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Année universitaire : 2022-2023 Spécialité : Agronome Spécialisation (et option éventuelle) : Sciences Halieutiques et Aquacoles (REA)	**Mémoire de fin d’études** ☒ d'ingénieur de l’Institut Agro Rennes-Angers (Institut national d'enseignement supérieur pour l'agriculture, l'alimentation et l'environnement) ☐ de master de l’Institut Agro Rennes-Angers (Institut national d'enseignement supérieur pour l'agriculture, l'alimentation et l'environnement) ☐ de l’Institut Agro Montpellier (étudiant arrivé en M2) ☐ d’un autre établissement (étudiant arrivé en M2)

Analysing the joint effects of climate change and fishing in the Celtic Sea: towards the selection of impact indicators on ecosystem functioning and productivity

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(Pelagis, 2023)

Soutenu à Rennes ***le 13/09/2023***

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Remerciements

Je tiens à remercier en premier lieu Mikaela, qui s'est montrée toujours disponible pour répondre à mes questions, m'aider, m'encourager et me rassurer quand j'en avais besoin.

Merci aussi au reste de l'équipe encadrante, Marie, Marianne et Didier pour le temps que vous m'avez consacré et pour tous vos précieux conseils, qui me seront utiles également pendant ma thèse. Ce stage aura été l'occasion de découvrir le monde de la recherche, avec tous ses imprévus et contre-temps. Merci de m'avoir donner l'occasion d'embarquer sur la campagne PELGAS pendant mon stage.

Enfin, merci à l'ensemble de l'équipe du labo pour tous les bons moments passés ensemble. Merci particulièrement à tous les adeptes de mots fléchés et aux joueurs de palet.

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Introduction

For many marine ecosystems, climate change and fishing represent the two greatest pressures (Halpern et al., 2015). Climate change has numerous effects on ecosystems. The impact of climate change is already being felt on ecosystems, with shifts in pH, temperature, oxygen levels, and food availability leading to changes in their structure, function, and ability to adapt (Henson et al., 2017). These lead to changes in primary production, shifts in species distribution and changes in community composition (Cheung et al., 2013; McLean et al., 2018; Merillet et al., 2020). These effects could lead to mismatches between preys and predators (Dulvy et al. 2008). The effects of fishing on marine populations include a reduction in their diversity, by a decrease in the number of age groups, a spatial contraction, a loss of population sub-units, and changes in life-history traits (Law et al., 2000; Perry et al., 2010). Long-lived species are replaced by short lived species with faster life histories (decrease of age and size of maturation) (Planque et al., 2010). Moreover, intensively exploited ecosystems tend to shift towards stronger bottom-up control, where top predators are depleted. The removal of top predators simplifies the ecosystem structure and reduces its diversity (Ellingsen et al., 2015). In summary, fishing leads to less resilient, more unstable ecosystems. Intensive fishing increases the vulnerability of ecosystem to climate change (Gascuel, 2019; Perry et al., 2010). The vulnerability can be defined as the degree to which ecosystem and associated functions are likely to change when exposed to multiple threats (Turner et al., 2003). The effects of fishing and climate change interact in complex ways (Planque et al., 2010). To be sustainable, fisheries management must take these cumulative effects into account, as well as existing interactions between different ecosystem compartments.

Traditional European fisheries management is characterised by a single stock approach and does not seem to be enough to keep healthy and productive marine ecosystems, especially in a climate change context (Ramírez-Monsalve et al., 2016). The Ecosystem Approach (EA) was first defined at the Convention on Biological Diversity in 2000 as *"a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way"* (CBD, 2000). In 2002, the concept of ecosystem-based approach to fishery management (EAFM) was first explicitly mentioned in the Common Fishery Policy (CFP). In the CFP Reform Regulation of 2013, the ecosystem-based approach to fisheries management was defined as "an integrated approach to managing fisheries within ecologically meaningful boundaries which seeks to manage the use of natural resources, taking account of fishing and other human activities, while preserving both the biological wealth and the biological processes necessary to safeguard the composition, structure and functioning of the habitats of the ecosystem affected, by taking into account the knowledge and uncertainties regarding biotic, abiotic and human components of ecosystems" (EU, 2013). Several terms are associated with EA, like Ecosystem-Based Fisheries Management (EBFM) and Ecosystem Approach to Fisheries (EAF). The previous definition merges the terms of "based" and "approach", which have different meanings in the implementation. "Based" is seen as stronger than "approach" and gives environmental considerations higher importance over socio-economic and social ones, and is not just taking some environmental considerations in conventional fisheries management (Garcia et al., 2003). Although the CFP is moving towards EAFM, some goals and management measures still remain contradictory with EA. For instance, the CFP promotes a management based on Maximum Sustainable Yields (MSY), and the advice system is mostly single stock (Prellezo and Curtin, 2015; Ramírez-Monsalve et al., 2016).

The selection and study of relevant indicators is a key step of implementing EBFM. Indicators have gained significant and legitimate role in monitoring, evaluating, and understanding ecosystem health, human activity impacts, and the efficiency of management strategies (Rice & Rochet, 2005). Among the qualities indicators should have according to Rice & Rochet, 2005, sensitivity is one of the most important to study management measures. In response to recent legal commitments, notably the Marine Strategy Framework Directive (MSFD; 2008/56/EC), Europe recognizes the necessity for indicators, especially in marine ecosystems. The MSFD mandates European Union Member States to attain "Good Environmental Status" (GES) across 11 Descriptors of the marine environment. Descriptor 4 (D4) addresses to marine food webs, requiring normal abundance and diversity to ensure species' long-term abundance and reproductive capacity. The European H2020 SEAwise project (2021-2025) aims to facilitate the widespread implementation of an EBFM in European fisheries and to draw common principles for it (Lynam et al., 2023). This study is part of the SEAwise project, with a focus on the Celtic Sea case study.

The Celtic Sea (*Appendix 1*) covers a significant part of the continental shelf in Western Europe, from the Western English Channel to the Celtic break delimiting Porcupine Sea Bight and the South-West of Ireland (Hernvann et al., 2020). This ecosystem is at the interface between Lusitanian and Boreal provinces meaning that it delimits the northern and southern limit of the distribution range of many species (Hatun et al., 2009). It is characterized by a diversity of substrate and in consequence a diversity of benthic habitats. A high biological diversity results in this variety of environmental conditions (Ellis et al., 2013, Martinez et al., 2013): The Celtic Sea presents some environmental gradients: depth (NE/SW), SST (latitudinal), SBT (two opposed pools of warm/cold waters) and salinity (lower near to coastal areas). Primary production in the Celtic Sea is relatively high. The coastal areas exhibit the highest values due to the presence of a mixing front (Sharples et al., 2013). This area displays a relative stability of the ecosystem regarding to other neighbouring regions (Kempf et al., 2022) due to the complex spatial structure and high biodiversity, the contribution of both benthic and pelagic pathways (Hernvann et al., 2020).

Fishing was defined as the first driver of ecosystem changes since 1950 (Gascuel et al., 2016; Merillet et al., 2020). The spike of fishing effort was reached in the 1990s, with a minimum level of stock biomass, especially the demersal ones. A reduction of fishing effort began in the mid-2000s, with the implementation of restrictive management measures. The Celtic Sea fisheries are highly mixed fisheries: a large diversity of gears exploits this area, targeting a wide diversity of species assemblages (Moore et al., 2019). The main gears used are bottom trawls and pelagic trawls, accounting for the highest fishing effort (in terms of hours fished) and landings. Bottom trawling is more prominent in the northern part of the Celtic Sea, while pelagic trawling is concentrated along the continental slope in the southwest. (Guénette & Gascuel, 2012). The majority of the landing comes from pelagic species. Demersal fisheries, less selective, are characterized by a high level of discards. Cod is the emblematic choke species. This area is exploited by 14 countries. Norway, Netherlands and Denmark exploit mostly pelagic species, whereas the UK and UE countries have a larger range of exploitation, targeting pelagic, demersal, deep sea and shellfish species (Mateo et al., 2017). Concerning the management, TAC and quotas are restrictive since the 1990s. Fishing pressure is managed at the MSY (Maximum Sustainable Yield). There is a precautionary approach for the biomass (Bpa). The MSY reference points are not known for a large number of stocks, especially for elasmobranch and demersal species (ICES, 2020). The relative stability is called into question in the last decades. In the future, changes in the functional structure of the communities are expected as climate change effects become more visible and overlay fishing ones (Merillet et al., 2021).

A shift in phytoplankton composition was identified with a decrease of large phytoplankton and an increase of the small one. A decrease of small mesozooplankton and an increase of large is also reported (Hernvann et al., 2020). Moreover, a net warming since the mid-1990s is observed. It can be explained by a shift in the Atlantic Multidecadal Oscillation and especially by climate change. These changes have consequences on the Boreal/ Lusitanian species' productivity and distribution. Boreal

species in the Celtic Sea show a decrease in productivity with a spatial concentration. On the other hand, there is an increase in productivity observed in Lusitanian species. Moreover, a decline of trophic diversity is observed overall the whole Celtic Sea, especially in coastal areas (Hernvann et al., 2020). The numbers of many seabird species breeding in the region have been declining in the past decade (ICES, 2022). Regarding fishing, catches have shown a decrease in trophic levels over the past few years (Pinnegar et al., 2002; Gascuel et al., 2016), suggesting a fishing-down (Pauly et al., 1998) or fishing-through effect on the marine food web (Essington et al., 2006). A shift towards a more pelagic-dominated ecosystem has been observed since 1907 (ICES, 2022). Pelagic fish have dominated Celtic Sea biomass since the 1970s, but the balance in the composition of species has shifted ("pelagic waltz"). Following rapid overexploitation, mackerel biomass sharply declined in the early 1980s (Lockwood & Shepherd, 1984). Horse mackerel, once a bycatch during mackerel's peak, prospered in the niche left by mackerel, transforming into a new target species for pelagic fleets (Eaton, 1983). Subsequently, as horse mackerel faced depletion, boarfish emerged as the primary fished pelagic species, especially after 2000.
While some fish stocks have shown signs of recovery due to stricter fishing management (Kempf et al., 2022), overall recovery is limited due to environmental changes. The current biomass of the main targeted stocks is equivalent to that of 1980, which is three times smaller than the biomass in 1950 (Hernvann & Gascuel, 2020). The overall current fishing mortality (multi stock assessment) for pelagic and demersal species is still above Fmsy (ICES, 2022).

Gascuel *et al*., 2012, highlight that ecosystem-based approach is particularly needed in areas where multiple fleets and gears share diversity of target species, and it is the case of the Celtic Sea. The interactions between species and between fleets must be considered. Fishing management needs to change from mostly species-based to fleet-based, to take into consideration these interactions (Ulrich et al., 2017). With climate change, the uncertainty of environment is increasing and must be taken into account in management, by more precautionary measures. To cope with EBFM objectives, a global decrease of fishing effort is needed in the Celtic Sea. But how should fishing effort be reduced? What potential fishing strategies can be implemented in the Celtic Sea to ensure a good state of ecosystem and to mitigate climate change effects? Change in fishing effort and intra and inter-species selectivity can be investigated.

The aim of our study is to select a set of indicators sensitive to fishing pressure and climate change, and to investigate their response under a range of simulated fishing strategies. This study is driven by the following issue**: In the context of ecosystem-based fishery management, which indicators are relevant to assess the effects of climate change, fishing pressure and inter and intra-species selectivity scenarios on the ecosystem? How do fishing management scenarios affect the different components of the ecosystem, as emphasized by these indicators?**

To answer this question, an EwE (Ecopath with Ecosim) model is used. EwE is an end-to-end model, which represents trophic functional groups from primary producers to large predators and fisheries. The interactions between functional groups, fisheries and the abiotic environment are modelled (Coll et al., 2015). A first model for the Celtic Sea and Bay of Biscay was developed by Guénette and Gascuel (2012). Then, improvements have been done. Hernvann, 2020, included spatial dimension (Ecospace) and incorporated environmental effects on ecosystem functioning. Potier *et al*. (in prep) has brought some improvements to this last model, to better fit with ecological and exploitation reality. Multi stanzas groups have been created to separate juveniles and adults. The model by Hernvann et al. (2020) consisted of monospecific fleets, with each fleet targeting a single species, which is not realistic for mixed fisheries. Potier (2021) redefined fleets in Ecopath to incorporate a multi-species definition.

1. Materials and Methods

1.1. The EwE model

1.1.1. The Ewe modelling framework

- **Ecopath**

The Ecopath with Ecosim (EwE) model is a modelling framework that focuses on the prey-predator interactions among species. (Heymans et al., 2016)

Ecopath (Christensen & Pauly, 1992) is a static mass balanced model. It provides a snapshot of an ecosystem, capturing its interactions and exploitation dynamics. It is an end-to-end model, as it represents the entire ecosystem from primary production to apex predators and fishing exploitation. Species are categorized into functional groups based on their characteristics. Inside a functional group, species are supposed to have similar diet, and biological characteristics. A functional group can be divided into multiple stanzas if life stages exhibit distinct diets, exploitation patterns and/or biological characteristics. Such functional groups are termed “multi-stanza” groups.

The original parameterization assumption of a steady state (developed by Polovina, 1984) was given up for the assumption of mass balance over a time period, usually one year. Two master equations lead Ecopath parameterization: the production equation (1) and the energy balance equation for each group (2).

Equation for the production of each group:
Production by i = Catch of i + Predation on i + Exportation of i + Accumulation of i + other mortality on i

$P_i = Y_i + M2_i.B_i + E_i + BA_i + MO_i.B_i$ (1) (Christensen & Walters, 2004)

where i is one functional group, Yi is the total fishery catch rate of i, M2i is the instantaneous predation rate for the group i, Bi is the biomass of i, Ei the net migration rate (emigration -immigration), BAi is the biomass accumulation rate for i, MOi is the other mortality rate for i. Pi is the production of the group i, calculated as the production of Bi and (P/B)i, the latter one represents in most case the total mortality rate (Z).
The other mortality represents all other sources of mortality neither due to predation nor fisheries:

$$M0_i = \frac{P_i \times (1 - \mathrm{EE}_i)}{B_i}$$

EEi is the ‘ecotrophic efficiency’ of i. (1-EEi) can be described as the proportion of the production that is not utilized in the system.

$$\mathrm{EE}_i = \frac{Y_i + E_i + \mathrm{BA}_i + B_i \times M2_i}{P_i}$$

The predation term M2 in (1) links predators and preys:

$$M2_i = \sum_{j=1}^{n} \frac{Q_j \times \mathrm{DC}_{ji}}{B_i}$$

With Qj the total consumption rate for group j and DCji the fraction of predator j's diet contributed by prey i.

The equation (1) can also be written as:
Production i = Predation on i + other mortality on i + Catch of i + Exportation of i + Accumulation of i

$$B_i \times \left(\frac{P}{B}\right)_i = \sum_{j=1}^{N} B_j \times \left(\frac{Q}{B}\right)_j \times DC_{ji} + \left(\frac{P}{B}\right)_i \times B_i \times (1 - EE_i) + Y_i + E_i + BA_i$$ (Christensen & Walters, 2004)

To parameterize Ecopath, a system is established with a number of linear equations equal to the number of groups. The model solves these equations to determine one of the parameters for each group, including biomass, production/biomass ratio, consumption/biomass ratio, or ecotrophic efficiency. The remaining three parameters, along with other required parameters such as catch rate, net migration rate, biomass accumulation rate, assimilation rate, and diet composition, must be provided for all groups. Once the missing parameters are estimated, in order to guarantee mass balance between the groups, energy balance is assured within each group using the following equation:

Equation for the energy balance for each group:

$$Q_i = P_i + R_i + UA_i \qquad (2)$$ (Christensen & Walters, 2004)

where i is the functional group, Pi the production rate of the group I, Ri the respiration rate of i and the parameter estimated, UAi the unassimilated food of i.

- **Ecosim**

Ecosim is a dynamic model. It allows the representation of past trends (hindcast) and future ones (forecast). The parameters for the first year are given by the Ecopath model of this year. Ecosim is based on a series of coupled differential equations, derived from the Equation (1) from Ecopath. (Walters et al., 1997)

$$\frac{dB_i}{dt} = \text{Production} - \text{Predation} - \text{Other Mortality} - \text{Fishery} - \text{Net migration}$$

$$\frac{dB_i}{dt} = g_i \times \sum_{j=1}^{N} Q_{ji} - \sum_{j=1}^{N} Q_{ij} + I_i - (M0_i + F_i + e_i + i_i) \times B_i$$

where Ii represents immigrations and Fi the fishing mortality rate of the group i. $\sum_{j=1}^{N} Q_{ji}$ is the total consumption by group i and $\sum_{j=1}^{N} Q_{ij}$ is the total predation on i.

In Ecosim, predator-prey interactions are based on the Foraging Arena Theory. This theory implies that the biomass of prey population is divided into vulnerable and invulnerable compartments. Only the vulnerable fraction of preys can be eaten by predators and so trophic interactions take place in the restricted foraging arena with vulnerable preys. Predation rates are dependent on exchange rates between the vulnerable and invulnerable components. This rate transfer determines if the control is top down, bottom up or an intermediate type (Ahrens et al., 2012).
Ecosim considers this theory for the calculation of the consumption rates Qij, which required foraging arena parameters (vulnerable rate transfer, predator rates of effective search). Vulnerability coefficients can be estimated by fitting the model to observed biomass, abundance or catch time-series.

To take into account the environment in the model, forcing time series can be used like temperature, primary production or zooplankton biomass. Forcing time series are drivers of the model. For primary production or zooplankton biomass, it is usually a relative index throughout the simulated years, for abiotic parameters, it is the parameter values throughout the simulated years. Forcing time series of primary production (and zooplankton biomass) act as multipliers of vulnerability, rate of effective search or foraging arena size for each prey, predator or couple preys/predators. Functional groups could have a response function (*Figure 1*) for certain environmental variables (temperature or another abiotic parameter in the forcing time series). When environmental conditions vary, the consumption rates of the species that respond to these conditions are modified.

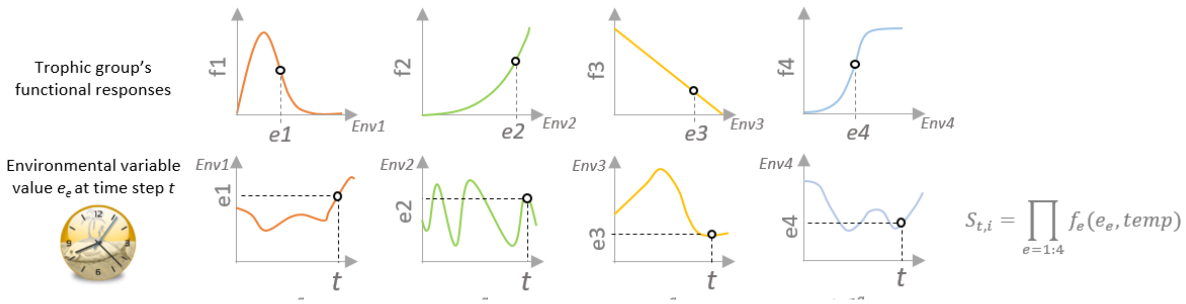


Figure 1. - Integration of environmental effects on functional group consumption in Ecosim (Hernvann et al., 2020). $S_{t,i} = \prod_{e=1:4} f_e(e_e, temp)$: multiplier of the whole consumption of the predator

Times series of biomass and/or catches for the functional groups are used to fit the model in the hindcast period and to reproduce observed temporal trends in the ecosystem. Ecosim can then be used in a forecast way, to do projections in the future.

