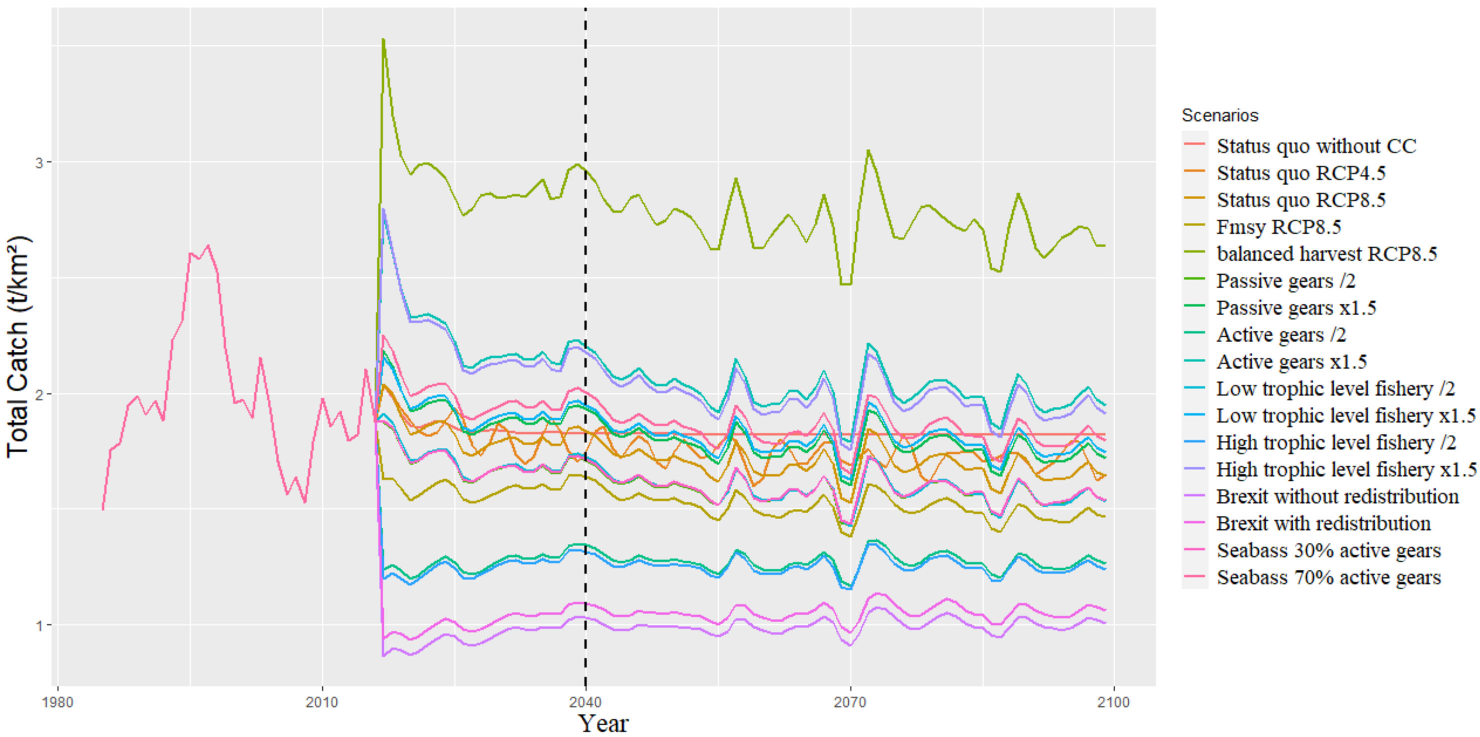


(b)

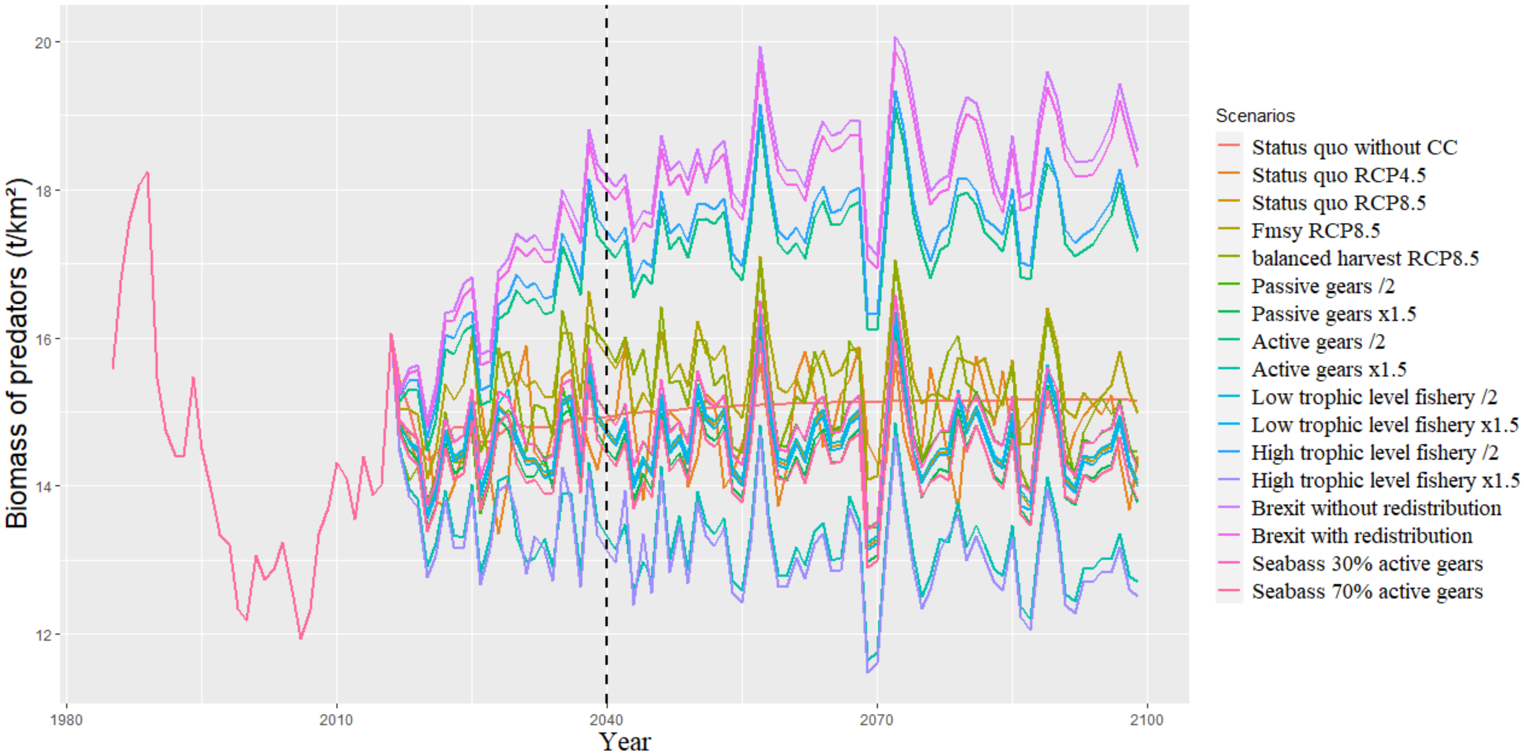


(c)