1.1.2. EwE model of Potier, 2021

In this study, Potier, 2021 has improved Hernvann model (2020). The model represents the ICES sub-divisions 27.7.e-h and 27.7.j2 7 of the Celtic Sea, from the coastline to the 200m isobath. The total area is 246 456 km² (*Appendix 1*).

- **Ecopath**

The Ecopath model represents the year 1985. It is composed of 49 functional groups. 3 multi-stanza groups are available for the main exploited species (cod, hake and anglerfish) in order to (1) fit better to ecological conditions as juveniles can have different diets than adults and (2) test scenarios based on age at first catch.
Fleets are defined in a multi-specific way (one fleet corresponds to several species). 34 fleets are represented in the model. The fleets were decided by performing a principal component analysis on international landings data (FDI2020 over the period 2015-2018).

- **Ecosim**

An Ecosim model has been developed for the period 1985-2016. The model is fitted on time series of observed data for this period. The biomasses for assessed species come from ICES stock assessment for which an assessment has been made, and others from scientific surveys (e.g EVHOE, UK-WCFS, CPR for the plankton). Catches by species come from CIEM working group (but the repartition of these data among fleets in Ecopath come from FDI from STECF and is considered to be constant). The model is forced by fishing mortalities and catches time series (catches only for small benthivorous demersal fish). The forcing functions added to the model are SST and SBT (Sea Surface Temperature and Sea Bottom Temperature respectively), relative primary production, zooplankton annual habitat index (Appendix 2). The phytoplankton forcing function comes from the coupling of two models, POLCOMS

(Holt and James, 2001) - ERSEM (Butenschön et al., 2016), a physical and biogeochemical model, and from a vertical production model with chlorophyll-a data. The zooplankton forcing function comes from a suitable habitat model for zooplankton, and represents the evolution of mesoscale structures which increase zooplankton productivity.

Functional responses to temperature (SBT and SST) are implemented into the model (*Appendix 3*). They are niche models calculated with GAM (Generalized Additive Model) or SCAM (Shape Constrained generalized Additive Model) models from respectively Hernvann (2020) and Hernvann *et al*. in prep. Multi-stanza groups (Anglerfish, cod and hake) have different responses for juveniles and adults. The initial model of Hernvann (2020) used GAM functions. However, the difference of response between the climatic scenarios was low and the use of the SCAM functions developed for the model of Hernvann et al. (in prep) were preferred. In this new model, groups are divided in Lusitanian and Boreal. For pouts, the Lusitanian species represent a major part of biomass so the corresponding function are chosen. For piscivore demersal fish and elasmobranchs, it is more complicated and the boreal function are chosen, in a precautionary way (more negative view with stronger response functions).

A stability test is done during this study *(Appendix 4).*

1.2.The indicators

1.2.1. Calculation of the indicators

To compare the different scenarios, 16 different indicators are used (*Table 1).* This study follows guidelines of the task 4.4 of SEAwise (Lynam et al., 2023). The SEAwise protocol is detailed in *Appendix 5*. The majority of the indicators used are taken from SEAwise and others are chosen to complete the list (from the IndiSeas European projects especially). 1/CV, MLS, the proportion of predators come from IndiSeas, API and Community Weighted Variance are also added. SEAwise uses the proportion of mature fish for size structured models, but in this study it seems more relevant to use the proportion of immature fish for the multi-stanzas groups.

The indicators reflect changes in evenness, richness, community composition and functional characteristic, trophic structure, in order to detect a change in the resilience and vulnerability of ecosystem. Resilience can be defined as the system's ability to bounce back to a reference state after a disturbance (DeAngelis, 1980) and the capacity of a system to maintain certain structures and functions despite disturbance (Holling, 1973). These indicators can be classified in several categories which are *biomass*, *composition within fish communities*, *pressure and impact*. Based size indicators are relevant as body size has been described as a super trait, determining many others and which can affect food web structure and energy flux, such as trophic level, access to resources, vulnerability to predation and sensitivity to perturbation (Brose et al., 2017). Some indicators are calculated for several species' groupings (SEAwise protocol-*Appendix 5*). They can be calculated either by pelagic/demersal groups or by trophic guilds (planktivorous, benthivorous and piscivorous groups). In total, 59 indicators are calculated, as variations of the 16 original indicators.

A function has been created in R (version 4.2.2) to calculate each indicator for a chosen time period and a chosen group. They have been incremented in a "for" loop to calculate them for each scenario.

For the *community size and age composition* indicators, the trait information (length and age) has been taken from survey data in the Celtic Sea used by SEAwise (*Appendix 5*). For the calculation of the LSI and the MML, the Lmax was choosen as a proxy of Linf (SEAwise protocol, *Appendix 5*). For the LSI, the threshold of 80cm has been used (*Appendix 6).*

Table 1.- List of indicators (Biomass, composition within fish communities, food webs, pressures). Red : Seawise indicators, Blue : Indiseas. (Pk : planktivores, Ps : piscivores, Be : benthivores). n = number of functional groups in the considered category, k = number of multi-stanzas groups, i = functional group considered

Indicator	*Description*	*Definition*	*Use*	*References*
Biomass				
Guild level biomass	t *All, fish, Pk, Ps, Be*	$\sum_{i=1}^{n} B_i$	Monitor change in ecosystem structure. Resource potential	(Thompson et al., 2020)
Ratio of biomass	Pairwise comparisons of trophic guilds	$\frac{B_{guild\ 1}}{B_{guild\ 2}}$	Ecological balance between functions	(Thompson et al., 2020)
1/CV	Inverse of coefficient of variation *total biomass*	$\frac{Mean_{total\ biomass}}{sd_{total\ biomass}}$ Mean/ sd for the last 10 years	Stability of the ecosystem	(Shin et al., 2010)
Composition within fish communities				
Shannon	Shannon diversity *all fish, demersal, pelagic, Pk, Ps, Be*	$-\sum_{i=1}^{n} pi.log2(pi)$ Pi = Bi/Btot Bi : biomass of the group i	Evenness in biomass distribution	(Hill, 1973)
LSI	Large species index biomass proportion of large species in a community *Fish, demersal*	$\frac{\sum_{i=1}^{n} B_i.I(l_i \geq g)}{\sum_{i=1}^{n} B_i}$ g = 0.80 cm I = 1 if $I(l_i \geq g)\ true$ Else I = 0	Changes in the abundance of species of different size	(Shephard et al., 2012)
PropMat	Proportion of immature fish for *multi-stanza group*	$\frac{\sum_{i=1}^{k} B_{juv,i}}{\sum_{i=1}^{k} B_{tot,i}}$	Productivity metric	-
MML	Mean Maximum Length. cm *Fish, demersal, pelagic, Ps, Pk, Be*	$\frac{\sum_{i=1}^{n} B_i.L_{inf,i}}{\sum_{i=1}^{n} B_i}$ Linf = Lmax	Changes in community composition	(OSPAR, 2017)
MTL	Mean trophic level of the community. *All species, fish, Pelagic, demersal, Ps, Pk, Be*	$\frac{\sum_{i=1}^{n} B_i.TL_i}{\sum_{i=1}^{n} B_i}$ + alternative forms with cut-off at a minimal trophic level (2, 3.25,4)	Effect of fishing on the food web	(OSPAR, 2017) (Shannon et al., 2014)
Prop_Pred	Proportion of predatory fish *Fish*	$\frac{\sum_{i=1}^{n} B_i(TL \geq 3.5)}{\sum_{i=1}^{n} B_i}$	Regulation, sensibility to environmental variability	(Shin et al., 2010)
MLS	Mean life span *Fish, demersal, pelagic*	$\frac{\sum_{i=1}^{n} B_i.age_{max,i}}{\sum_{i=1}^{n} B_i}$	Turnover rate of species, communities. Buffering capacity, stability, resistance of the ecosystem	(Shin et al., 2010)
API	Apex predator indicator *All species*	$\frac{\sum_{i=1}^{n} B_i(TL \geq 4)}{\sum_{i=1}^{n} B_i(TL \geq 3.25)}$	Fishing pressure, focus on the most impacted group.	*(Bourdaud et al., 2016)*
CWV	Community Weighted Variance Variation in trait values within the community. Length, age-max *Fish, demersal, pelagic*	$\sum_{i=1}^{n} p_i.(x_i - CWM)^2$ p_i : relative biomass of group i x_i the trait value of group i CWM: community weigthed mean of trait	Trait convergence or divergence. Community responses to environmental or management changes	(Beukhof, 2019)

Pressure and impacts				
MTLc	Mean trophic level of catch *All catches*	$\frac{\sum_{i=1}^{n} C_i.TL_i}{\sum_{i=1}^{n} C_i}$	Catch diversification, fishing down/through the marine food web	(Shin et al., 2010)
Depletion	Depletion risks within the community *all fish demersal, pelagic, Ps, Pk, Be*	$D_{i,E} = \begin{Bmatrix} 0 \ \ if\ SSB_{i,E} \geq SSB_{i,0} \\ \left(1 - \frac{SSB_{i,E}}{SSB_{i,0}}\right) otherwise \end{Bmatrix}$ $D_{G,E} = \frac{\sum_{s=1}^{n}(s^{-1}.D_{s,E})}{\sum_{s=1}^{n}(s^{-1})}$ G : relevant group (guild, community) E : fishing effort s : rank order of the species. s=1 for the species with the maximum $D_{s,E}$	Potential impacts of spawning stock biomass depletion	(Thorpe & De Oliveira, 2019)
Land_chloro	*Landings/chlorophyll* *All catches*	$\frac{\sum_{i=1}^{n} Landings_i}{B_{phytoplankton}}$	Delineate Ecosystem Overfishing	(Link and Watson, 2019)
Tot_catch	*All catches*	$\sum_{i=1}^{n} C_i$	Exploitation efficiency	(Lynam et al., 2023)

1.2.2. Selection and indicators analysis

The indicators and the scale of calculation (e.g trophic guild, pelagic/demersal) which present the best response to changes in fishing pressure and climate are investigate. All the indicators are calculated for the decade 2090s decade, in order to investigate the long-term effects of fishing and especially climate change and not only climate variability. (Philippart et al., 2011).

PCA (Principal Component Analysis) is used to separate indicators in multivariate ordination space, to rank indicators relative to one another in terms of explanatory power and response to changes in fishing pressure and environment, and to examine indicators redundancies. 4 PCAs for the different categories of indicators are done: *biomass* (21 indicators), *trophic* (15), *trait-based* (23), *structure of the community* (10). The statistical individuals are the different simulations (combination of fishing and climate scenarios). The quantitative active variables are the indicators and the scenarios are put in illustrative variables (climatic scenario and fishing multipliers mF). 21 individuals are considered (3 climatic scenario X 7 mF). The PCAs are done with the package FactoMineR. The function dim.desc is used to investigate the correlations between dimensions and active/ illustrative variables. A one way analysis of variance with the coordinates of the individuals described by the categorical variables is done to investigate the correlation between the illustrative variables and the dimensions (fisher test for the p value). For each modality of the illustrative variable, a student test is done to compare the average of the modalities to the overall mean.

Then, the redundancy between indicators is investigated in two ways: firstly, by using the position of the variables in the PCA correlation graphic if the variables are well projected (cos2) and secondly by using the Pearson correlation coefficient between variables. The Spearman coefficient could have also been used, but the PCA hypothesis of a linear relationship between variables was retained.

<u>The criteria to select indicators were the following:</u>

- Eliminate those not significantly correlated with fishing or climate change scenarios

- Among the highly correlated to a dimension, if a scale of calculation (position in the water column or trophic guild) is redundant with another, the “higher” level of calculation is chosen (all species or all fish)
- If the position in the water column is redundant with a trophic guild, the water column is chosen as it seems to present less uncertainty about the distribution of species within this group. In fact, (1) diets are sometimes ambiguous for omnivorous species, (2) some species have changed their diets significantly in recent years in the Celtic Sea. At the same time, it is sometimes challenging to classify species as demersal or pelagic, such as blue whiting, which is classified as pelagic even though it mostly feeds on demersal species and resides at lower depths in the water column.

If a trophic guild or position in the water column is chosen for an indicator, the all fish or all species level is kept to have a global vision.
A last PCA is done after the selection with all the categories of indicators. Regarding the expected behaviour of indicators, the following assumptions can be made:

- <u>Assumptions on the redundancy among indicators</u>
    - Pelagic and planktivore indicators may be redundant, as benthivore and demersal due to the composition of those groupings (*Appendix 7*)
- <u>Assumptions on the sensitivity of global indicators to fishing and climate change</u>
- MTL are supposed to be among the indicators less sensitive to fishing (Bourdaud et al., 2016)
- Biomass of predators is supposed to be negatively correlated with climate change (Perry et al., 2010)
- <u>Assumptions on the particular behaviour of trophic guilds and position in the water column</u>
- Demersal and predator indicators are supposed to be correlated to fishing. In fact, high trophic level predators in the North Atlantic have decreased by around 66% since the 1950s (Christensen et al., 2003). Additionally, due to overfishing, the stocks of demersal fish species have shrunk by 5-fold or even more (Froese et al., 2008; Worm et al., 2009). A release of fishing pressure is expected to improve the general state of these groups.
- Planktivore fish are mainly pelagic forage fish, except pouts. They have a crucial role in the ecosystem by transforming zooplankton production into food available to higher trophic levels (Cury et al., 2000). They are expected to respond strongly to climatic changes (Tourre et al., 2007). Likewise, pelagic group is supposed to be sensitive to climate change.

1.2.3. <u>Indicator thresholds</u>

As in SEAwise, thresholds for indicators are investigated utilizing depletion indices (Appendix 5). The objective is to prevent the occurrence of low biomass for any individual species within the community. Here, "low" corresponds to a state of over-exploited depletion, defined as 30% of the SSB at a virgin state. For this study, the depletion index threshold values from the Bay of Biscay were adopted due to time constraints preventing the calculation of thresholds specific to the EwE Celtic Sea model. A threshold value of 0.48 is considered for the depletion indice, with an additional value of 0.49 for the demersal depletion indice. Indicators displaying linear or curvilinear relationships with the depletion index can be utilized to determine thresholds for these indicators.

1.3. Presentation and comparisons of scenarios

Table 2. – Summary of the different fishing, climate and recovery scenarios
Fishing scenarios in blue are used to study the response of the indicators to fishing intensity and climate change. Those in purple are used to investigate the response of the indicators to changes selectivity in an intermediate climate change scenario.

Fishing scenario	Climate scenario	Period of calculation of indicators	Recovery
All fleets scaled equally **mF = [0, 0.2,0.4,0.7,1,1.5,2,2.5]**	Constant climatic conditions (WCC): mean of 2014,2015, 2015 environmental conditions	2090-2100	Constant environmental conditions (averaging the last 10 years) and setting mF = 0 since 2100. Calculation of indicators for 2125-2135.
All fleets scaled equally **mF = [0, 0.2,0.4,0.7,1,1.5,2,2.5]**	RCP 4.5	2090-2100	-Constant environmental conditions (averaging the last 10 years) and setting mF = 0 since 2100. Calculation of indicators for 2125-2135. -
All fleets scaled equally **mF = [0, 0.2,0.4,0.7,1,1.5,2,2.5]**	RCP 8.5	2090-2100	Constant environmental conditions (averaging the last 10 years) and setting mF = 0 since 2100. Calculation of indicators for 2125-2135.
Sparing juveniles **mF = [0.4,0.7,1,1.5]**	RCP 4.5	2045-2055	X
High discard rate fleets **pmF = [0.4, 0.6, 0.8]**	RCP 4.5	2045-2055	X
High discard rate on elasmobranch fleets **pmF = [0.4, 0.6, 0.8]**	RCP 4.5	2045-2055	X
High trophic level fleets: **pmF = [0.4, 0.6, 0.8]**	RCP 4.5	2045-2055	X
Low trophic level fleets: **pmF = [0.4, 0.6, 0.8]**	RCP 4.5	2045-2055	X
Optimized MSY: specific mF on the 7 most impacting fleets	RCP 4.5	2045-2055	X

- **Presentation of scenarios and main issues related**

In this study, fishing scenarios are used to investigate response of indicator to change in fishing intensity and intra and inter-specific selectivity, in a context of climate change. The scenarios proposed aim to reflect possible ecosystem-based management strategies. Fleet-based scenarios are investigated to represent realistic management policies. The model is forced by fishing mortality by functional group so multipliers of fishing effort by fleets cannot be used directly. The scenarios represented are scenarios of fishing mortality's evolution by functional group. From a technical point, this means incorporating series of fishing mortality per functional group, taking into account changes in the fishing pressure relative to fleet-based scenarios. To do this, the partial fishing mortalities are extracted from Ecopath for the years 2014, 2015 and 2016, once the Ecopath models have been balanced (*Appendix 8*). These partial mortalities indicate the distribution of species fishing mortalities among fleets. A multiplier is applied to the fishing mortalities associated with the selected fleets and the average for the three-years period is calculated. Using these adjusted values, the total fishing mortalities per group is recomputed and incorporated in the model.

During this study, the combination of a fishing scenario and a climate scenario will be called a simulation (*Table 2*). Firstly, the respective effects of climate change and fishery scenarios are examined. Initially, a uniform set of fishing mortality multipliers is applied to all fleets under constant climatic conditions. Afterward, the RCP 4.5 IPCC scenario is incorporated, which represents an intermediate climate change scenario. In order to prepare for the "worst-case" scenario, the RCP 8.5

scenario is then explored. Additionally, the ecosystem's capacity to recover within a 30-year timeframe is examined for each fishing mortality multiplier, similarly to recovery scenario of Seawise (*Appendix 5)*. This aims to investigate resilience. The previous simulations with the three climatic scenarios are extended for an additional 50 years with zero fishing mortalities and constant climatic condition (mean of the 10 last years), to evaluate the long-term effects and recovery time. The objective of recovery simulations is to examine the possible recovery of ecosystem components, to highlight long-term and potentially irreversible effects of fishing in a context of climate change and to identify indicators reflecting these dynamics. Initially, the sensitivity of this recovery to climate change is explored. In the first recovery simulation, the aim is to compare the different climatic scenarios and assess their influence on the recovery process. The reference value to compare with is a zero fishing mortality since 2016 under constant climatic conditions. Then, the sensitivity of recovery to previous fishing intensity is investigated, under the RCP4.5 scenario. Indicators are calculated for the period 2075-2085 for constant climatic conditions since 2050 and comparing with indicators for zero fishing mortality since 2016 in RCP4.5 with also constant climatic conditions since 2050. The upcoming intra and inter selectivity fishing simulation are conducted under RCP4.5 scenario.