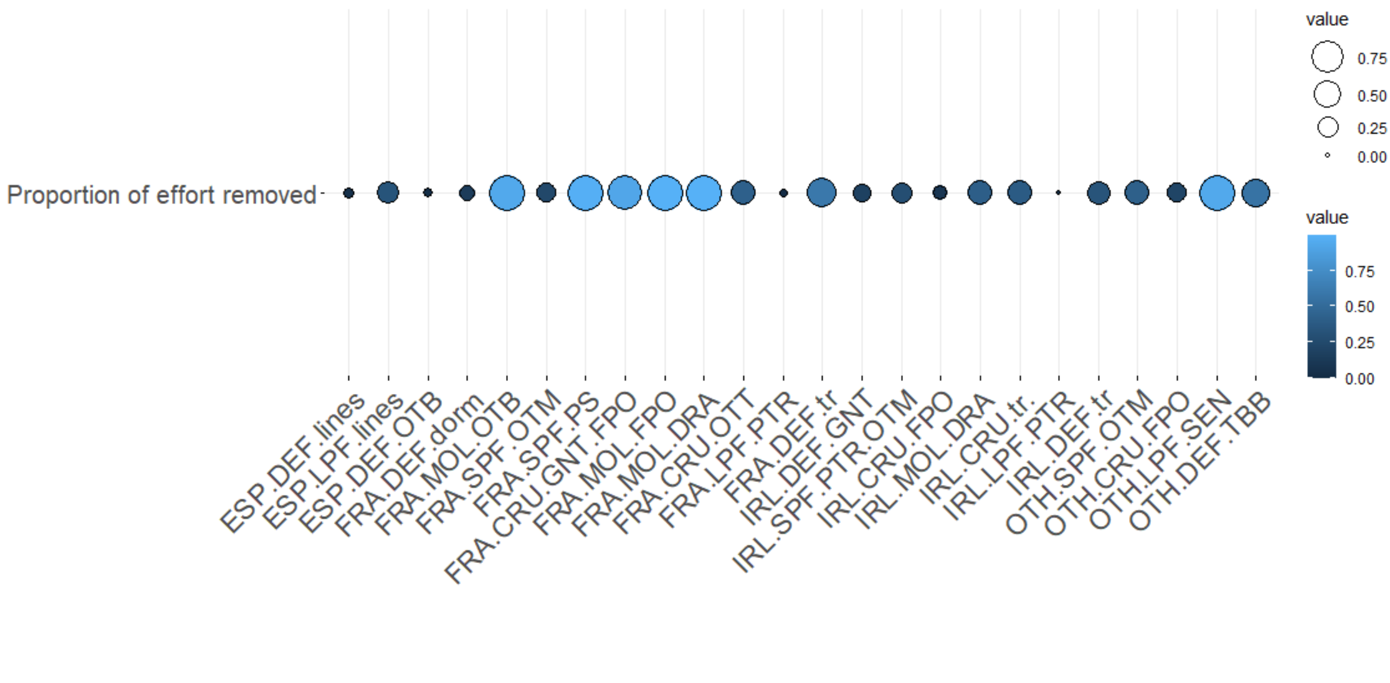
Appendix 18.- Evolution of the total catch over 1985-2099



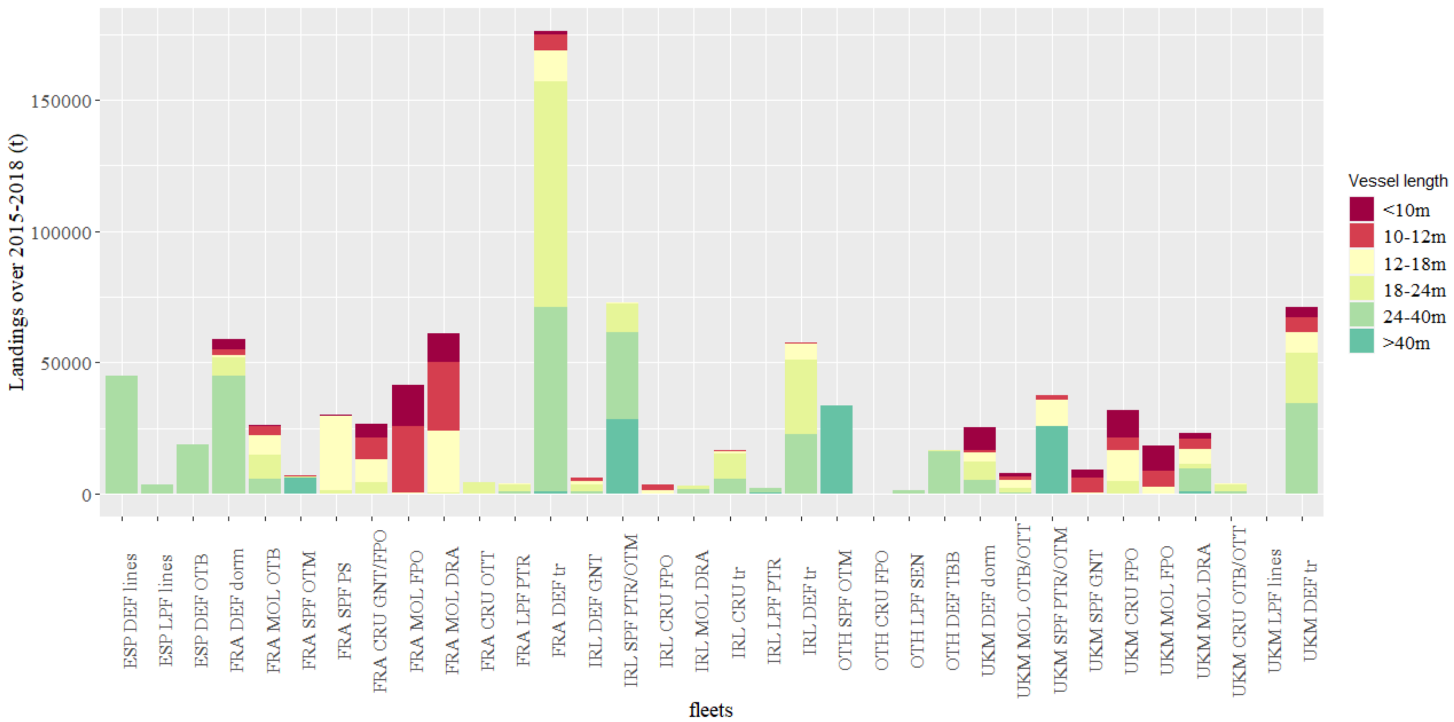
Appendix 19.- Evolution of the biomass of predators over 1985-2099