- **Spare the juveniles**

Another scenario to explore is the protection of juveniles. Selectivity of fleets can be improved by changing the mesh size to let juvenile fish escape. To fish in a sustainable way, fish should have time to reproduce at least once in their life before being captured. Moreover, escaped juvenile fish could be recaptured later, older and bigger. When fishing effort is high, increasing mesh sizes leads to a lower impact on the resource and a higher catch (Gascuel, 2019). An optimal mesh size optimizes catches in relation to effort. In short, by sparing juveniles, it is possible to fish as much with less impact. For example, for 9 stocks from the North Sea and the Baltic, a scenario involving fishing on sizes beyond Lopt (optimal length where the cohort’s biomass is maximal) while maintaining the same yields as a MSY scenario demonstrates the least impact on the stocks comparing to MSY, with an age structure similar to an unfished stock. This helps juveniles and adults perform their ecological roles more effectively, representing a significant stride toward ecosystem-based fisheries management objectives (Froese et al., 2008). Moreover, sparing juveniles enables to reduce the fishing induced selection on population. For instance, it has been suggested that harvesting only fish above a certain size threshold would lead to an optimal strategy of slower growth and earlier maturation (Miller et al., 1957 and Law et al., 1989 in Jørgensen et al., 2009). To model this scenario, the fishing mortality is set to zero for the juvenile stanzas (cod, hake and anglerfish). The fishing mortality is not reported on the following stanza. The same set of multiplicators as the first scenario is used.

- **High discard rates fleets**

Thereafter, another aspect of selectivity is examined: discard rates. The Celtic Sea fisheries as a highly mixed fisheries present high discard rate (ICES, 2020). High discards rates represent important social, economic and environmental concerns (wasting, threat for some vulnerable species). To tackle this issue, various measures have been implemented, such as the Trevose box closure (EC, 2005), the utilization of squared mesh panels (EC, 2012), and the introduction of the Landing Obligation (Mateo et al., 2017). Two types of simulations are conducted. First, the effort exerted by fleets with high discard rate is reduced using a set of multiplicators, while maintaining the efforts of other fleets unchanged. Then the effort of fleets with high discard rates specifically concerning elasmobranchs is reduced. **To be clear, each set of fishing mortality multipliers that does not concern all fleets will be called partial fishing multipliers (pmF).** High discard rate fleets are selected by filtering those exceeding the third quantile of all fleets. The mean of discard rates from 2016 to 2021 is taken. The data comes from the ICES MIXFISH group database and the Fisheries Dependant Information (FDI; from 2016-2021). Starting in 2016 allows to have the latest trend and the most complete database. The selected fleets are presented in *Appendix 9*.

- **Trophic level of catch**

Then, a scenario with the trophic level of the catch is explored. The potential different impact on the functioning of ecosystem according to the trophic level (TL) of exploitation is investigated. The threshold for high/low trophic level is taken as 3.5 (new trophic threshold for predators). The fishing effort of the low TL fleets and the high TL fleets is reduced, with multiplicators. The details of the selection are available in *Appendix 9*. The description of the code used for each fleet is presented in *Appendix 10*.

- **Optimising MSY for demersal species**

The aim is to estimate F multipliers (mF) for each fleet that will give fishing mortality by functional group (Fi) close to the Fmsy. In Lynam & Mackinson (2015), mF are estimated for 8 species and 3 families of fleets, with classical inference. The same method is used but with Bayesian inference. In our model, 6 commercial species with an MSY reference are represented (Cod, Anglerfish, Plaice, Sole, Seabass, Hake). They are species with a ratio fishing mortality on total mortality higher than 0.45 in the Ecopath model of 2016 (*Appendix 11*). Fmsy were taken from ICES advice for 2020. The 34 fleets are included in the model, but F multipliers will only be estimated for the 7 fleets with the highest mortality rates for stocks with defined MSY tagets (ESP DEF lines, ESP DEF OTB, FRA DEF dorm, FRA DEF tr, IRL DEF tr, OTH DEF TBB, UKM DEF tr). For the other fleets, the multipliers are set at 1. The partial mortality matrix (mortalities for each fleets and functional group) in the 2016 balanced Ecopath model is used. The relationship between the partial fishing mortality and the fishing effort of fleet is assumed to be linear (total instantaneous fishing mortality for a species is calculated as the linear summation of the catchability coefficient on the species for a fleet, multiplied by the standardized fishing effort exerted by this fleet, Murawski and Finn, 1986).

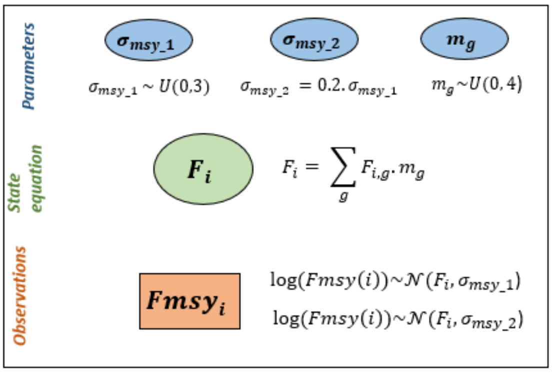


Figure 2.- Bayesian model

A Bayesian model (*Figure 2*) is built to estimate the fishing mortality multiplier mF for each fleet. The equation of state of the process is deterministic, involving linear combinations between mF and partial mortalities, which are then summed to obtain an estimated fishing mortality F for each species. We want estimated F to be as close as possible to Fmsy for each group. A uniform distribution is assumed for the parameters mF. The likelihood function between F estimated and Fmsy follows a lognormal distribution, with parameter sigma_msy. Sigma_msy is estimated with a uniform distribution between 0 and 4. Our model did not fit well for some species, with Festimated too much higher than Fmsy. A higher accuracyof fit is forced for these species (Cod, Anglerfish, Hake and Plaice), with a sigma_2 5 times smaller than sigma_msy. The results of the estimation are presented in *Appendix 12*.

- **Comparison of scenarios**

In the SEAwise task 4.4 (*Appendix 5*), the reference values for the indicators are calculated for a "virgin" ecosystem. This reference will be taken for analysing our recovery scenario. A scenario with no fishing pressure and no climate change will be considered to be a proxy for a "virgin" ecosystem. The difference between indicators at the virgin state and after 30 years of stopping fishing pressure is calculated. To compare fishing and climate scenarios, the reference is the status quo in fishing (mF =1) and in climate (constant climatic conditions). This reference allows to assess the effect of fishing and of climate change. To investigate changes in intra- and inter-selectivity fishing scenarios, the reference taken is the status quo in fishing with RCP 4.5 scenario, to assess the effects of the exploitation pattern on the ecosystem in a context of climate change.

2. Results

2.1. Which set of indicators are relevant to assess the effects of climate change and fishing strategies?

2.1.1. Which indicators are correlated with fishing and climate change?

The detailed results of the PCAs are available in *Appendix 13.* The *Table 3* resumes the indicators positively/negatively correlated to fishing intensity or climate change scenario.

- **Biomass-based indicators**

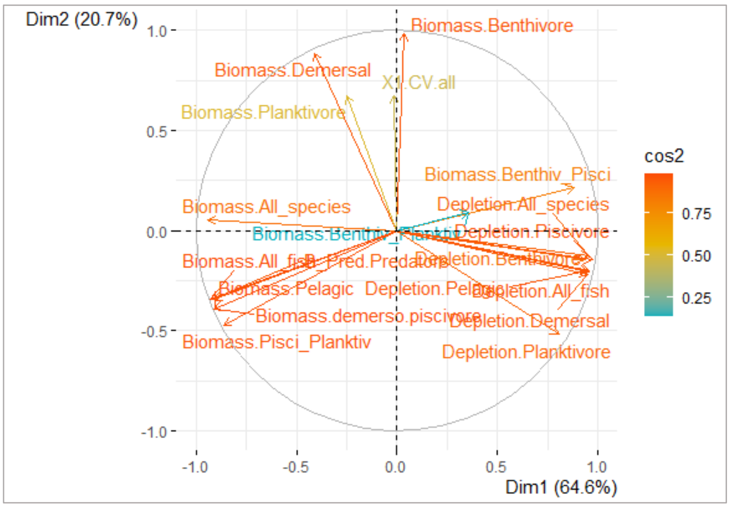


Figure 3. – Variable correlation diagram, PCA analysis with biomass indicators

The first two dimensions of the PCA explain 85**%** of the total dataset inertia. The illustrative variable mF explains significantly 87 % of the variability on the first dimension (so 55 % of the variability on the total dataset). The individuals corresponding to a fishing multiplier of 2.5 have higher coordinates on the dimension on average while those with the multiplier of 0.2 have lower ones. The depletion indices and biomass benthivore/piscivore are highly positively correlated with the first dimension (from 0.97 to 0.81). The biomass of all fish, all species, predators, piscivores, pelagics, piscivores/pelagics are highly negatively correlated to the first dimension (from -0.94 to -0.86). (*Figure 3*)

The second principal component (21% of the variability explained) is representative of a climate change scenario effect. Climate scenario explains 58% of the variability on the second dimension (so 12% of the total variability). The individuals corresponding to constant environmental condition have higher coordinates on the dimension on average while those corresponding to RCP 8.5 have lower ones. It does not seem to have a lot of differences in the constant climatic scenario and the RCP 4.5. The biomass of benthivores (0.98), demersals (0.89), planktivores (0.67) and the inverse coefficient of variation (0.67) are positively correlated with the second dimension, and therefore negatively with an increase of climate change intensity. 1/CV and Biomass of planktivores have a lower quality of projection on the first plan. The depletion of planktivores (-0.52) and the biomass of piscivores/planktivores (-0.48) are negatively correlated with the second dimension (positively with an increase of climate change intensity).

Biomass indicators are correlated to fishing and climate change, especially the biomass of demersals and benthivores for climate change.

For the other indicator categories, correlation graphs for the variables and detailed analysis of the results are available in *Appendix 14*. Below are the main conclusions and the table X summarising the key information.

- **Trophic indicators**

Trophic indicators are correlated to fishing intensity, low correlation is found with climate change and it concerns especially MTL of benthivore and planktivores.

- **Community structure indicators**

All Shannon indices are correlated to fishing intensity scenarios, as the proportion of predators. API shows less correlation. Community structure indicators demonstrate low correlation to climate change, except the proportion of immatures.

- **Trait-based indicators**

Trait-based indicator appear to be more correlated to fishing intensity than to climate change. CWV_ age_max_demersal is the trait-based indicator the most correlated to climate change.

Table 3.- Correlation of the indicator to fishing, climate change or both according to the ACPs results. Indicators in red show positive correlations while those in blue show negative correlations. Indicators in bold with a + are highly correlated and well projected on the plans.

	F	CC	F + CC
Biomass	**Depletion indices +** Benthivore/piscivore **Biomass all fish, all species, predators, piscivore, pelagic, piscivore/planktivore +**	Depletion planktivore Piscivore/Planktivore **Biomass benthivore and demersal +** Biomass of planktivore 1/CV	
Trophic	MTL piscivore **MTL dem, pelagic +** **MTL all species, all fish +**	**MTL benthivore** +, planktivore	
Community structure	**Shannon all fish, piscivore, pelagic/demersal +** **Prop predators, Shannon benthivore +** Shannon planktivore, all species, API	Proportion of immatures	
Trait-based	**All CWV indices +** MML pelagic, **piscivore +** MLS piscivore LSI all fish **MML dem, plk +, benthi +** **MLS dem, pel, plk, benthi, all fish +** **LSI demersal +** MML all fish		**CWV age max dem +** MLS piscivore MML all fish LSI all fish MML Pelagic

2.1.2. Is the position in the water column (pelagic/demersal) a relevant trait for distinguishing indicators? Likewise, is it worth to differentiate indicators according to trophic guilds? Which indicators are correlated with each other?

- **Biomass-based**

According to the correlation diagram (Figure 4) and the projection of indicators in the PCA, three sets of biomass-based indicators can be identified. The first involves all depletion indices except planktivore, biomass of all fish, all species, predators, pelagics, piscivores and piscivore/planktivore ratio. In this set, the biomass of all fish will be retained (highly correlated with fishing scenarios, well-projected on the first plan). The second comprises biomass of demersals with biomass of benthivores. The biomass of demersals will be preferred to benthivores (both are highly correlated with climate change scenarios and well-projected).

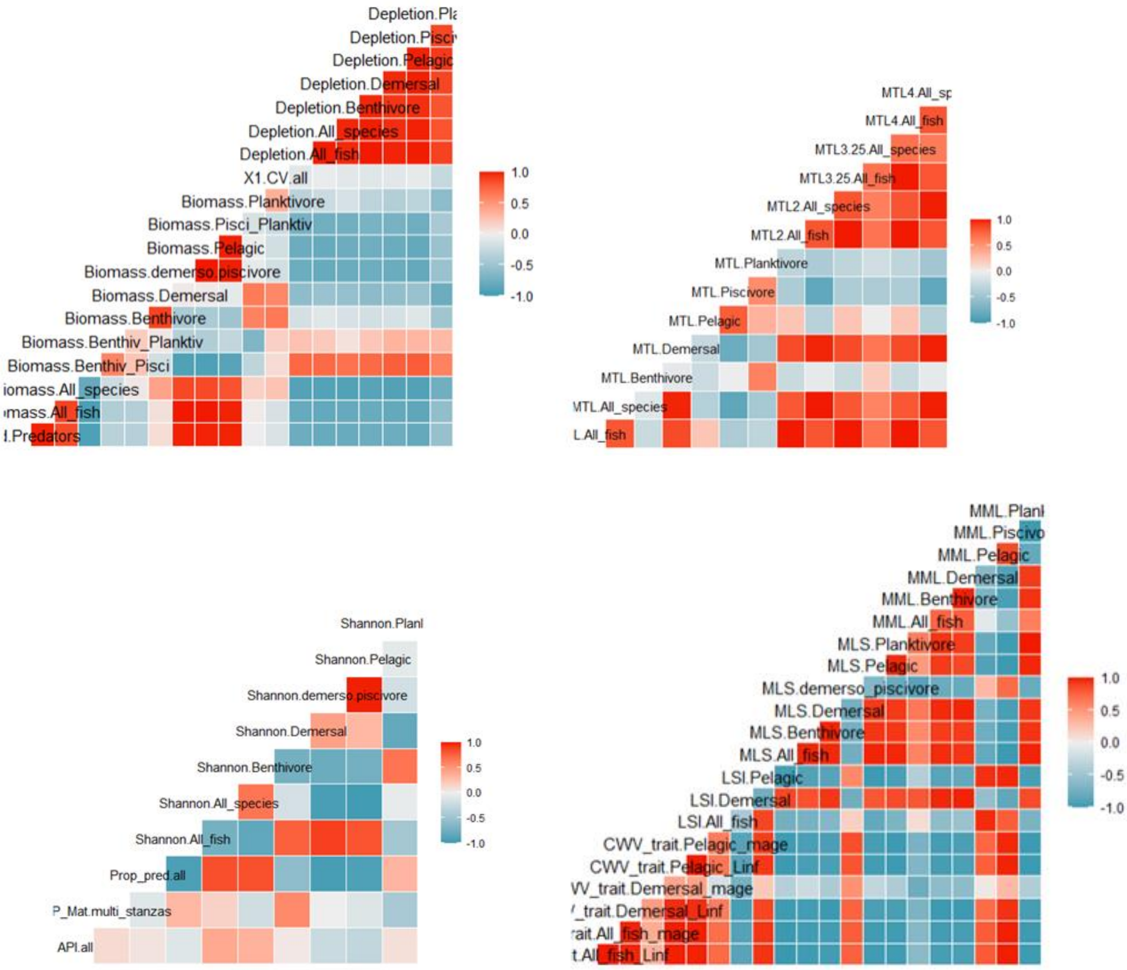


Figure 4. – Pearson correlation between biomass, trophic, community structure and trait-based indicators

The last set involves depletion and biomass of planktivores. Depletion of planktivores will be retained since it is better projected on the first plane and display a better correlation with climate change scenarios.

Thus, according to this analysis, the position in the water column seems to be a relevant trait for distinguishing biomass indicators. Trophic guilds are redundant with the position in the water column. Only the biomass of planktivores is not redundant.

- **Trophic level**

Among the indicators that display high correlations with fishing intensity or climate change scenarios and are reasonably well projected on the first or second plane, two sets of can be identified. The first set involves MTL of demersals, all species, all fish and MTL with all cut-offs. MTL of all species is retained. The second set consists of MTL of the benthivores.

Thus, water column indicator division is not interesting with MTL. Only the trophic guild's benthivore level seems to provide novel information without being redundant with other

- **Structure community**

According to the correlation diagram and the projection of indicators in the PCA, three indicators demonstrate weak correlations with others and offer valuable insights: API, the proportion of immatures and shannon of planktivores. While other shannon indicators display relative strong correlations among each other, the shannon indices of demersal and pelagic do not show high correlation among them. Therefore, retaining both would be valuable.

Thus, it can be worth to distinguish Shannon index according to the position in the column water and to focus on the planktivore category within the trophic guilds

- **Trait-based indicators**

According to the correlation diagram and the projection of indicators in the PCA, four sets of traits-based indicators can be identified. Among these, one combines the majority of the indicators. MLS and MML indicators are quite redundant. It would be interesting to retain CWV_Linf_all_fish, MML of piscivores and planktivores as they show the highest correlation with fishing intensity scenarios. The second set involves LSI all fish and MML of pelagics. LSI will be retained. The third set comprises MML of all fish and the fourth set CWV_age_demersal.

Overall, the trait-based indicators demonstrate considerable correlation. It can be worth to retain MML for planktivores and piscivores.