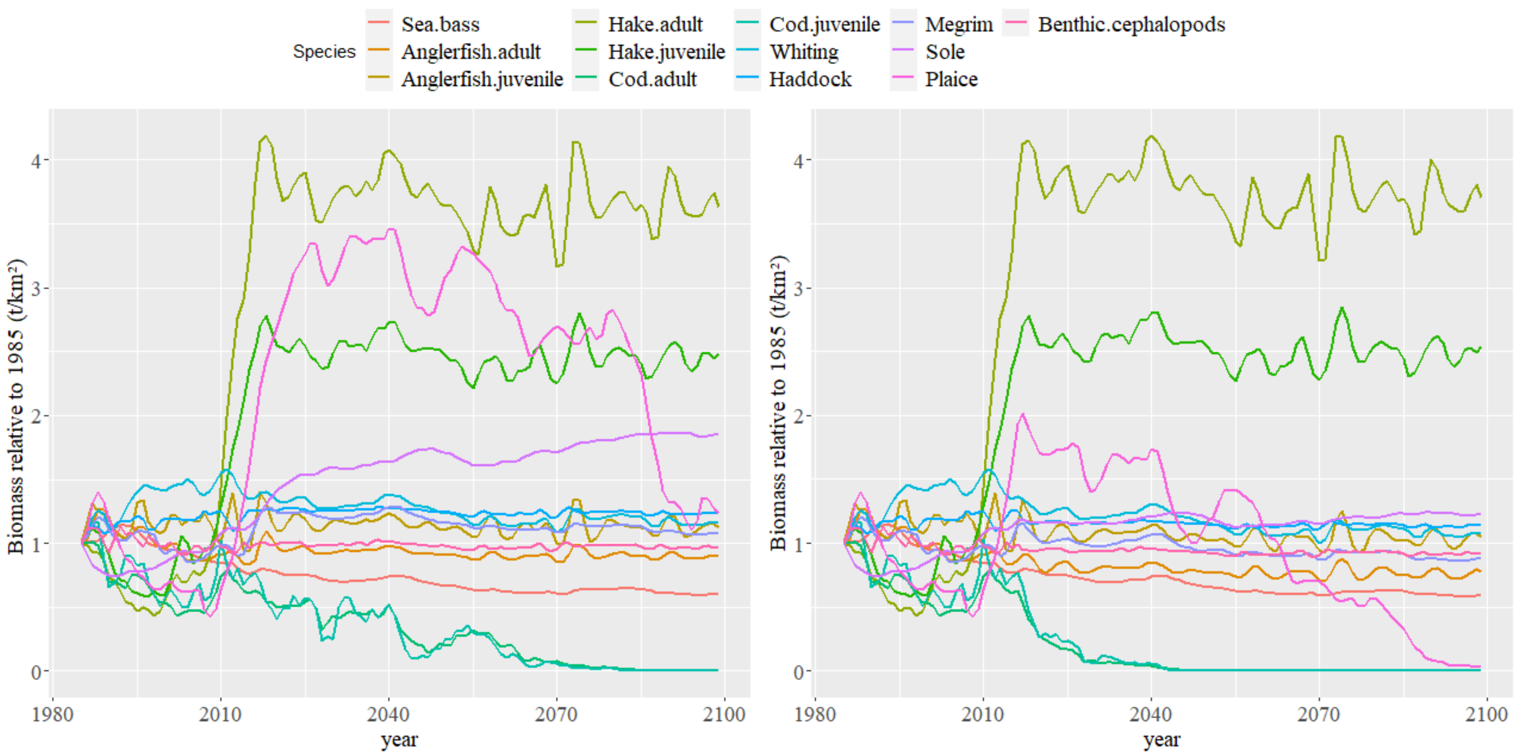
Appendix 20.- Proportion of effort removed by fleet in "Brexit" scenarios for each of the European fleets



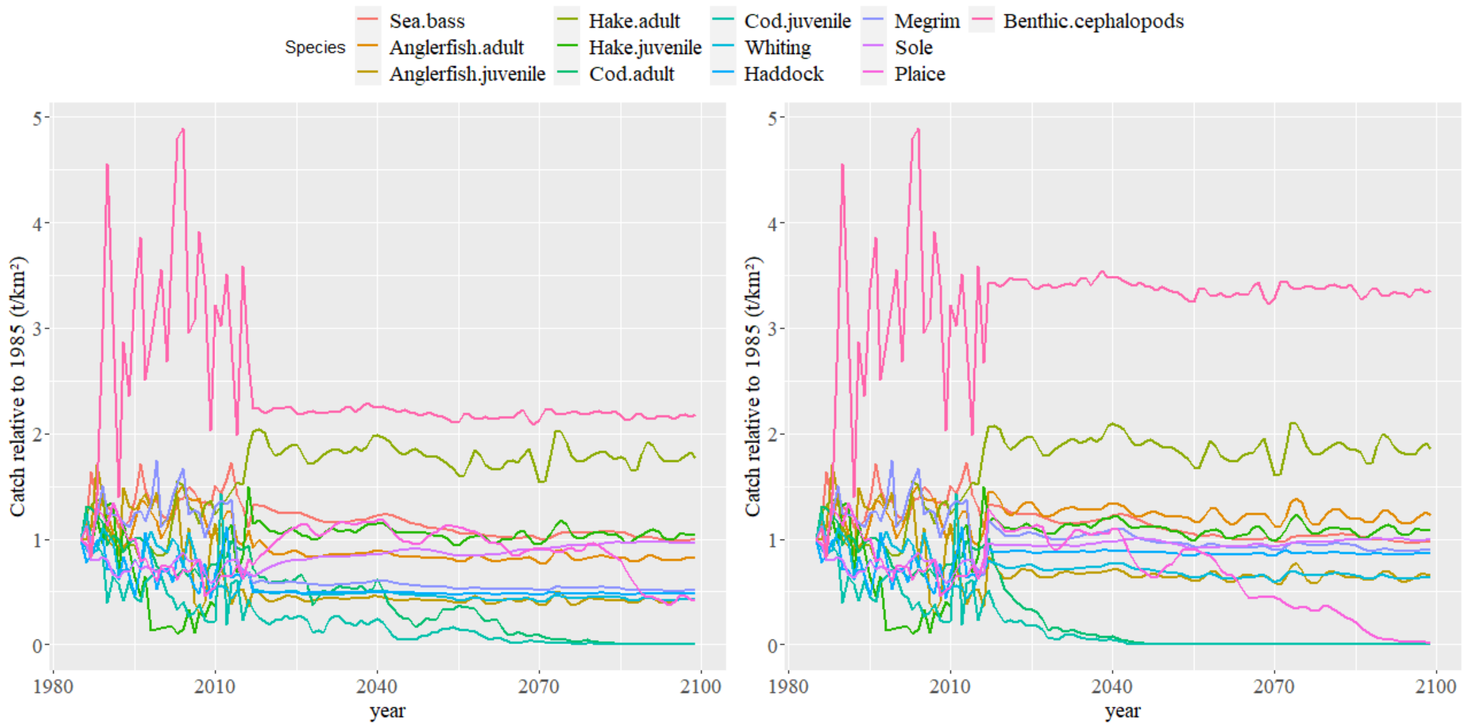
Appendix 21.- Description of landings of the 34 fleets in terms of vessel size