2.1.3. Which minimal set of indicators can be selected to keep all information and to avoid redundancy?

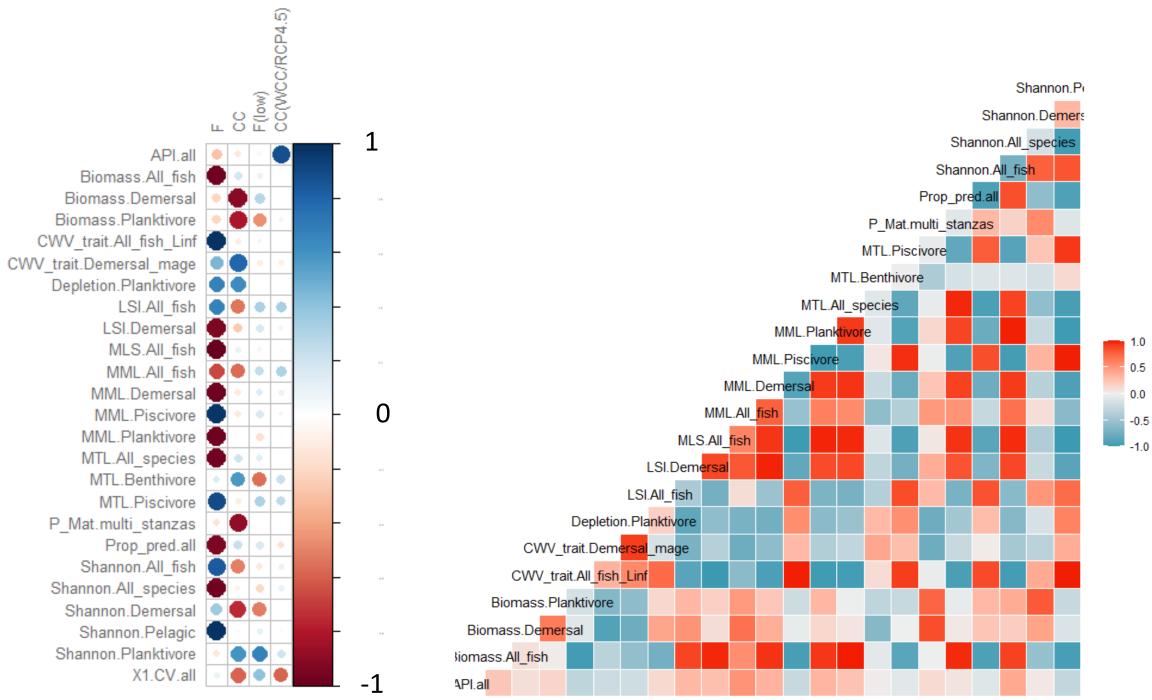


Figure 5. – Correlation diagram of indicators and factors (left) and correlation matrix between indicators (right)

The previous table was reduced by eliminating the most redundant variables, according to the analysis in 2.1.2. An PCA is made with the elected 25 indicators. The dimensions 1 and 3 are anti-correlated with fishing intensity and accounts for 63% of the total variability in the dataset. The dimension 1 separates fishing multipliers from 0.2 to 2.5. The third dimension separates low multipliers, from 0.2

to 0.7. The dimensions 2 and 4 are correlated to climate change scenarios and accounts for 30% of the total variability of the dataset. Dimension 2 separates constant climatic conditions and RCP8.5. Dimension 4 separates RCP4.5 and RCP8.5. *Figure 5* presents the correlation between the indicators and climate/fishing scenario intensity, according to the dimension in ACP.

API, biomass of planktivores and demersals, the proportion of immatures, shannon of demersal, CWV_age_max of demersals and depletion of planktivores are highly correlated with climate change intensity scenarios. The MTL benthivore finally did not show high correlation with climate change or fishing, so it will not be kept for further analysis.The other indicators show correlation to fishing scenarios and some demonstrate correlation for both fishing and climate change (MML_all_fish, LSI_all_fish, depletion_planktivore). 1/CV cannot be used further to compare constant climatic conditions scenario with RCP4.5 and RCP8.5 as it seems logical that under constant climatic conditions, biomass is more constant. It is used only to compare RCP4.5 and RCP8.5 and fishing intensity. MML Planktivore and MTL all species are redundant and show the same patterns of correlation with other indicators. MLS all fish, LSI demersal and MML all fish present also the same correlation pattern. So, for further analysis, MLS all fish indicator will not be used.
After this last PCA, a set of indicators is selected (*Table 4*). The level all species and/or all fish for indicators is kept even if they are redundant to better understand the global dynamics.

Table 4. – Selected indicators after the ACPs analysis

Biomass	TL	Structure	Trait-based
All species All fish Depletion planktivore Demersal Planktivore 1/CV	MTL all species	Shannon pelagic Shannon demersal Shannon planktivore Shannon all species Shannon all fish Prop predators Prop immatures API	CWV Linf all fish CWV mage dem MML all fish MML planktivore MML piscivore LSI demersal LSI all fish

2.1.4. Which indicator threshold can be identified to ensure a good state of the ecosystem?

Four indicators show linear or curvilinear relationships with depletion indices: Shannon all species, LSI demersal, MML all species and the proportion of predators (*Figure 6*). Indicator thresholds (black and bold values) are defined for a depletion score of 0.48 for all species indicators and 0.49 for demersal (SEAwise protocol, *Appendix 5*). For Shannon all species, MML all species and to a lesser extent LSI demersal and the proportion of predators, another threshold can be identified. The curves remain almost flat, before dropping sharply for Shannon all species and MML, or before changing slope for LSI demersal and proportion of predators. This turning point (orange and italics value on the graph) can be identified as the depletion value at which the indicator falls sharply, corresponding to a higher level of depletion that previous, above 0.6.

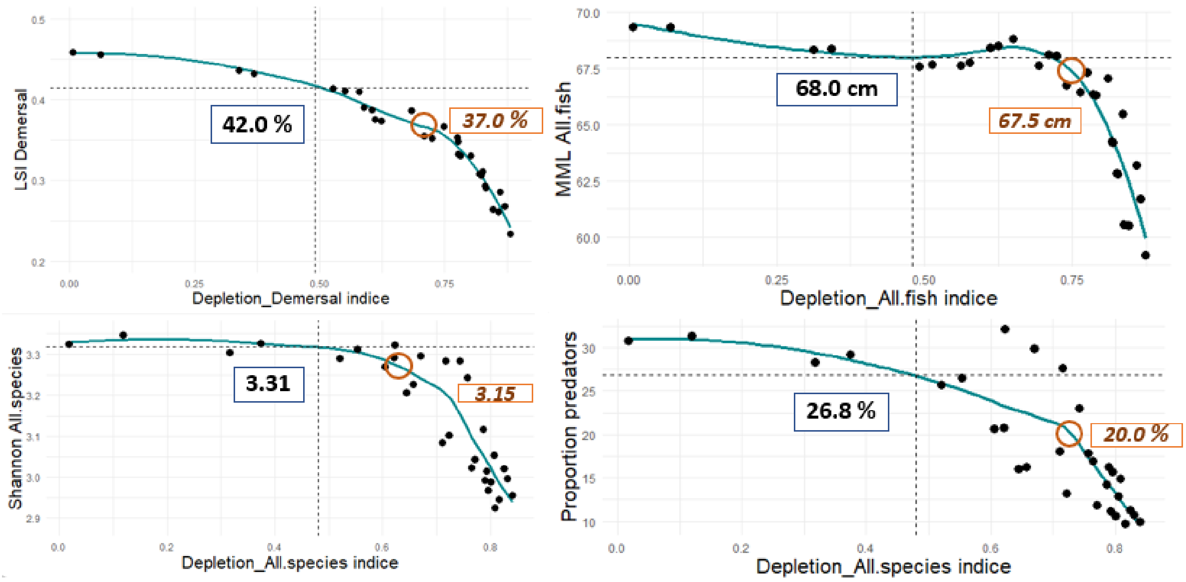


Figure 6.- Visualization of indicator thresholds for defining by depletion indices (LSI demersal, MML_all_fish, Shannon_all_species, proportion of predators)

2.2. What level of reduction in fishing effort and changes in exploitation patterns are efficient to keep productive and healthy ecosystem, especially in a context of climate change? Which indicators are sensitive to fishing strategies, climate change and the interaction between both?

2.2.1. What are the effects of fishing intensity pressure on the ecosystem components in a climate change context? What does it mean in terms of sensitivity to fishing intensity and to climate change?

The following heatmap (*Figure 7*) allows to investigate the response of indicators to fishing intensity, climate change and the interaction between both. It shows the relative difference with the value of the indicator in a status quo of fishing under constant climatic conditions.

- **Productivity and impact of fishing**

The variation in the ratio landings on chlorophyll (land_chloro_catch) remains relatively constant across different fishing scenarios and climate change conditions. A fishing multiplier of 0.7 leads to an increase of total catch (10-20%), even with RCP8.5 scenarios. At constant climatic conditions, the total catch increases also by 5-10% for 2.5 mF. But it is not the case anymore with RCP4.5 or RCP8.5. The decrease in total catch is larger with climate change scenarios for mF 0.2 and 1.5. 0.7 mF leads to a higher all-fish biomass and this compensates the decrease in fishing effort. This can mean that currently, the fishing level is not at the MSY in an ecosystem meaning, and the ecosystem is globally overfished.

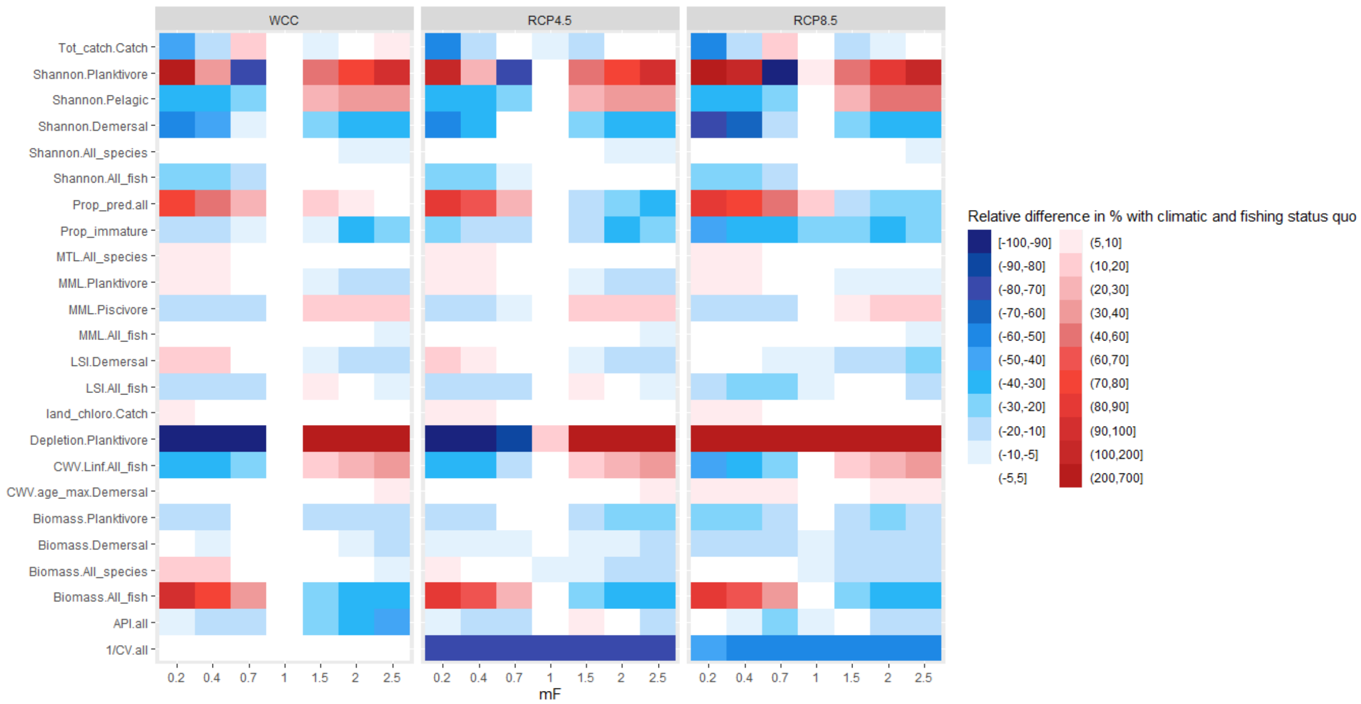


Figure 7. - Differences between the indicator values for the considered fishing pressure and CC scenario and for the status quo scenario (WCC 1, i.e. mF= 1, constant climate)

- **Biomass-based**

Fish biomass shows a distinct linear trend with fishing effort. Reducing the fishing effort to 0.7 leads to an increase in biomass of the order of 30 to 40%. It increases to 70 to 80% for 0.4 mF. The biomasses of pelagics and piscivores (not shown), which are strongly positively correlated with the biomass of all fish, follow the same trends. The biomass of all species demonstrates less marked trends with fishing intensity, but is more sensitive to climate change scenarios especially in the interaction with high mF, with higher decrease.

The differences in biomass sensitivity of demersals and trophic guilds can be explained by the composition of the guilds and the sensitivity of the species to fishing and climate change (*Appendix 7,16,17,18*). In RCP4.5, all fish functional group are "losers" (in comparison to a constant climate and for F=Fcurrent), only *microzooplankton*, *bacteria*, *small phytoplankton* are "winners" (*Appendix 18*). *Sprat*, *herring, endobenthivorous demersal fish*, *horse mackerel*, *blue whiting* and *cod juveniles* show biomass loss respectively between 35% to 10%). With RCP 8.5, the depletion in biomass is higher, biomass is almost divided by 2 for *carnivorous demersal elasmobranchs*, *endobenthivorous demersal*, *herring*, *cod*, *sprat*. The biomass of *blue whiting* (23%), *horse mackerel* (17%), *plaice* (16%), *sole* (12%), and *mackerel* (3%) increase with RCP8.5. *Sole*, *mackerel, horse mackerel* are Lusitanian species but it is quite surprising for *plaice* and *blue whiting* which are boreal species.

The demersal group is mainly composed of *pouts*, *benthivorous demersal elasmobranchs* and *suprabenthivorous demersal fish*. Demersal biomass varies little from the status quo, with a decrease of 5 to 10% for multipliers of 0.4 and 2, and 10 to 20% for 2.5. This decrease is amplified with climate change scenarios, rising from 10 to 20% in RCP8.5 for all multipliers. Demersal biomass is more sensitive to the interaction between climate and the intensity of fishing. The same trend is slightly more pronounced for planktivores (and benthivores). *Benthivorous demersal elasmobranchs* have a loss of biomass of 12% with a fishing intensity multiplier of 2, while *pouts* have a 5% increase and *suprabenthivorous* a 8% (*Appendix17*). This can explain why the loss of biomass is not as high as expected, biomasses compensate. With a decrease of fishing effort, leading species of the demersal group have mainly a decreasing biomass. *Plaice*, *piscivorous demersal elasmobranchs*, *cod*, *hake*, *megrim* present a high percent of increase with a 0.2 fishing multiplier while *pouts*, *suprabenthivorous* and *benthivorous demersal elasmobranchs* decrease in biomass. In the pelagic category, the largely predominant group, *horse mackerel*, has a high response to fishing, its biomass is reduced by 2 with a fishing multiplier of 2 and increase by 5 with a fishing multiplier of 0.2. Other pelagic fishes show inverse trends like *blue whiting*, *sprat*, *medium pelagic* but represent low biomass in the pelagic category respective to *horse mackerel* and *large pelagic*.

The coefficient of variation of biomass from 2090 to 2100 is lower in the RCP8.5 scenario. The biomass is more unstable in RCP4.5 than 8.5. This is quite surprising but can be explained by lower biomass maybe.

Depletion of planktivore demonstrates sensitivity to climate change and sharply decrease with a decrease of fishing intensity and inversely with an increase.

Thus, biomass of all species, planktivores and demersals appear to be more sensitive to an interaction fishing-climate change. Biomass of all fish is highly sensitive to fishing intensity.

- **Homogeneity in biomass repartition**

Shannon of all species and all fish indices show limited responsiveness to climate change. The indice for all fish decreases (20-30%) when fishing intensity decreases whereas for all species it decreases (5-10%) with an increase of fishing intensity. Shannon_demersal and shannon_pelagic show inverse trends with an increase of fishing intensity. Shannon of demersals and of planktivores demonstrates sensitivity to extreme climate change scenarios only at low fishing multipliers.

With an increase of fishing, the pelagic category has a biomass repartition more balanced across functional groups. In fact, horse mackerel biomass reduces regarding to the status quo, and groups like blue whiting, sprat, medium pelagic and large pelagic increase in biomass, and they have low biomass in 2016 in the group. A decrease of fishing effort leads to an increase of horse mackerel biomass and to a more heterogeneous biomass. The repartition among demersals is more homogeneous in 2016 so an increase of fishing leads to a decrease in homogeneity, targeting non-dominant groups. It is the same for a decrease of fishing effort. However, fishing can select directly groups and decrease their biomass and/or remove predators of species which see their biomass increasing.

Shannon indicators do not display sensitivity to climate change except in extreme climatic scenario with low fishing intensity for planktivores and demersals. Shannon of pelagics is the most sensitive to fishing intensity among shannon indicators

Composition and structure of community

The proportion of predators (Prop_pred) shows a linear increase with a reduction of fishing multipliers in RCP4.5. In constant climatic conditions, it does not decrease with increasing mF. This increase is higher with climate change (around 10-20%). A decrease of this proportion is observed for RCP 4.5 and RCP8.5 at mF>1.

The API (Apex predator index) indicator decreases by 10-20% with lower fishing pressure and by 20-30% with higher fishing pressure. It seems to be complementary to the proportion of predators to appreciate the dynamic of high trophic level group at constant climatic conditions. There are not clear trends with climate change (while in the PCA it was correlated with climate change scenarios). The decrease in API value with decreasing mF is quite surprising.

The proportion of immature fish is lower (10-20%) in low fishing multipliers than in a status quo in fishing. It decreases more sharply with an increase in fishing effort (20-30%). This reduction is even more pronounced with the climate change scenarios, especially for the low effort multipliers (around 20% in less). Juvenile multi-stanzas in Ecopath are part of the consumption of many fish predators. A decrease in fishing intensity leads to more fish so more predators for juveniles, whereas an increase of fishing intensity increase the fishing pressure on the juvenile groups too. Lower fishing pressure also increases the proportion of adults while higher pressure decreases it.

The proportion of predators is more sensitive to fishing intensity in climate change context than API. The proportion of immatures fish is mostly sensitive to climate change scenarios.

- **Functional diversity**

The MML (Mean Maximum Length) indicators demonstrate relatively limited variability in response to climate change, except in extreme RCP8.5 with a general 10% decrease at high mF. MML of piscivores and planktivores are sensitive to fishing with inverse trends. At constant environmental conditions, the MML of piscivores shows an increase of 10-20% due to an increase of fishing intensity, while the MML of planktivores decreases. The planktivore category with the highest Linf comprises *mackerel* and *herring*. Among them, *mackerel* contributes significantly to the biomass of the category. This group proves highly sensitivity to fishing pressure, with its biomass halving under a multiplier of 2 and increase by 25% with a 0.2 fishing multiplier, even in constant climatic conditions. Piscivores are predominantly led by *horse mackerel* and this group also shows sensitivity to fishing pressure. However, horse mackerel presents the lowest Linf of the category. The CWV Linf for all fish is sensitive to fishing intensity and increases significantly with fishing effort.

LSI (Large species index) of demersal is sensitive to fishing (decreasing value with increase of fishing intensity) and is sensitive to extreme climate change scenarios. LSI of all fish shows less sensitivity to fishing, with inverse trends at low mF and while LSI_demersal exhibits more sensitivity to the interaction high mF and RCP8.5, LSI_all_fish is more sensitive to the interaction low mF and RCP8.5. With an increase in mF, all groups with a Linf greater than 80cm have a decreasing biomass, except for *piscivorous demersal elasmobranchs* which increases. However, in a climate change context, *piscivorous demersal elasmobranchs* have a decreasing biomass when F increases. These 11 functional groups are part of the demersal category except *large pelagic fish* and *pelagic sharks*. *Piscivorous demersal elasmobranchs* does not represent a large part in biomass (1.2% of demersal category). All LSI groups have an increasing biomass with a decrease of fishing effort. LSI species are heavily impacted by fishing (*cod, seabass, hake*) but other smaller groups have greater reactions in biomass to fishing.

MTL of all species does not seem to be sensitive to climate change. It shows a slight increase (5-10%) at 0.4 and 0.7 mF. The indicators MTL all species and biomass of all fish are highly correlated. Thus, the slight change in MTL with reduction of fishing intensity can probably be explained by the increase of fish biomass, with high trophic level species (the proportion of predators increase too), even if it can be also simultaneous with a change in diet of some species. Highest trophic level groups such as *large pelagic, anglerfish*, *cod*, *pelagic sharks* or *hake* increase with a reduction in fishing pressure, as do medium trophic level groups such as *horse mackerel* or *plaice*.

Fisheries target species with a medium length (and medium age) in the ecosystem. With extreme climate change, the age distribution among demersals is less balanced. Extreme climate change seems to penalize large species (often long-lived species) and favours short lived species if combined with high fishing mortality, with more heterogeneity especially in age structure of demersal. CWV_Linf_all_fish shows the highest sensitivity to fishing intensity and LSI, CWV_age of demersals demonstrates the highest sensitivity to extreme climate change.

2.2.2. Capacity of the ecosystem to recover after disturbance

The following heatmaps enable to investigate the possible recovery of ecosystem components through indicator values, and the sensibility of this recovery to fishing intensity and climate change. It shows the relative difference with the value of the indicator in a "virgin state". The first heatmap (*Figure 8*) allows to compare climate scenarios. Indicators are calculated for 2125-2135 under constant climatic conditions since 2100. The virgin state (virgin state 1) corresponds to a simulation with zero fishing mortality since 2016 under constant climatic conditions, and the indicator targets are calculated for 2100-2150.

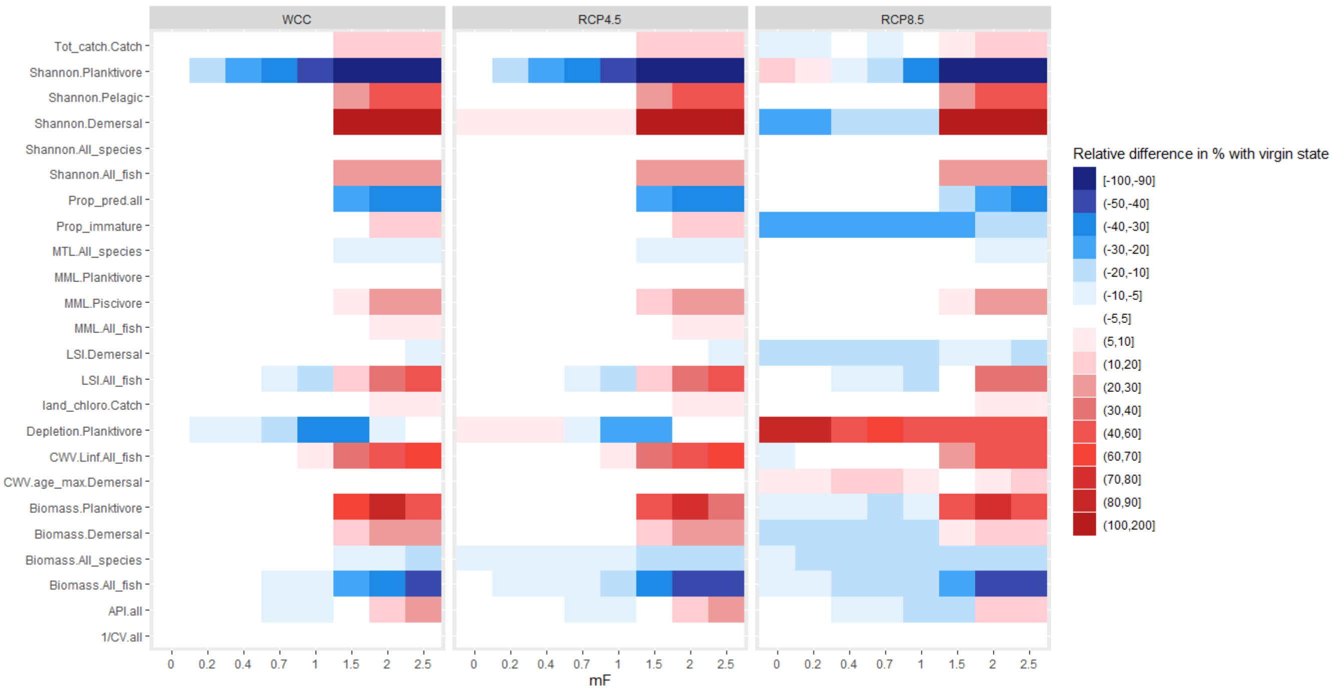


Figure 8. - Differences between the indicator values for recovery simulations and for the reference "virgin state 1"

Indicators suggest that the ecosystem recovers better globally at low fishing pressure. The pattern between constant climatic conditions and RCP4.5 is very similar. RCP 8.5 show some differences for certain indicators as proportion of immatures, Shannon demersal and depletion of planktivore, but the overall pattern is not that different. The management of fishing pressure intensity is determinant to the capacity to recover of the ecosystem and can compensate the effects of climate change, especially in non-extreme climate scenario.

The second heatmap (*Figure 9*) allows to investigate the impact of fishing intensity on the recovery of ecosystem components under the scenario RCP 4.5. Indicators are calculated for 2075-2085, with "frozen" climatic conditions since 2050. The virgin state (virgin state 2) corresponds to a simulation with zero fishing mortality since 2016 under RCP4.5. In 2050, the climatic conditions are "frozen" until 2150. The indicator targets are calculated for 2100-2150.

The indicators highlight ecosystem recovery for reduction of fishing mortality. Shannon_planktivore indice decreases with the increase in fishing pressure prior to the recovery period, compared with the reference. The biomass of planktivores is less evenly distributed, which may reflect a difficulty for some species to recover. The proportion of predators decreases at high mF, as does MTL. If fishing mortality is not reduced from current levels, fish biomass will not improve in 30 years, remaining 5-10% lower until mF of 1.5, then 20-40% lower at 2,2.5. For fishing multipliers between 0.7 and 1.5, API is lower than the recovery target and become higher for 2.5. LSI indicators are lower for mF between 0.4 and 1.5 and then become higher.

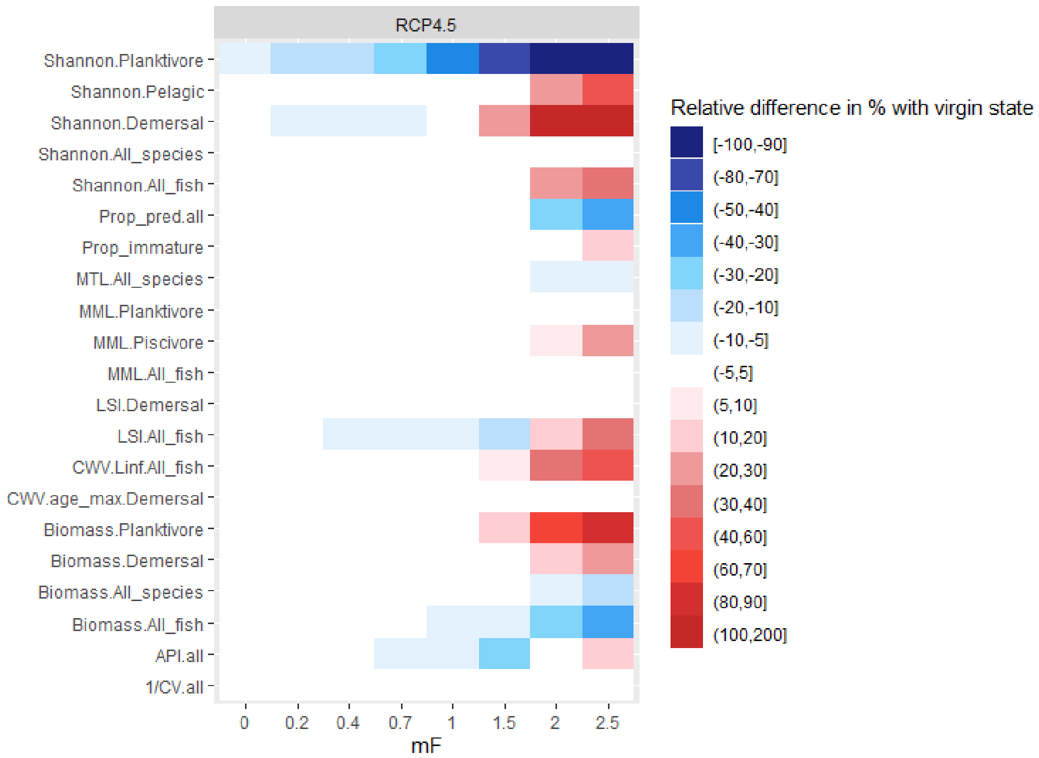


Figure 9. - Differences between the indicator values for recovery simulations and for the reference "virgin state 2"

2.2.3. Which change in intra- and inter-specific selectivity scenarios offers the best gains in terms of ecosystem health?

The aim of this part is to investigate if indicators respond to fishing management scenarios, and to study the effects of these changes in exploitation patterns on ecosystem components.

- **Sparing juveniles**

This scenario investigates the effects of a zero-fishing mortality on juveniles (*Figure 10*). In the Ecosim simulation, the fishing mortality of the multi-stanza hake juvenile, anglerfish juvenile and cod juvenile are set to 0. Indicators are calculated for 2045-2055 under RCP4.5. The heatmap shows relative difference in % with status quo in fishing under RCP4.5 for 2045-2055.

The great loss of catch between sparing juvenile scenario in RCP4.5 and the normal RCP 4.5 scenario is quite surprising and need further checks. Therefore, the following results must be interpreted with caution. Between the two scenarios, earlier improvements in ecosystem good health trends are noticed (proportion of predators, biomass of species, MTL all species, MML_planktivore, LSI_demersal, API) for the juvenile scenario respecting to the status quo RCP4.5, even for an increasing fishing intensity. However, evenness indicators are lower respecting to "not sparing the juveniles".

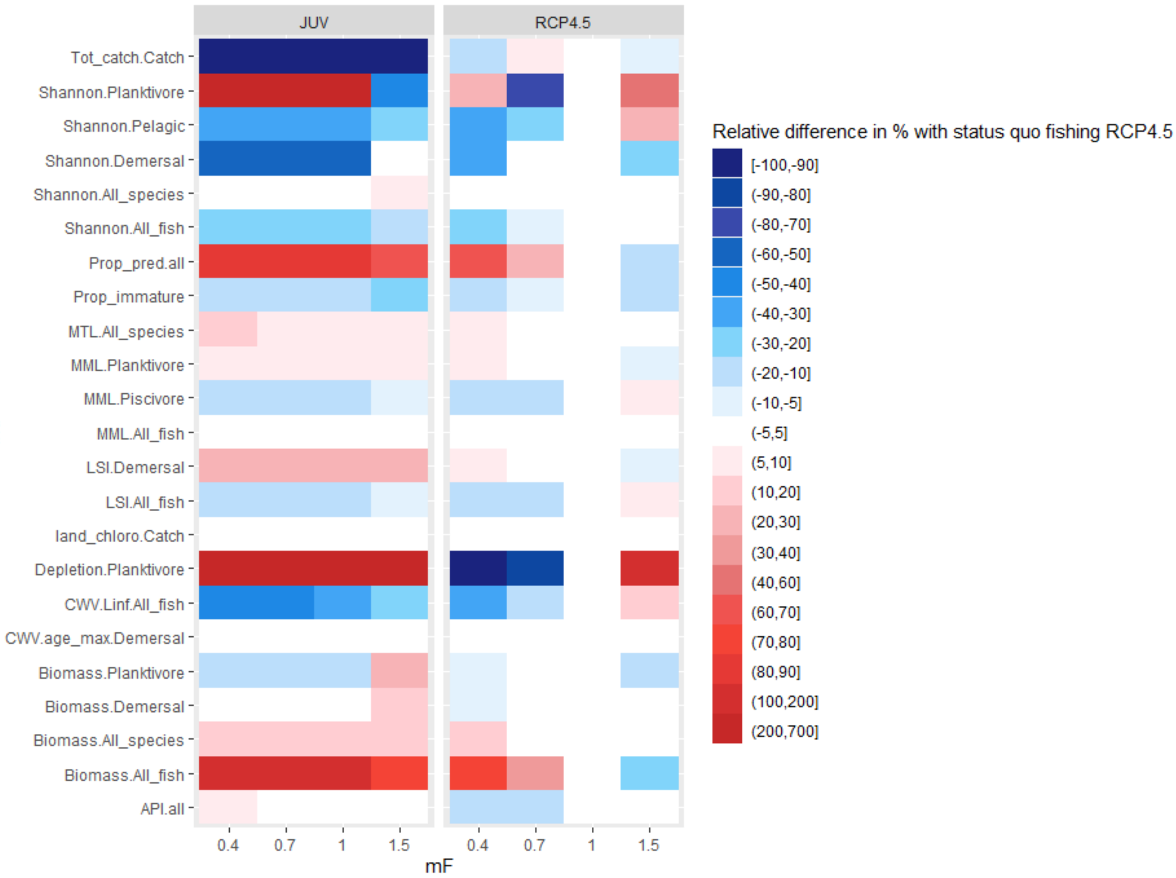
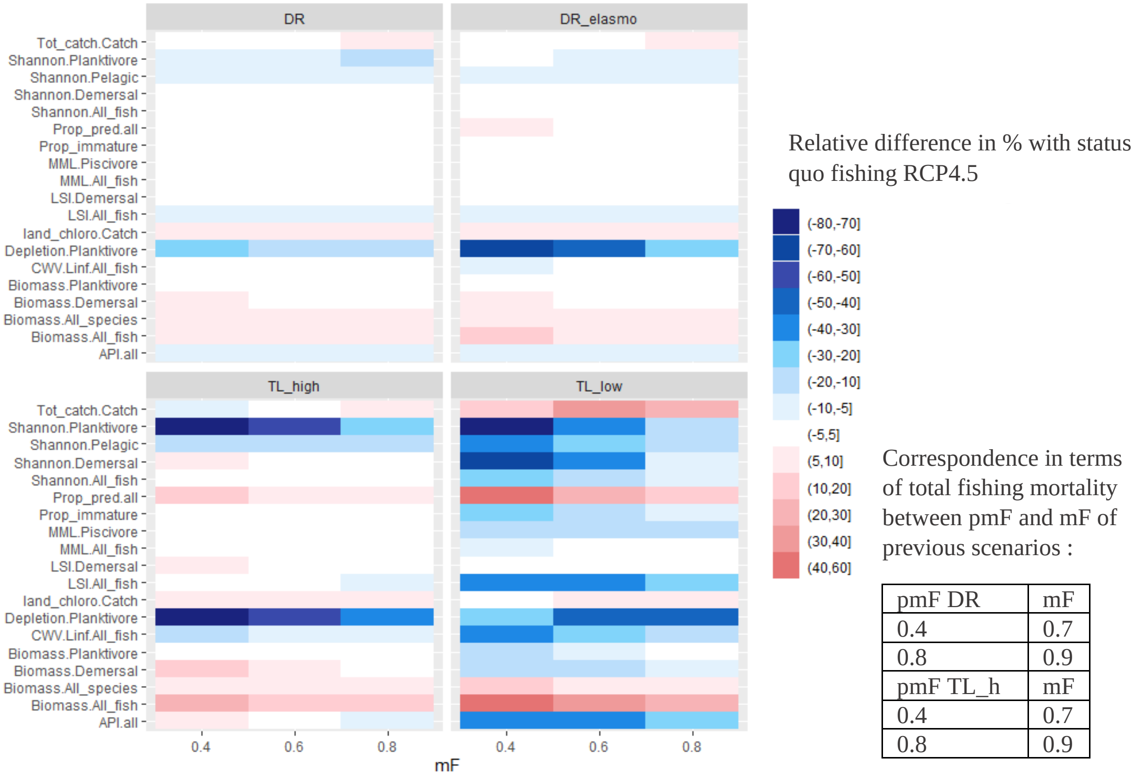


Figure 10. - Difference between the indicator for the "sparing juvenile" scenario in RCP4.5 environmental conditions and the status quo in fishing under RCP4.5 assumption

- **Discard rates and trophic level of fishing targets**

The following heatmap (*Figure 11*) presents four scenarios of inter-species selectivity. The indicators are calculated for the period 2045-2055 under RCP4.5. The heatmap shows a relative difference with status quo in fishing under RCP4.5. As fishing mortality multiplier is not applied to the same fleets, total fishing mortality (F) between the different scenarios can be different. The scenario "high discard rates of elasmobranchs" shows a total fishing mortality (F) less than 0.01 higher than "high discard rates" scenario for all pmF, so they are quite similar. Reducing fishing effort specifically on "fleets with high discard rates of elasmobranchs" seems to be more efficient to maintain ecosystem health than focusing on "discard rates for all species". Indeed, depletion of planktivores is lower than for "all species", and if the reduction in fishing mortality is more important (pmF = 0.4), the proportion of predators and the biomass of all species increase more. Respecting to RCP4.5 scenario with "equally mF among all fleets", reducing fishing mortality on fleets with high discard rates improve the biomass of all species, of demersals and landings/chlorophyll. However, the proportion of predators does not increase as much with a decrease of fishing intensity than in the "equally mF among all fleets". For the scenario with "high discard rates fleets on elasmobranchs", this can be explained by the fact that *benthivorous demersal elasmobranchs* have a TL just below 4 and are therefore not considered as "predators". The decrease of effort on "fleets with high discard rates" mostly benefit to intermediate trophic level species.