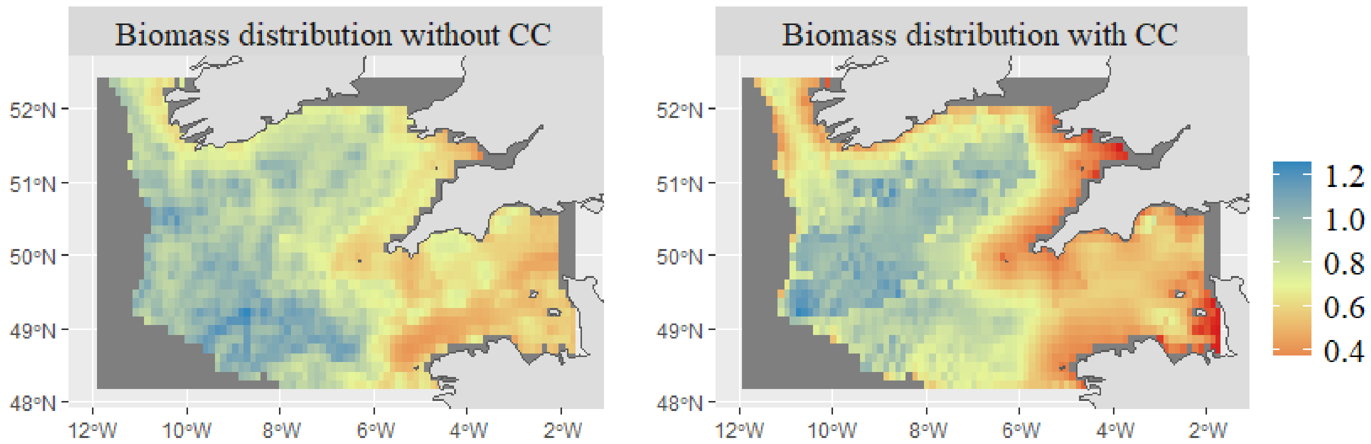
Appendix 22.- Evolution of biomasses of some species in "seabass" scenarios. At left 30% of targeting gears are active. At right 70% of targeting gears are active.



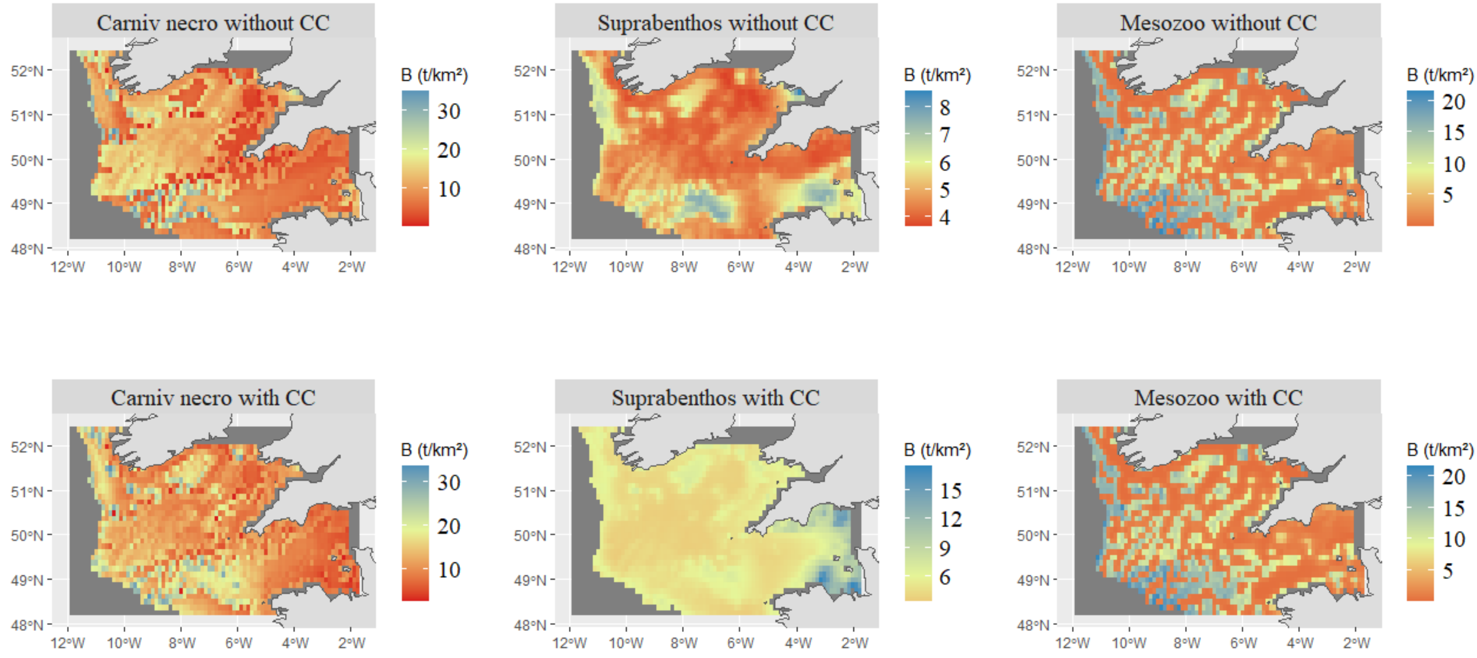
Appendix 23.- Evolution of catches of some species in "seabass" scenarios. At left 30% of targeting gears are active. At right 70% of targeting gears are active.



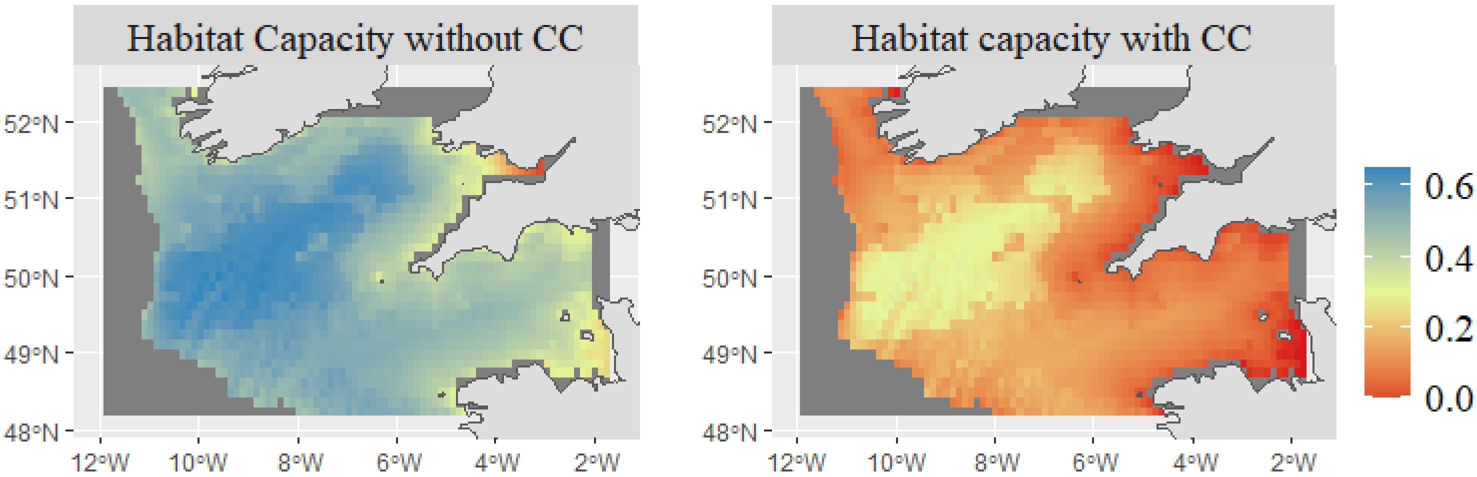
Appendix 24.- Epibenthivorous demersal fish biomass distribution in 2090s without or with CC (RCP8.5)