Correspondence in terms of total fishing mortality between pmF and mF of previous scenarios :

pmF DR	mF
0.4	0.7
0.8	0.9
pmF TL_h	mF
0.4	0.7
0.8	0.9

Figure 11. - Difference between the indicator values for the management scenarios in RCP4.5 environmental conditions and the status quo in fishing under RCP4.5 assumption.
DR = fleets with high discard rates on all species, DR_elasmo = fleets with high discard rates on elasmobranchs, TL_high = fleets with high trophic level, TL_low = fleets with low trophic level

"Fleets targeting low trophic level" are mostly pelagic fleets and "fleets targeting high trophic level" are demersal. The gap in total fishing mortality between reducing fishing intensity on fleets targeting low trophic level (TL_l) or high trophic level (TL_h) is 0.05 for 0.4 pmF, 0.03 for 0.6 pmF and below 0.2 for 0.8 pmF. Reducing fishing mortality on "fleets targeting low trophic level" leads to an increase of catches, more than in reducing fishing mortality on "fleets targeting high trophic level". Respecting to RCP4.5 scenario with "equally mF among all fleets", reducing pmF on TL_l leads on a stronger decrease in the evenness of pelagics, indicating an increase of a functional group in the pelagic category that reacts strongly to fishing pressure (horse mackerel). It is the same explanation for MML indicator. However, the biomass of planktivores and demersals decreases more in TL_l. A slight decrease in fishing effort on "fleets targeting high trophic level" leads to a stronger increase in the proportion of predators and biomass of all species and a decrease in the depletion of planktivores, respecting to the scenario with "equally mF among all fleets".

A clustering analysis (*Figure 12*) is done to investigate similarities between scenarios, according to their indicator values. Analysis of these four scenarios by clustering shows that reducing the fishing mortality on (1) "fleets with high trophic levels" or (2) "fleets with high discard rates" produces similar indicator values. Reducing fishing mortality on "fleets with low trophic levels" show higher values for biomass of fish and all species while the others scenarios share high value in evenness of all fish and demersals, MML of all fish, LSI of all fish and landing/chlorophyll. TL_high with pmF = 0.4; 0.6 and DR elasmo with pmF= 0.4 share lower value than other scenarios for depletion of planktivores.

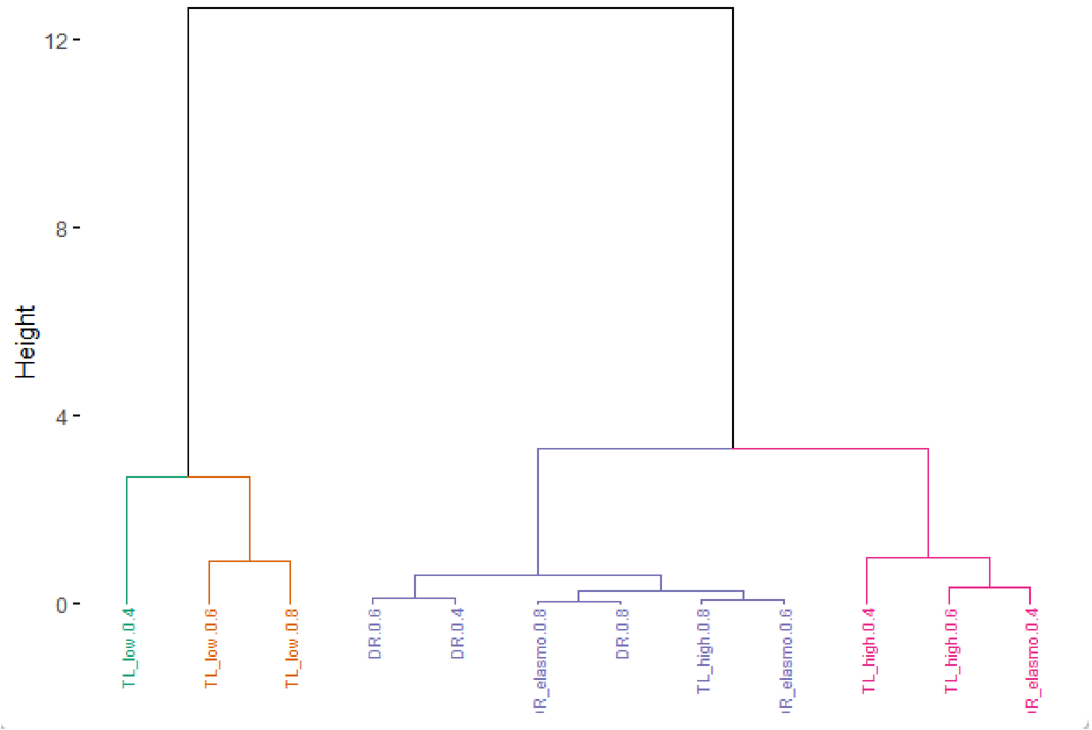
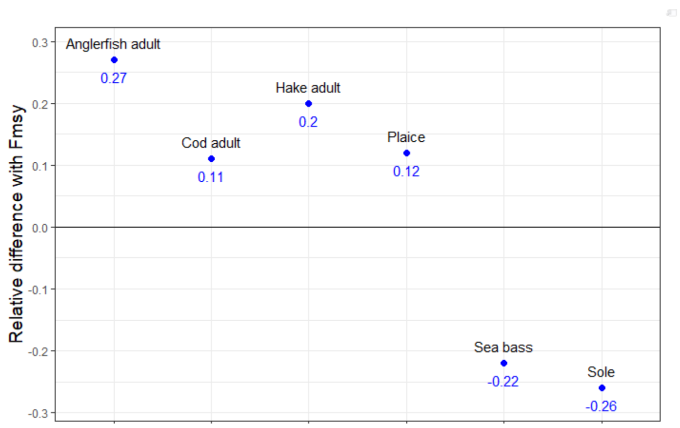


Figure 12. – Clustering classification for the management scenarios according to their values in indicators

Thus, reducing fishing pressure from fleets with high discards is more efficient for those targeting specific elasmobranchs, leading to a more stable trophic network with higher total biomass and more predators. Compared to the other three scenarios, reducing fishing pressure on fleets targeting low trophic levels results in higher total biomasses but also greater inequality among different trophic guilds and pelagic/demersal species.

- **Optimisation of multispecific MSY on demersal species**

Analyses of convergence for the Bayesian estimation of pmF are available in *Appendix* 11. The majority of the fleets have a reduced mF (*Figure 13*), except OTH DEF TBB which is the most impacting fleet for Sole. FRA DEF tr and UKM DEF tr have a particularly low mF, they are seines or trawls and are respectively the most impacting fleets for cod and Plaice.



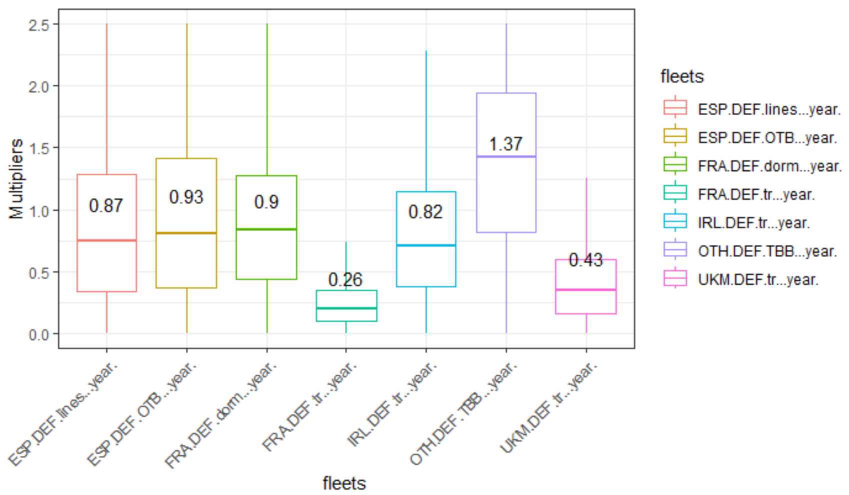
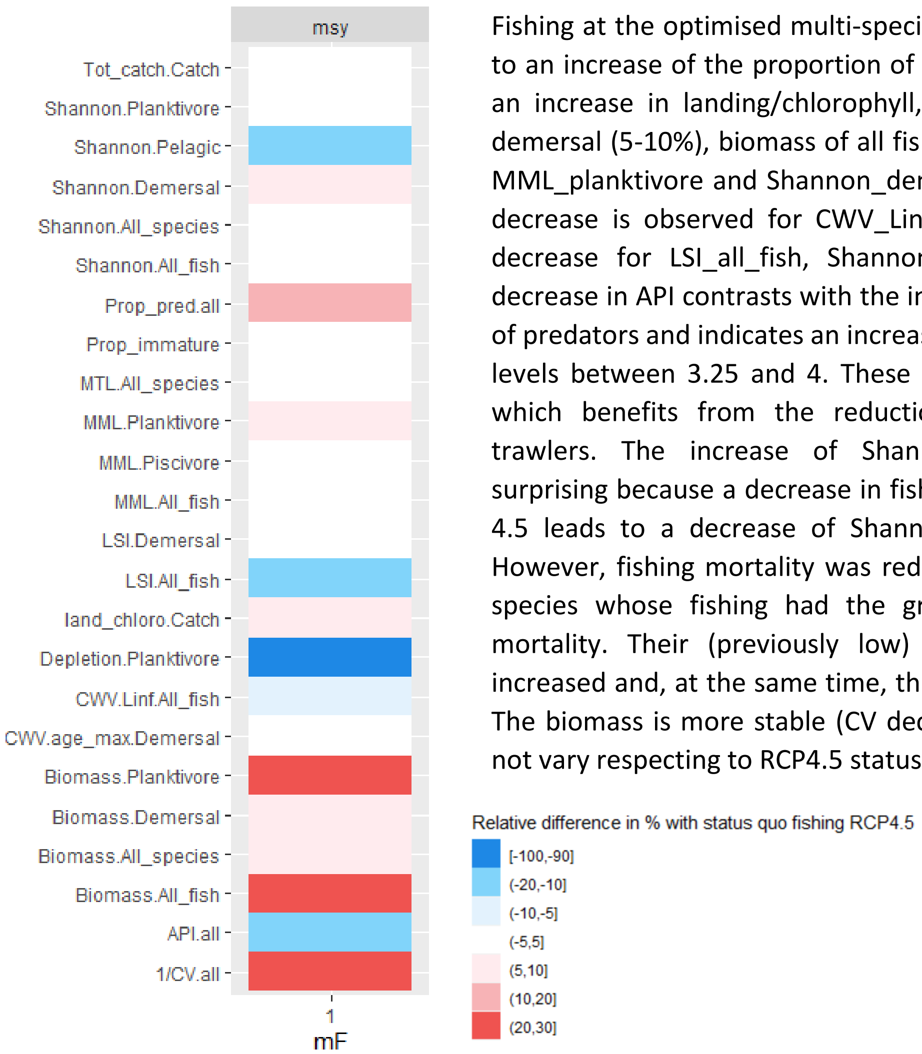


Figure 13. – Bayesian optimisation of mF results: a) relative difference between the estimated fishing mortalities for the 6 species and their fishing mortality MSY reference. b) range of estimated fishing mortality multipliers for the 7 fleets



Fishing at the optimised multi-specific MSY (*Figure 14*) leads to an increase of the proportion of predator of 10-20%, and an increase in landing/chlorophyll, biomass of all species, demersal (5-10%), biomass of all fish, planktivores (20-30%), MML_planktivore and Shannon_demersal of 5-10%. A slight decrease is observed for CWV_Linf_all_fish and a 10-20% decrease for LSI_all_fish, Shannon_pelagic and API. The decrease in API contrasts with the increase in the proportion of predators and indicates an increase in species with trophic levels between 3.25 and 4. These are the horse mackerel, which benefits from the reduction in French demersal trawlers. The increase of Shannon_demersal is quite surprising because a decrease in fishing mortality under RCP 4.5 leads to a decrease of Shannon demersal (figure X). However, fishing mortality was reduced for the 6 demersal species whose fishing had the greatest impact on total mortality. Their (previously low) biomass has therefore increased and, at the same time, the evenness of the group. The biomass is more stable (CV decrease). Total catch does not vary respecting to RCP4.5 status quo F scenario.

Figure 14. - Difference between the indicator for the optimisation MSY scenario in RCP4.5 environmental conditions and the status quo in fishing under RCP4.5 assumption

2.3. Indicator thresholds and good state of ecosystem

The following heatmap (*Figure 15*) retakes the combinations of all fleets scaled equally in constant climatic conditions, RCP 4.5 and RCP 8.5.

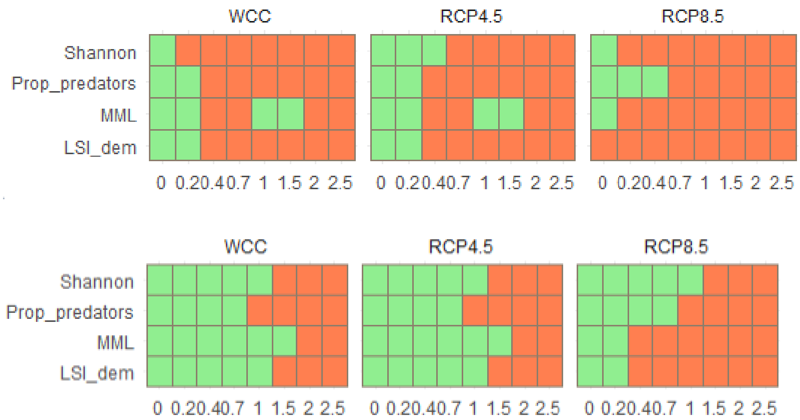


Figure 15. – Identification of climate change scenarios which indicators are above the threshold (green) and below (red). Green zones correspond with depletion indices under 0.48 and 0.49 for demersal group in a), while in b) they correspond with indicator values under the sharply decreasing indicator threshold.

To achieve depletion indices below 0.48 (0.49 for demersal), fishing intensity must be drastically reduced, by dividing current fishing mortality by 5. Climate change does not appear to have any effect on reaching the threshold for Shannon all species and the proportion of predators. For demersal LSI, it is not possible to be below the threshold in the RCP8.5 scenario, and a cessation for fishing is required for MML. Regarding the second thresholds (b), the current fishing mortality makes it possible to reach them, except for the proportion of predators, where a fishing multiplier of 0.7 is required. However, an extreme climate scenario has a considerable impact on achieving the MML and demersal LSI, for which a 5-fold reduction in current fishing mortality is required.

3. Discussion

3.1. Reliability of EwE model and model dependency of indicators

The value and trends of the indicators depend on the model used to calculate them. If the model does not respond effectively to fishing or climate change, meaning it does not exhibit plausible ecosystem trends (due to parameterization issues, strong assumptions...), the indicators will not show anything. Thus, it is crucial to investigate the reliability of the model. The stability test (*Appendix 4*) reveals worrying aspects. Large pelagic and benthivorous demersal elasmobranchs have biomass decreasing to 0 in constant fishing conditions and in increasing fishing mortality scenario. Moreover, in forecast simulations, biomass of large pelagic largely increase, in a suspicious way. It may be a problem with the baseline Ecopath parameters. In addition, the biomass of horse mackerel seems to be far too high. Ecosim does not reproduce well the decrease in biomass observed after 2010. The result is a biomass that is almost identical to the 1985 peak, due to exceptional recruitment. In 2016, the biomass of horse mackerel was greater than that of large phytoplankton and large mesozooplankton (*Appendix 19*). This problem was identified in the PREBAL diagnostics by Hernvann et al. (2020) for the 1985 base model, but justified by exceptional recruitments and by the fact that at this time, it was the predominant pelagic species. For these two reasons, analyses were redone without horse mackerel and large pelagic (*Figure 16*).

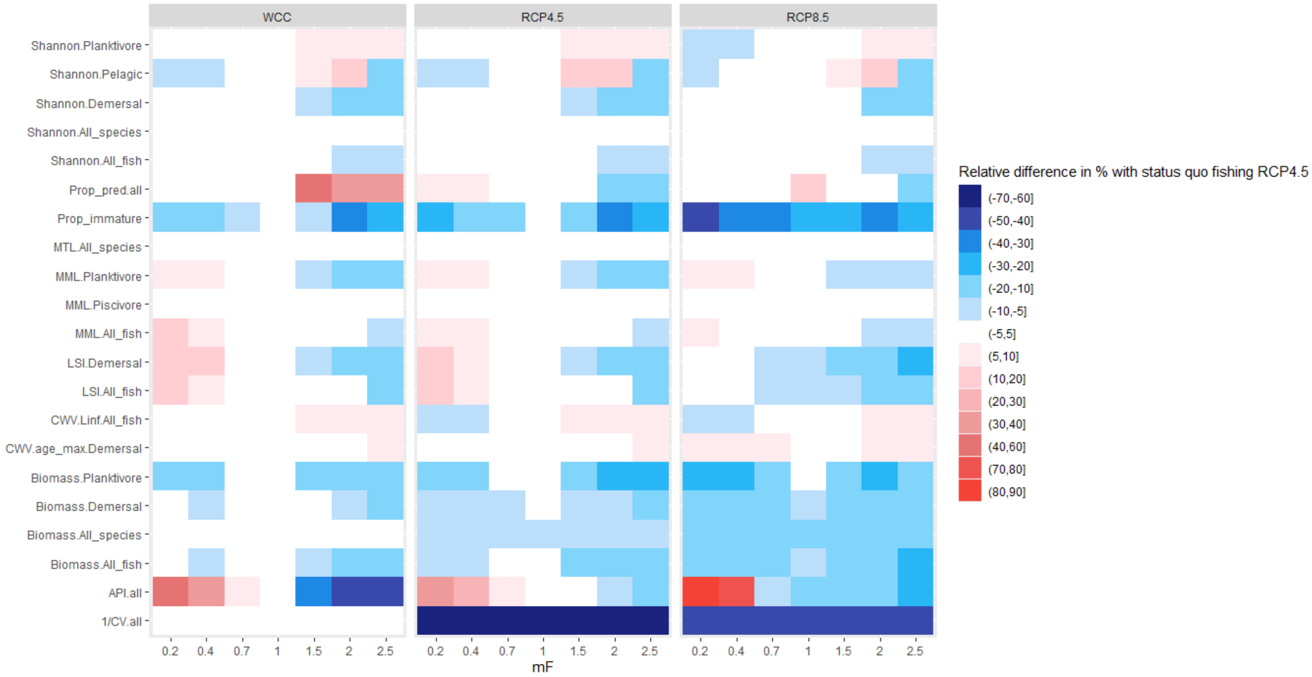


Figure 16. – Relative difference between the indicators and the value of the indicators at a status quo in climate and in fishing (WCC 1).

One of the most striking changes is the evolution of the API. API becomes very sensitive to the impact of fishing pressure, decreasing linearly with an increase in fishing intensity. Climate change reduces the API value in the RCP8.5 scenario by 10-20%. API becomes less sensitive to fishing with a joint effect of fishing and climate change, especially in RCP4.5, although higher values are still present for low mF values and lower for high mF values. Biomass of all fish and all species are less sensitive to fishing but more sensitive to climate change respecting to the calculation with horse mackerel and large pelagic. Biomass of all species decrease by 5-10% in RCP4.5 and 10-20% in RCP 8.5. Biomass of fish decreases of 10-20% in low mF in RCP8.5, 5-10% in RCP4.5. Length based indicators increase with a decrease of fishing and decrease with a rise of fishing, except piscivore.

One of the advantages of EwE model is that it includes all species of the ecosystems, both vertebrates and invertebrates. However, the indicators explored mainly focused on fish population and it would be worth to look at other compartments. Our model is poorly structure in size/age, with only three multi-stanzas groups. This influences the outcomes and values of indicators, respective to other size structured models.

3.2. Ecosystem dependency of indicators

Before starting to choose and calculate an indicator, it is worth looking at which species or groups of species predominate, drive the trophic guilds and position in the water column. Depending on the structure of the community, the relevance of the indicators to look at differs. If intermediate trophic level species predominate, API is not relevant for analyzing the effects of fishing, as the proportion of predators will be more efficient, especially in climate change context. HTI may also be more interesting in this case, although it was not looked at in the study. Indicators that exclude predominant species can also be interesting to look at, as opposed to global indicators that erase the trends of species in minority. Looking at indicators on a finer scale in order to detach oneself from the predominant species that drive the indicator signal seems more interesting than eliminating the predominant species from the indicator calculation. In fact, these species still play a part in the dynamics of species with lower biomass, via trophic interactions. Some studies have indicated that ecological indicators were responsive to environmental changes, with fishing generally exerting a stronger influence, though this varies among ecosystems (Blanchard et al., 2005; Link et al., 2010). Our ACPs goes into that way, suggesting that for the majority of indicators, fishing pressure is predominant on climate change, and this is consistent with the historical study of Hernvann et al., 2020 on the Celtic Sea. Indicator's behaviour depends on ecosystem traits (Heymans et al., 2014), fishing history, and fishing patterns (Shannon et al., 2014), the indicators calculated in the study of Shin et al., 2018 exhibit varying degrees of specificity to fishing across different ecosystems and fishing strategies. When indicators were calculated without horse mackerel and large pelagic (ecosystem with more even biomass across fish), it changes their trends and sensitivity to fishing and climate change. Moreover, marine ecosystems are affected differently by climate change, depending on various characteristics (open/close oceans, coastal areas…) (Philippart et al., 2011). Establishing absolute reference values for ecosystem indicators might not align well with the ecosystem-based and precautionary approaches. Reference levels for ecosystem indicators should be tailored to individual ecosystems or ecosystems with similar typologies (such as location and ecosystem type), rather than being compared across all ecosystems (Heymans et al., 2014).

3.3.Selection of indicators

3.3.1. PCAs and assumption of linear relationship between indicators and fishing

Instead of PCA, the selection of indicators can be done with GAM, because of its ability to deal with non-linear relationship between the response and the set of explanatory variables (Fu et al., 2020). GAM models can be used to assess the relative part of environmental change, fishing pressure and fishing exploitation pattern in the variability of the indicator. GAM models also allow to explore the type of response of indicators (linear or not) and the presence of tipping points.

Using either GAM or PCA for indicator selection can result in the retention of certain indicators exhibiting minimal overall variation, yet displaying sensitivity to fishing or climate change. It was the case for "MTL benthivore". Our primary focus was on the responsiveness of indicators to the impacts of climate change and fishing. Therefore, in the context of the Principal Component Analysis (PCA), the indicators were employed as active variables, similar to how they will serve as response variables in the Generalized Additive Models (GAMs). However, an interesting alternative approach could involve exploring the issue in reverse, determining which indicators explain the observed variability within climate change and fishing scenarios. In other words, identifying the indicators that exhibit the most significant distinctions between fishing scenarios and those that highlight variations across climate scenarios. Our initial attempt involved clustering indicators through PCA with scenario variables, but this approach resulted in the aggregation of all indicators. A more promising approach involves constructing separate GAM models, each addressing fishing, climate change, and the interaction between the two. In this context, climate change would be represented as a quantitative variable, potentially utilizing primary production or temperature as a proxy. All indicators would serve as explanatory variables. Through AIC (Akaike Information Criterion), the most appropriate model would be identified, with the indicators that explained the best climate change, fishing or the interaction. However, a more extensive set of simulations is necessary to undertake this investigation effectively. Increasing observations, potentially through intermediate mF levels or additional climatic scenarios (such as an intermediary like RCP2.5), or expanding the temporal scope (by introducing a time factor) could enhance the robustness of our analyses.

The selection of indicators using PCA appears to be an interesting initial approach when dealing with a high number of indicators. It allows for an initial sorting process, retaining those indicators that exhibit sensitivity to fishing or climate change. But low sensitivity indicators are selected and the specificity of the indicators to fishing or climate change is sometimes difficult to investigate. Examining sensitivity to climate change proved to be intricate, as the signal was often overshadowed by the influence of fishing. The PCA should be followed by a gam model for example.

3.3.2. Focusing on trophic guild scale or position in the water column

A finer scale indicator makes it possible to erase an average effect for certain contradictory trends and to better understand certain dynamics. But it is important to be careful not to lose any overall information. Moreover, focusing solely on the fish group results in the loss of the ecosystemic perspective of the indicators. It would be valuable to extend the analysis to trophic guilds and positions in the water column for all species within the ecosystem. Furthermore, trophic guild indicators are heavily influenced by the model, including how groups are defined and how functional groups are assigned to trophic guilds. Some groups exhibit ambiguous trophic guilds, particularly those straddling planktivore and piscivore roles, such as horse mackerel. It represents a significant biomass of piscivores and drives the group a great deal. However, it could also be defined as a planktivore; in our model it feeds on 30% zooplankton. Many species thus have somewhat mixed diets, even more so between the different life stages. Dividing more groups into stanzas in the EwE model could improve the realism of these indicators. The indicators per trophic guild are therefore very model-dependent and ecosystem-dependent, depending on the fishing history of each zone. Groups dominated by one species (pelagic and piscivorous) are less interesting to look at and amount to looking at the dynamics of one or two species.

3.3.3. Depletion thresholds

The depletion is calculated with a tolerance risk concentration of 1 (Seawise protocol, *Appendix 5*). This heavily penalizes outcomes where the depletion is loaded disproportionately onto a small number of stocks. Having a tolerance risk different than 1 which allows more disproportionality is maybe more interesting when some groups are largely predominant as it is the case in our model. Moreover, we do not have time to calculate the depletion threshold specifically for our model and we take the value of Bay of Biscay EwE. For the EwE model of Bay of Biscay, the threshold is 63 % for MML all fish. For the demersal LSI, it is 48% (Lynam et al., 2023). The thresholds found are not that closed (68cm for MML and 42% for LSI). SEAwise does not look at the proportion of predators and no threshold was found for the EwE model for Shannon all species. However, the SEAwise methodology for determining indicator thresholds deserves discussion. There seems to be no apparent reason for the two considered indicators to drop below the limit at the same time (i.e., at the same F threshold).

3.3.4. Other indicators

It should be interesting to look at ENA (Ecological Network Analysis) indices. It is quite expensive in time because it requires to balance Ecopath models for each simulation and sometimes not very easy to understand. However, it gives a picture of the ecosystem in the whole. Ascendency (Ulanowicz, 2004; Kones et al., 2009) could give some information about the “evenness” in the trophic flux between groups and the intensity of these links. The Omnivory index (Ulanowicz, 2004; Kones et al., 2009) informs on the diversity of diet and could be interesting to compare with MTL, as well as it gives information on the resilience of the ecosystem.

3.4. Sensitivity of indicators to fishing and/or climate change

3.4.1. Sensitivity to indicators to climate change

3 categories have indicators that are sensitive or correlated to climate change: demersal, planktivores

and benthivores. All benthivore functional groups are included in the demersal category. Within their shared functional groups with high abundance, *suprabenthivorous demersal* species respond negatively to climate change and have a strongly negative functional response to SBT in Ecosim. All functional groups in pelagic category are included in the planktivore category, except *large pelagic* and *horse mackerel*. Planktivore category mainly feed on zooplankton which biomass and composition change with climate change scenario (Annex 7 and Hernvann et al., 2020). Indicators for pelagic do not react that much to climate change (the predominant horse mackerel group is mostly influencing by fishing). Thus, it contrasts with the initial assumptions (pelagic and planktivore indicators more sensitive to climate change and demersal indicators more sensitive to fishing).

It was not possible to investigate the potential difference in biomass stability with 1/CV between constant climatic conditions and the RCP scenarios, as the environmental conditions were kept constant. It would be interesting to put an alea on environmental conditions for the climate change frozen scenario, or maybe to take a low intensity climate change scenario like RCP2.5 instead.

The indicators sensitive to climate change are those highlighted by the PCA, with the exception of Shannon planktivore, which had a fairly low correlation. Thus, the evenness of planktivores increases with climate change, and it is the only category with an evenness that reacts somewhat to climate change. Depletion of this category increases with climate change. The biomass of all species decreases with climate change, and this is more obvious when horse mackerels are removed. The proportion of immature individuals also decreases. The size-based indicators (MML of piscivores and planktivores for the scenario without horse mackerel and the LSI for the normal scenario) are essentially sensitive to extreme climate change scenario. According to Lynam & Mackinson (2015), climate warming may decrease biomasses of bentho-piscivores and piscivores, while biomass of planktivores, benthivores may increase. This was not confirmed in this study. Thus, the indicators with the highest sensitivity to climate change (in normal simulations) are the proportion of immatures, the biomass of demersals and the depletion of planktivores.

3.4.2. Sensitivity to fishing intensity

Some indicators do not show expected sensitivity to fishing. This is the case with API. Whereas the proportion of predator increases with a decrease of fishing intensity, API decreases. With constant climatic condition and status quo in fishing, API has a value of 38%, Bourdaud *et al.* (2016) finds a value of 28% in 2012 for the Celtic Sea. Sole, horse mackerel, plaice, large pelagic have a larger increase with lowering fishing than group with a TL > 4 (hake, cod, elasmobranchs, seabirds…), and horse mackerel and large pelagic represent high biomass. If horse mackerel and large pelagic are removed, API becomes one of the most sensitive indicators (but the proportion of predators no longer shows the expected trends). High trophic levels are more sensitive to fishing because of their smaller productivity and turn over on average (Gascuel et al., 2011).

Size based indicators are proven to be sensitive to fishing impact according to Shin *et al.* (2005), as largest fish are specifically targeted by fishing. However, the impact of fishing pressure varies according to the composition of the community. A community largely dominated by a species with average traits has an MML and LSI that varies little at the level of all the fish with an increase in F, whereas it decreases in a more homogeneous community (without horse mackerel and large pelagic). It is the same for evenness, fishing can reduce the biomass of the dominated species. But for the all species scale and not only fish, the evenness decreases with fishing pressure. Shephard *et al*. (2012) finds that the biomass of large species declined significantly over 19 years of exploitation in the Celtic Sea while there was a significant increase in the biomass of small fish species, even during the period of reduction of fishing pressure. According to the study of Lynam & Mackinson (2015), in the North Sea, reduced fishing effort leads to increases in size-based indicators and biomasses of benthivores, planktivores and piscivores (Lynam & Mackinson, 2015). In our analyses, the MML of planktivore increases but the

MML of piscivore decreases or does not vary in the scenario without horse mackerel. It is because piscivore are largely dominated by horse mackerel with intermediate Linf. Trophic indicator as MTL show low sensitivity to fishing pressure, even worse when horse mackerel are removed. MTL is known to be less sensitive to fishing that other indicator like API (Bourdaud et al., 2016) but other studies have shown fall of MTL with increase of fishing intensity (Perry et al., 2010). Thus, the indicators with the highest sensitivity to fishing are the biomass of all fish, Shannon of pelagics, and CWV Linf of all fish.

3.4.3. Interaction between climate changes and fishing

With an increase in primary production variability as a result of global change (Winder & Cloern, 2010), the specificity of indicators to fishing may decrease (Shin et al., 2018). In our study, and even more in the simulation without horse mackerel and large pelagic, API, biomass of all fish and the LSI indicators shows less variation among mF with climate change and appear to be less sensitive to fishing. Exploitation results in reduced top predator stocks, potentially altering control structures from top-down to bottom-up in such systems, exacerbating control in already bottom-up systems. This renders ecosystems more susceptible to climate impacts. Exploitation can simplify ecosystem structure by depleting top predators and decreasing diversity. The decline of top marine predators can lead to increased biomass fluctuations of short-lived prey under bottom-up influences. Fisheries can thus heighten ecosystem sensitivity to climate variability (Perry et al., 2010). The rise in pelagic fish species' proportion in global fish catch over the past 30 years, influenced by predation and environmental factors, underscores these dynamics (Caddy and Garibaldi, 2000). Reduction of predator or high trophic level biomass is observed in our simulations like the rise in pelagic fish although predominance of short-lived prey with fishing intensity is unclear. Thus, the indicators with the highest sensitivity to the interaction climate change and fishing are the biomass of all species, the proportion of predators and for extreme climatic scenario Shannon of planktivores and demersals and LSI of demersals.

3.4.4. Sensitivity to intra and inter-species selectivity scenarios and efficiency of management measures

Reducing fishing mortality on fleets targeting high or low trophic level do not lead to the same ecosystem's response. Low trophic level fleets mainly correspond with pelagic target (but some fleets corresponding to large pelagic fish are in high TL category). Moullec *et al*. (2017), finds that the reduction of fishing mortality on pelagic fish instead on demersal fish seems more efficient at maximizing catch and total biomass and at conserving both top-predator and intermediate TLs in the Celtic Sea ecosystem. The results of our simulations also reflect this. However, this also reduces the biomass of demersal species and total evenness, as well as the proportion of large species. This scenario mainly increases the biomass of one predominant species, the horse mackerel. In the end, this may not be the best scenario for optimising ecosystem health. The effort reduction scenarios for fleets with high trophic levels or high discard rates make it possible to maintain a higher evenness, as well as higher size indicators and no loss of demersal biomass. The biomass increases less but more evenly, with more predators. Once again, the type of management preferred depends on the initial state of the ecosystem. Sparing juveniles seems also to be an interesting scenario as it enables an increase of biomass, MTL, MML and API, even if evenness is lower.

Approaching MSY simultaneously for some demersal species enables an increase of biomass and proportion of predators without reducing global catches. The evenness of demersal is also improved. However, this study operates under the assumption that modifying fishing effort by a certain percentage leads to an equivalent percentage adjustment in fishing mortality across all species. It essentially presumes that the catchability coefficient remains constant across all functional groups. This supposes a consistent selectivity for each functional group over time. However, these assumptions are not verified in any developing fishery (Forrest et al., 2015). Moreover, the optimizing mF by fleet to reach Fmsy is calculated only for 6 demersal species and the 7 most impacting fleets. It would be interesting to calculate mF by fleet for each fleet and each fishing species. This was not possible with our Bayesian model as too many parameters in linear combination should have been estimated. However, a R package calibraR (Oliveros-Ramos & Shin, 2016) exists to optimize parameter of trophic model like ISIS Fish and Osmose, it would be interesting to develop it for Ecopath with Ecosim too. Travers-Trolet et. al (2020) demonstrate that F_{MSY} projections decrease as climate conditions changed from historical to RCP scenarios in the Eastern English Channel. Adopting an approach that aims for 80% of MSY, as suggested by Hilborn (2010), delivers reasonable yields and multiple benefits in fisheries management. This is especially advantageous for mixed-fisheries scenarios, where different species have divergent MSYs and reaching all of them simultaneously is complex (Rindorf et al., 2017; Ulrich et al., 2017). Employing F_{MSY} reference points as upper limits or choosing lower reference points is a cautious strategy, beneficial in cases of mixed stocks or climate change considerations. Thus, an interesting management approach for EBFM could involve establishing the Fmsy as an upper boundary to avoid surpassing, and strategically optimizing the fleet multiplier to align as closely as feasible with 0.8 Fmsy. Prioritizing species sensitive to climate change within the fitting process is recommended. Greater reductions in mF might be assigned to fleets with significant environmental impact or, if selective measures are not feasible, to fleets with high discard rates.

Conclusion

In conclusion, the utilization of multivariate statistical analyses helps in having a preview in selecting indicators sensitive to the impacts of fishing and climate change. Assessing redundancy enables to determine whether calculating indicators by trophic guild is worthwhile. Comparisons between simulations on Ecosim involving several fishing mortality multipliers and three climatic scenario, highlight indicator sensitivity to fishing, climate change and the interaction between both. Thus, the biomass of all fish, shannon of pelagics and the CWV on Linf for all fish are the indicators the most sensitive to fishing. The proportion of immatures, the depletion of planktivores and the biomass of demersals appears to be the indicators the most sensitive to climate change. Biomass of all species, shannon of planktivores and demersals, the proportion of predators and LSI of demersals are the indicators the most sensitive to the interaction between climate change and fishing. Therefore, the state of the ecosystem was investigated but a dynamic component of ecosystem is also crucial to investigate. The recovery scenarios aim to investigate resilience of the different components of the ecosystem. Fishing intensity has more impact on recovery than climate change. The eveness among planktivore is the component that shows the most difficulty to recover. The biomass of all fish does not return at the reference value after disturbance if fishing intensity is too high. Then, the responsiveness of the indicators to fishing management scenarios on intra and inter-species selectivity and an optimized multispecific MSY is explored. They have varying effects on ecosystem health, biomass, evenness, and predator proportion. The applicability of indicators varies depending on community structure, making it crucial to tailor the selection according to prevailing conditions. Furthermore, considering indicators at a finer scale, which isolates signal-contributing species from the prevailing dominant ones, proves more insightful than excluding these species from indicator calculations. Notably, even minor species, through trophic interactions, significantly influence the dynamics of species with lower biomass. Indicator sensitivity to climate change, fishing and the interaction between both is dependent on the ecosystem considered and to the image given by the model, a simplification of the reality which do not show all the variations and trends. Incorporating multi-stanza groups for more meaningful trophic guild representation and including fishing effort as a driver should facilitate the testing of more realistic fleet management strategies.