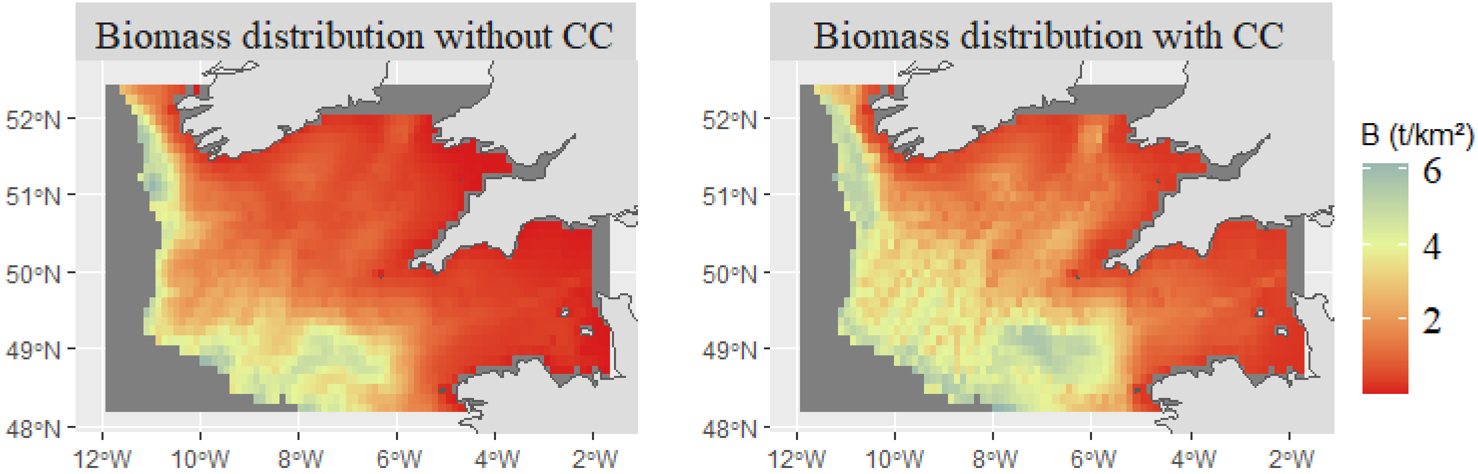
Appendix 25.- Biomass distribution of epibenthivorous demersal fish preys in 2090s without or with CC (RCP8.5)



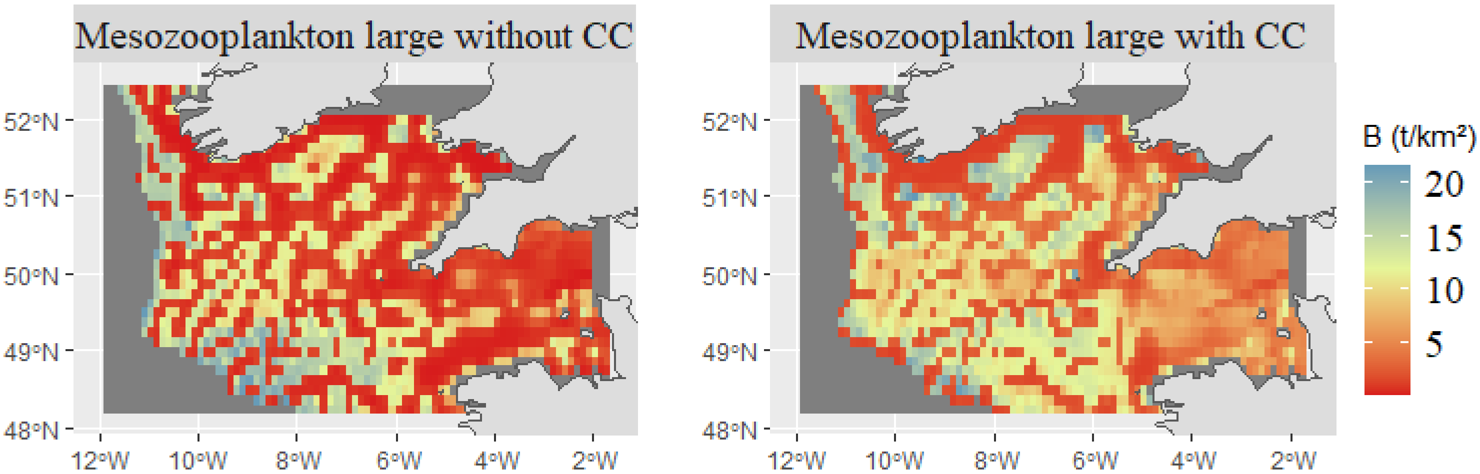
Appendix 26.- Epibenthivorous demersal fish habitat capacity in 2090s without or with CC (RCP8.5)



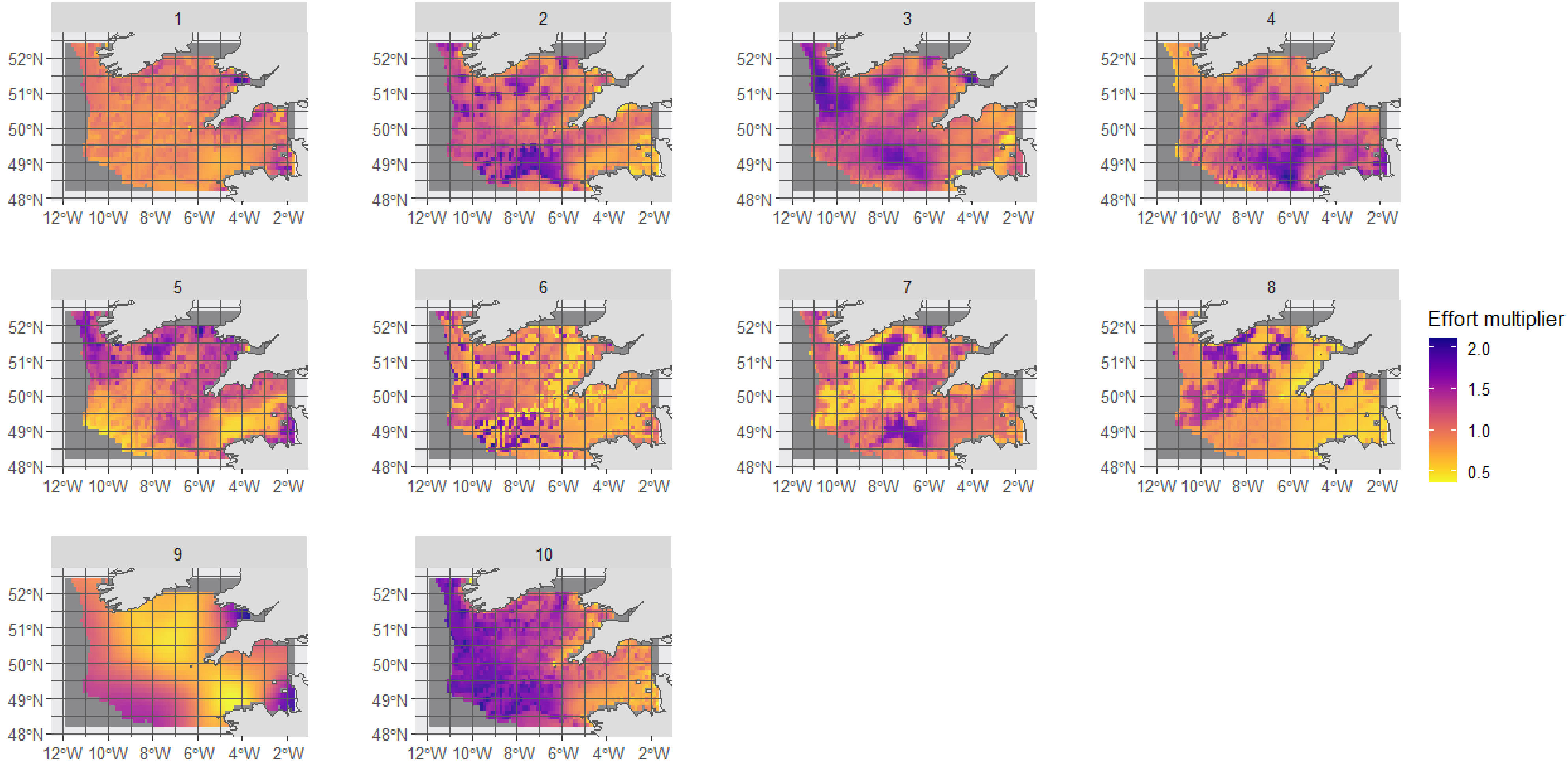
Appendix 27.- Boarfish biomass distribution in 2090s without or with CC (RCP8.5)



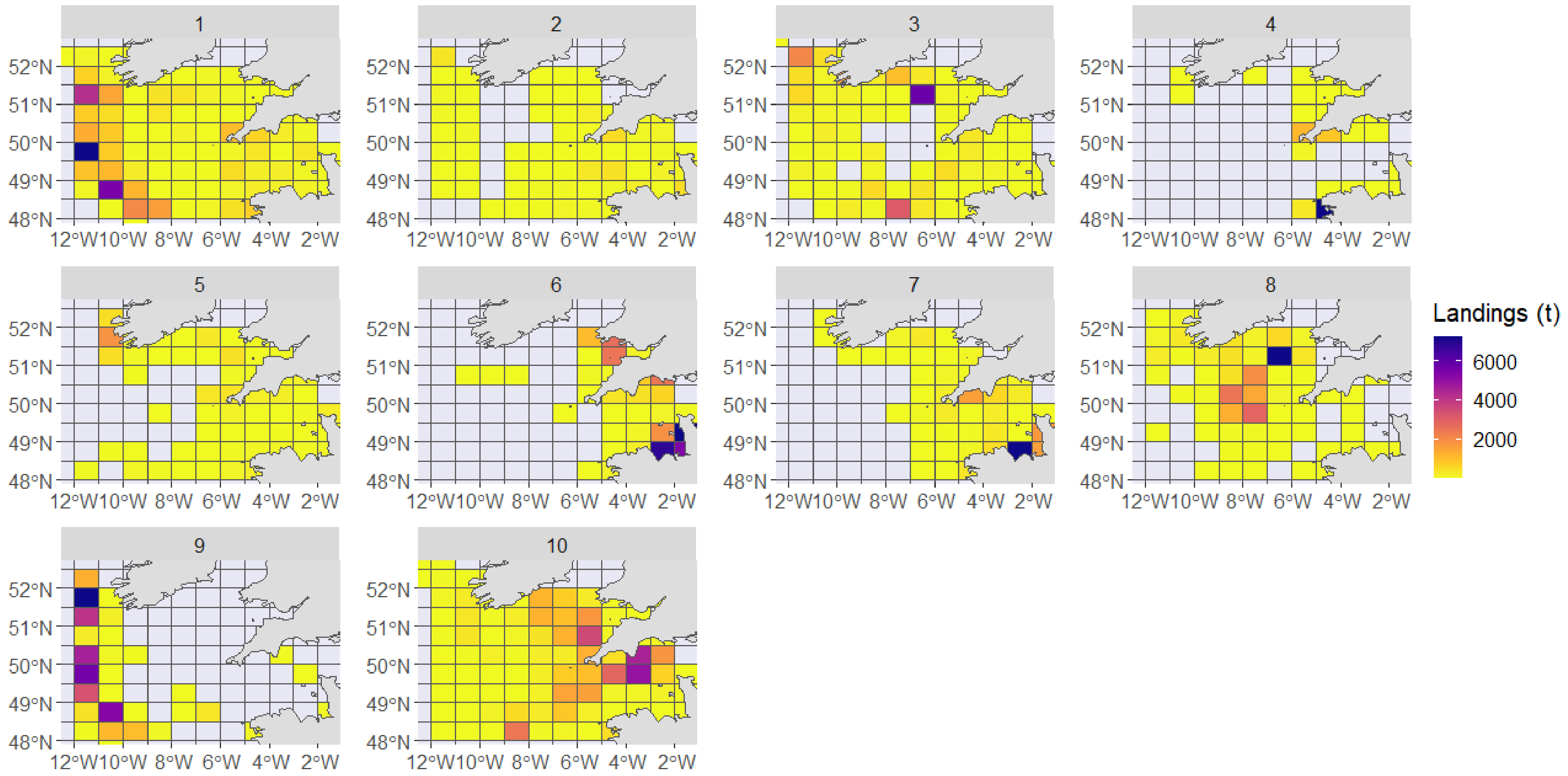
Appendix 28.- Mesozooplankton biomass distribution in 2090s without or with CC (RCP8.5)



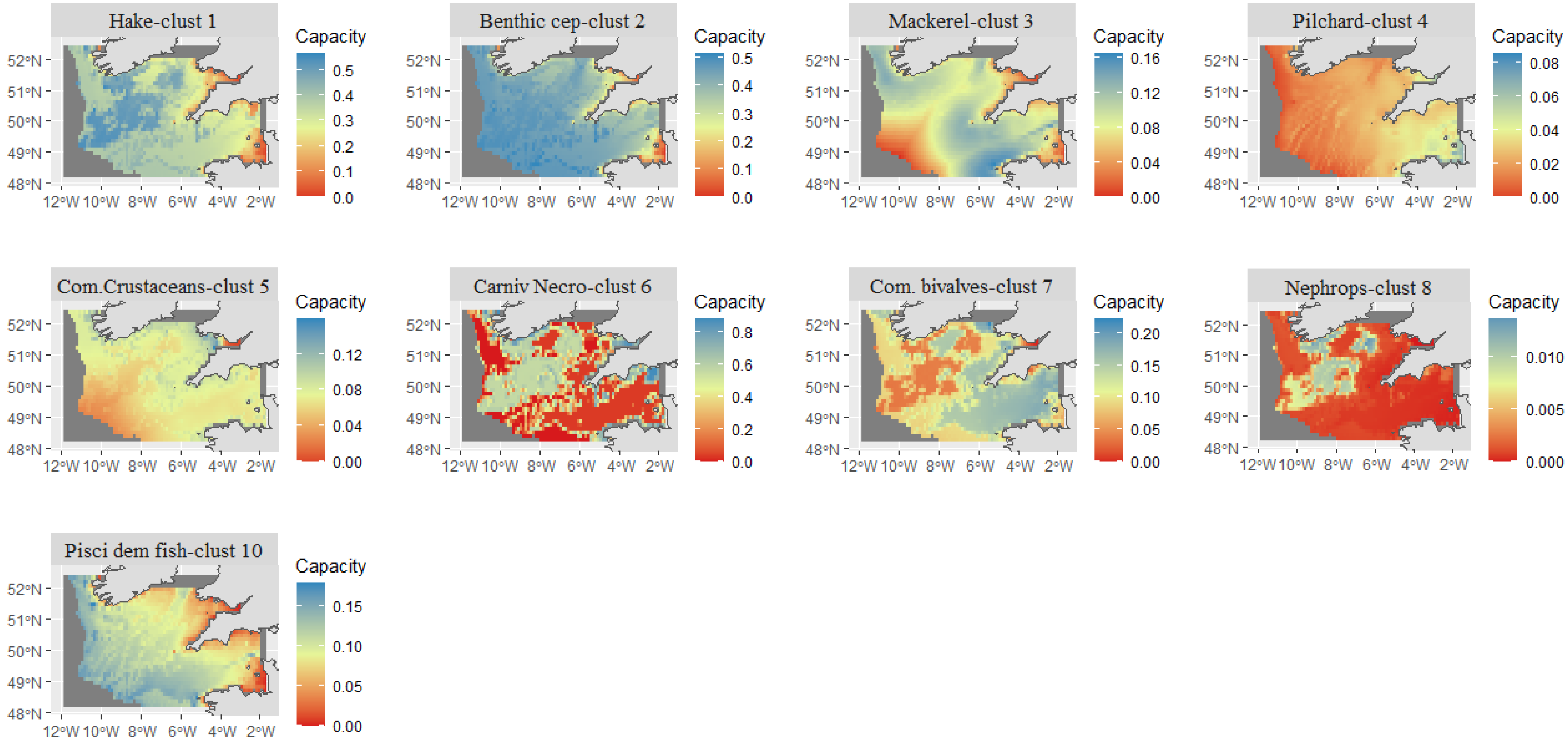
Appendix 29.- Effort multiplier maps by fleet cluster



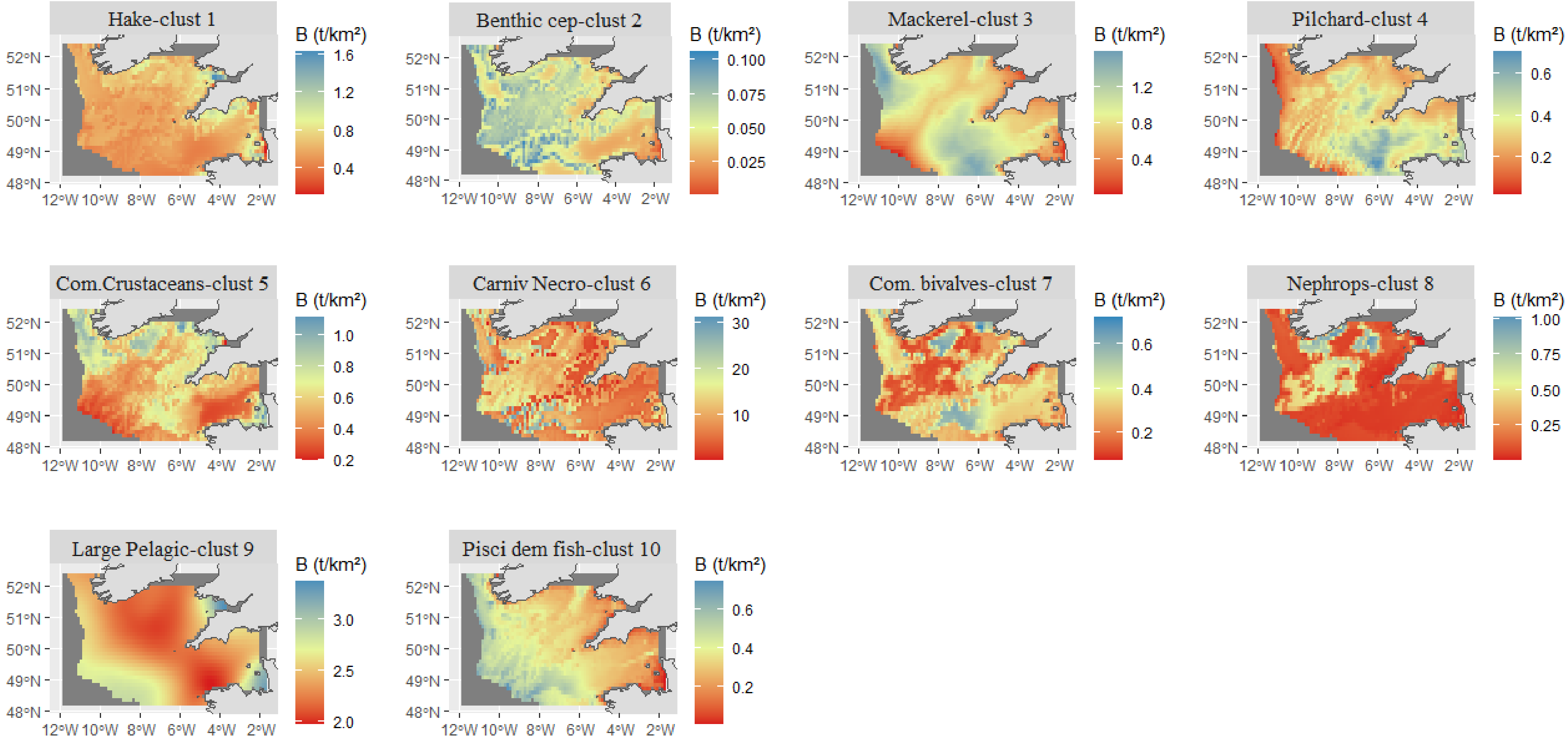
Appendix 30.- FDI database catches by cluster and statistical rectangle over 2015-2016



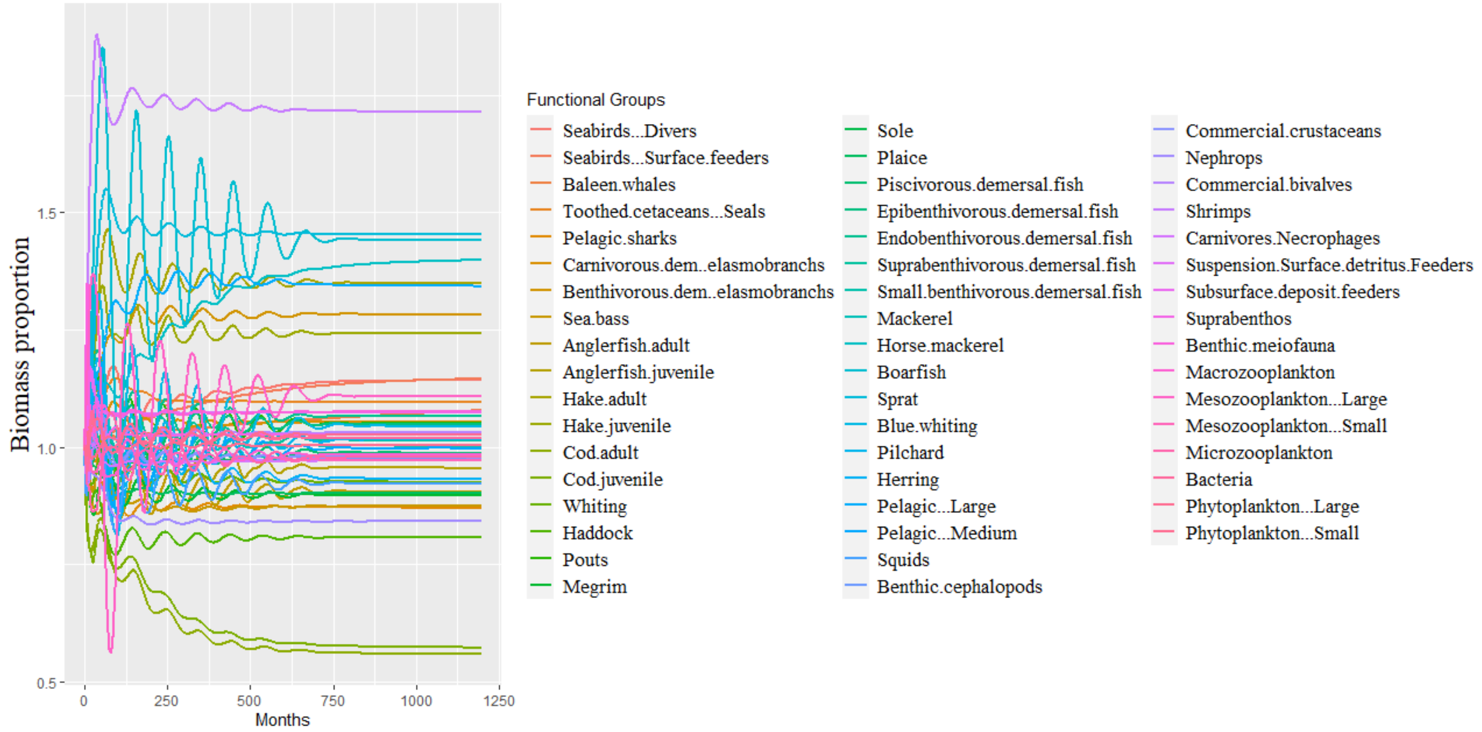
Appendix 31.- Habitat capacities of main species fished by cluster for 2010-2016



Appendix 32.- Distribution of main species fished by cluster for 2010-2016



Appendix 33.- Relative biomass of functional groups simulated by Ecospace from the 2013 Ecopath model



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Nb pages : 40 **Annexe(s) :** 33	**Maîtres de stage:** Didier GASCUEL, Marie SAVINA-ROLLAND, Marianne ROBERT
Année de soutenance : 2021	

Titre français : Etude des impacts temporels et spatiaux des flottilles de pêche mixtes sur l'écosystème de la mer Celtique dans le cadre du changement climatique via la modélisation trophique

Titre anglais: Investigating temporal and spatial impacts of mixed fisheries fleets on the Celtic Sea ecosystem in the frame of climate change through trophic modeling

Résumé : Le changement climatique (CC) et la pêche ont un impact sur les écosystèmes marins. La modélisation écosystémique (ex : Ecopath with Ecosim) est un outil clé pour les étudier et envisager une approche écosystémique des pêches. Notre cas d'étude, la mer Celtique (MC), est un écosystème exploité par des pêcheries mixtes. L'existence de ces pêcheries amène à penser à une gestion par flottille plutôt que par quotas monospécifiques. Un modèle Ecopath existe pour la MC mais ne représente pas la complexité de ses pêcheries. Sur cette base, l'étude vise à comprendre l'impact des flottilles dans le cadre du CC. Les flottilles sont définies et incorporées au modèle via une méthode d'analyse de données de débarquements (ACP) suivie d'une classification (CAH). Leur impact dans le cadre du CC est analysé via certains indicateurs pour une année puis dans le temps et l'espace en effectuant des scénarios de CC et de gestion de pêche et calculant 4 indicateurs écosystémiques. Le CC semble diminuer la biomasse des prédateurs et les captures. Parmi les scénarios effectués sur l'effort par flottille et la mortalité par espèce, l'objectif de "récolte équilibrée" semble aggraver les effets du CC alors que la cible 0,8 Fmsy semble les compenser (dans certaines zones de la MC) même si les résultats ne sont pas toujours significatifs par rapport au status quo avec ou sans CC. Certaines flottilles sont plus impactantes et les flottilles ciblant les hauts niveaux trophiques ou d'engins actifs semblent être des leviers pour améliorer la santé des écosystèmes.

Abstract: Climate change (CC) and fisheries impact marine ecosystems. Ecosystem modeling, as Ecopath with Ecosim framework, is a key tool to study those impacts and to think of an ecosystem approach to fisheries. This study focuses on the Celtic Sea (CS), an ecosystem exploited by highly mixed fisheries. The existence of mixed fisheries leads to think of a management by fleet rather than by single-species quotas. An Ecopath model exists for the CS but does not take account of the mixed fisheries' complexity. The aim of this study is to investigate temporal and spatial impacts of mixed fisheries CS fleets in the frame of CC by modifying this model. The first step was to define fishing fleets to incorporate in the model using a method of analysis landings data analysis (PCA) followed by a clustering (HAC). The impact of fishing fleets for a given year was analyzed through different impact's indicators. Finally, fleets' impact in the frame of CC were investigated through time and space by making CC and fisheries management scenarios and studying different ecosystem indicators. Among 5 over 34 fleets seemed to be quite impacting. CC change appear to decrease predator biomass and catches. Within scenarios made on the effort by fleet or fishing mortality by species, the "balanced harvest" target seemed to worsen CC effects when the 0.8Fmsy target seemed to compensate it (only in some parts of the CS) even if results are not always significant compared to status quo with or without CC. Fleets targeting high trophic levels or using active gears appear to be levers to improve ecosystem health.

Mots-clés : changement climatique, modélisation écosystémique, pêcheries mixtes, gestion des pêches

Key Words: climate change, fisheries, ecosystem modeling, mixed fisheries, fisheries management