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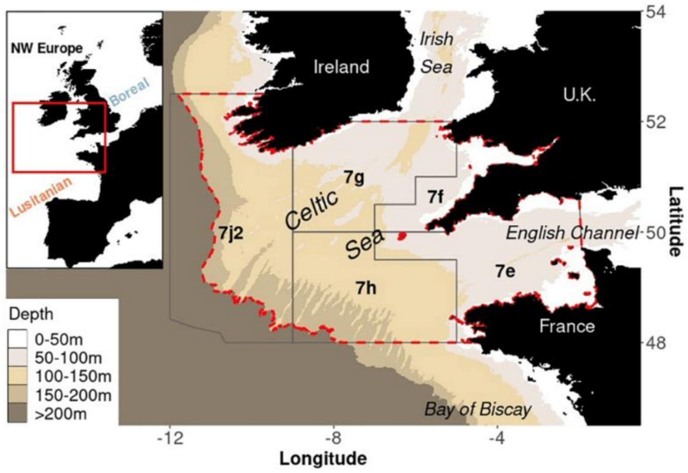
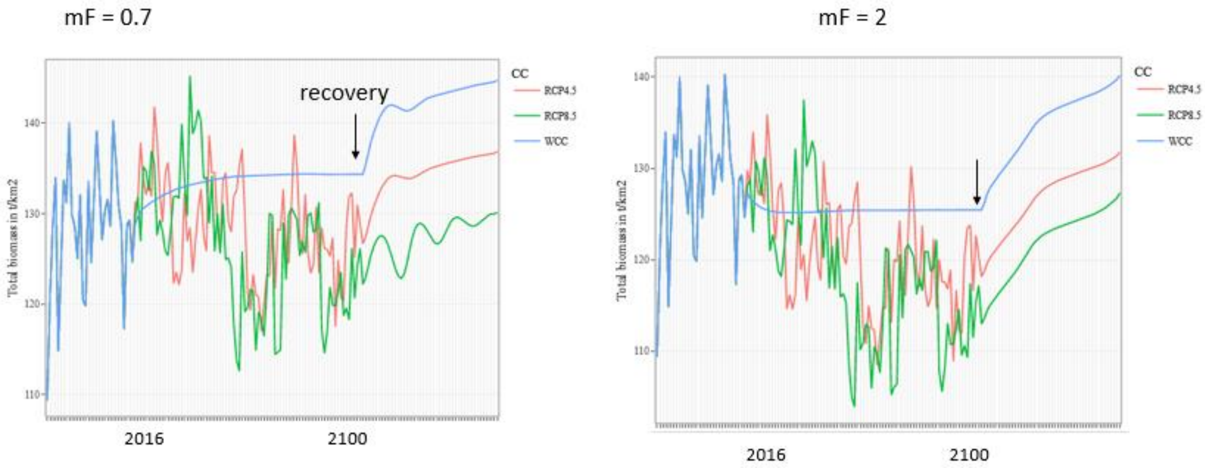
ANNEXES

Appendix 1. – Study area (Hernvann et al., 2020)

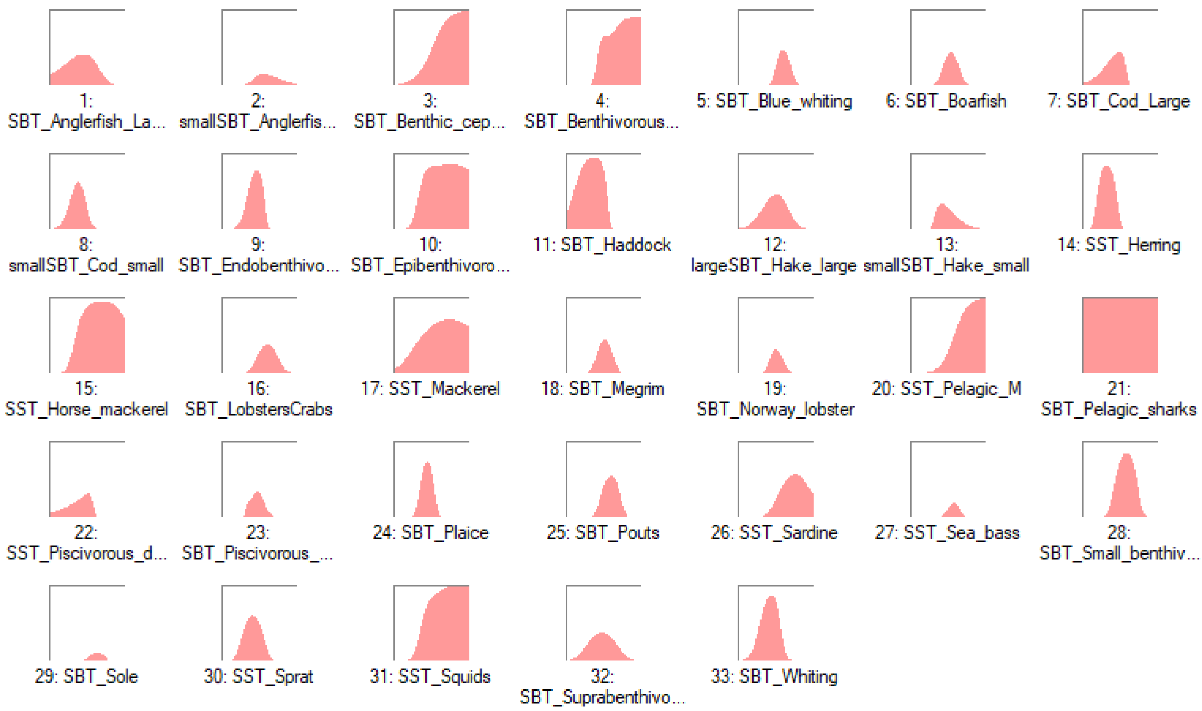


Appendix 2. – Forcing time series and total biomass

Total biomass in t/km2 for two mF



Appendix 3. – Functional responses (Hernvann et al., 2020)



Appendix 4. – Stability test

A stability test should be conducted prior to any time series forcing or fitting in the model. This test aims to identify potential issues, such as prey-predator cycles across multiple trophic levels, significant reduction in the biomass of certain compartments due to predation, competition, or stock recruitment instabilities.

Simulations are carried out over a span of 100 years, considering four scenarios:

1. A cessation of fishing mortality immediately after the base year.
2. Brutal and temporary (10 years) increase in fishing mortality after the base year (between 1985 and 1995).
3. Brutal and temporary (10 years) decrease in fishing mortality after the base year (between 1985 and 1995).
4. Constant fishing mortality

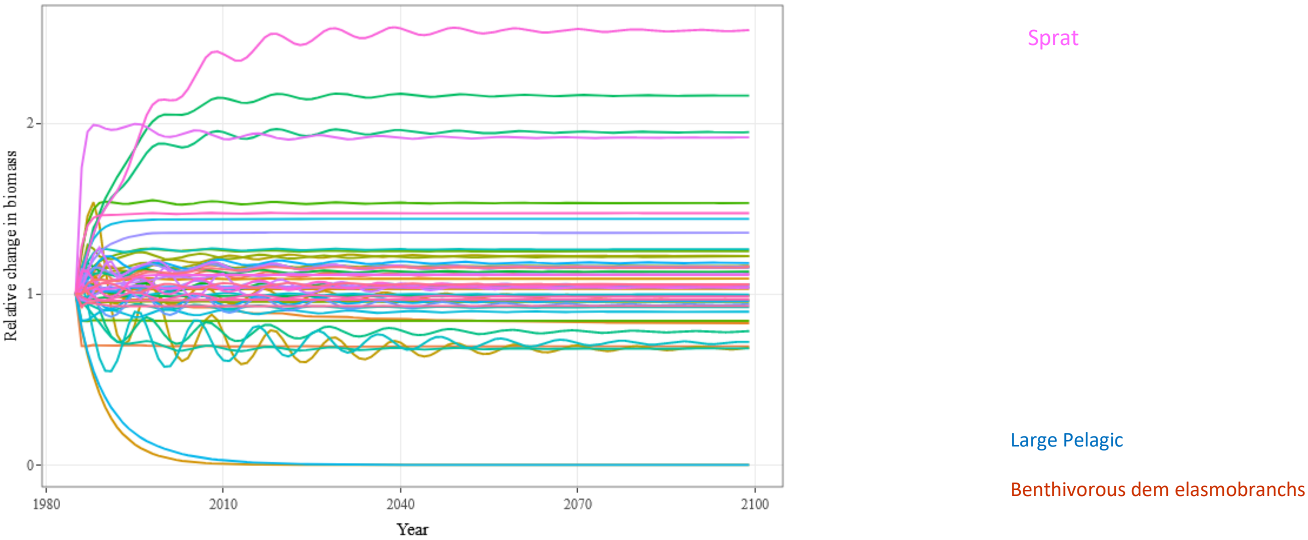
Some groups exhibit oscillation patterns. In the frame of this study, the recruitment parameters were modified to investigate stock recruitment instabilities, but no issues were found. The groups tend to stabilize, indicating that there is no cause for concern. However, the biomass of the groups "Large Pelagic" and "Benthivorous Demersal Elasmobranchs" approaches zero after 30 years with constant fishing mortality, after 10 years with the increased fishing mortality scenario, and after 40 years with the decreased fishing mortality scenario. The fishing mortalities applied to these groups are consistent (0.32 and 0.24, respectively, for elasmobranchs and large pelagic groups).

This phenomenon can be viewed as normal since large pelagic fish did not have a high biomass in this area, and benthivorous elasmobranchs are already heavily fished with high discards. There might not be enough biomass to account for the catches or there are excessive catches relative to the biomasses. Additionally, it could be attributed to the model underestimating P/B values for these groups. Increasing the P/B values for these two groups would be an interesting option to explore.

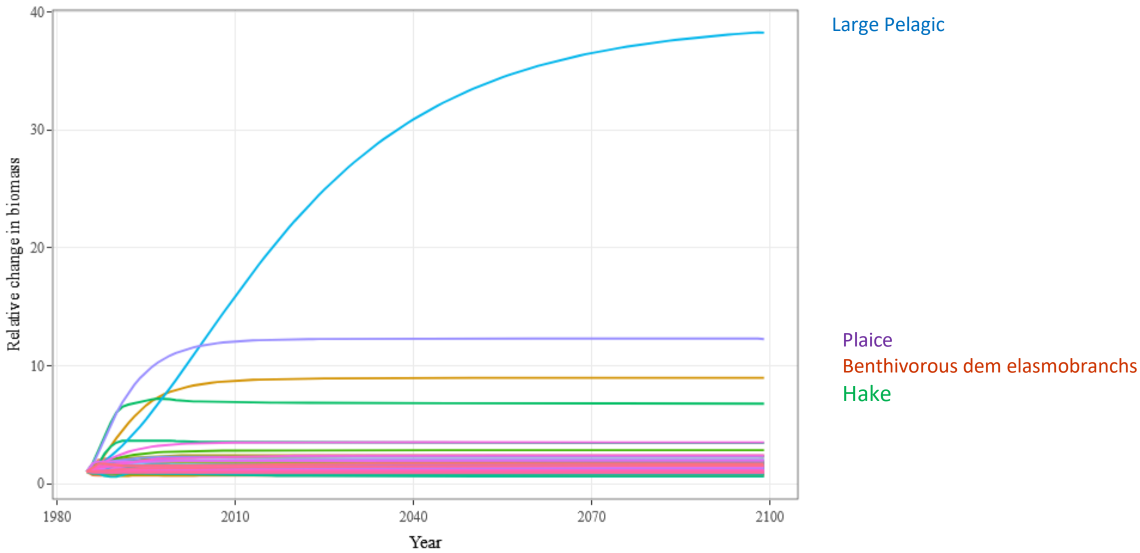
Nevertheless, it's important to note that these groups have low biomass in the Ecopath 1985 and represent only a small proportion of the total biomass, so the impacts on the biomass dynamics and indicator calculations are expected to be minimal. Moreover, when the time series data are incorporated, the model successfully reproduces past trends for these groups.

In order to ensure the global consistency of the model, investigating a change in P/B for "Large Pelagic" and "Benthivorous Demersal Elasmobranchs" in the 1985 Ecopath model would be necessary, but this task was beyond the scope of the current study.

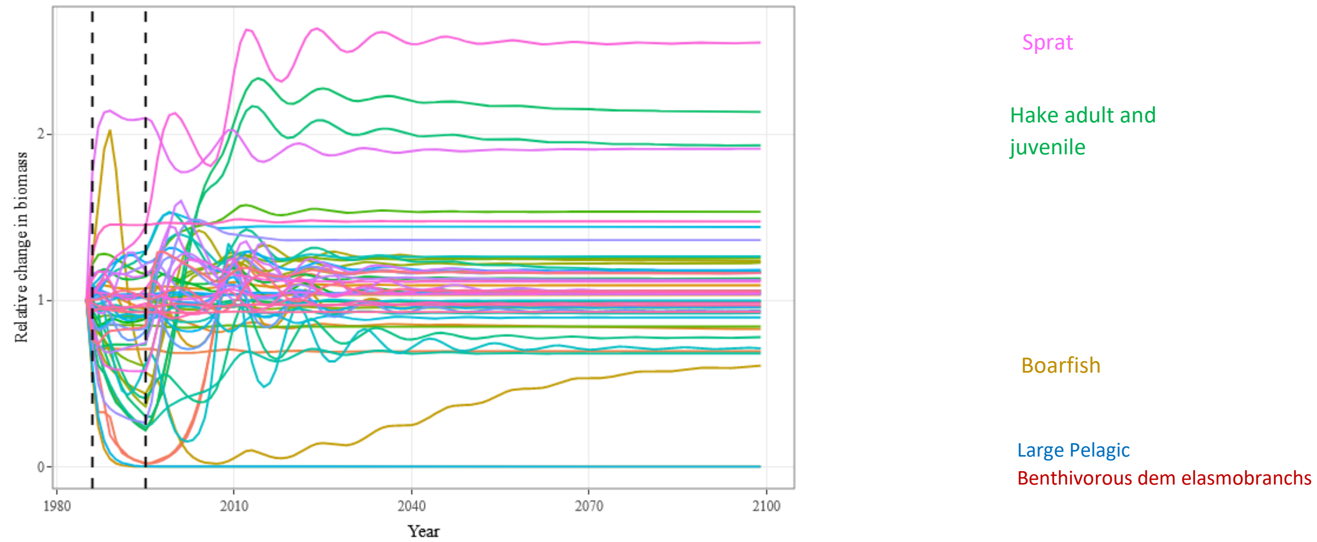
Relative biomass with the constant fishing mortality scenario:



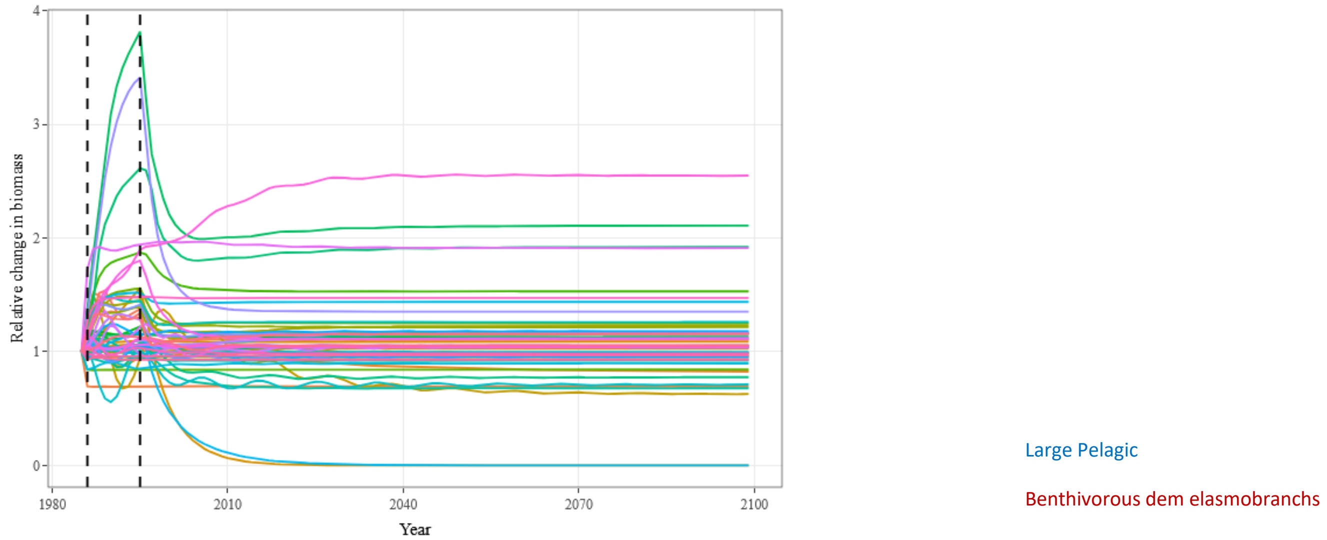
Relative biomass with the cessation of fishing mortality scenario:



Relative biomass with the increase in fishing mortality scenario:



Relative biomass with the decrease in fishing mortality scenario:



Appendix 5. – SEAwise protocol

The SEAwise methodology, and more precisely those of the task 4.4, is used in this study. SEAwise task 4.4 aims at supporting the use of ecological indicators in fishery management, in order to guide managers towards strategies that lead to an ecologically safe space for fisheries (providing yields for sustainable fisheries, maintaining ecosystem functions and leading to low risk of overexploitation. It studies the response of selected indicators to fisheries impacts through a range of simulations, based on the postulate that fisheries are the dominant driver of change in fish biodiversity and food web structure.

In this task, climate change is not investigated, therefore, the methodology is mostly used in the constant environmental conditions part of this study and a similar method is used for each climatic scenario.

The response of indicators under a range of fishing strategies is investigated. The task 4.4 develops a novel methodology capable of generating ecological targets for indicators and management limits in ecosystem context.

Simulations and scenarios:

Simulations are conducted forward to equilibrium (circa. 100 years) with constant climatic conditions to represent current prevailing conditions with fishing scenarios:

0. Recovery potential as a possible target for 'good' in GES (Good Environmental Status)
With zero fishing, create estimates of unfished spawning stock biomass of each species/stock and of each indicator (IND target) based on a long-term average (the final 50 years of a 100-year projection).
1. All fleets scaled equally: set of fishing effort multipliers [0, 0.2, 0.4, 0.7, 1, 1.5, 2, 2.5, 3, 4]
2. Reduce seabed impacting bottom trawl fleets
3. Recovery scenarios from changes in activity of all fishing fleets
Run case 1 and extend a further 50 years with fishing effort and/or mortality to zero to model return to equilibrium. An indicator is considered to be able to recover to the long-term average when unfished, if within 30 years of the relaxation of fishing, it is able to reach the target value as it is defined in the scenario 0.
4. Recovery scenarios, following reductions in activity by seabed impacting bottom trawl fisheries

Calculation of the size indicators:

In SEAwise, it was decided to use Lmax to calculate both MML and LSI, as a proxy of Linf. Linf and Lmax are very highly correlated, especially when there is a lot of data and the maximum in any observation since 1983 was used in any otter or beam trawl survey in the NEA area (using the datasets listed on the OSPAR assessment page during IA2017 - Pilot Assessment of Mean Maximum Length of Fish (ospar.org)). The values of Linfiny in the literature and on fishbase were not used because they can differ and may or may not be relevant for the OSPAR area (NEA).

Trophic guild approach:

"Species that share common prey items can be grouped into functional feeding guilds and indicators of change in the biomass of guilds have been proposed to monitor change in ecosystem structure (e.g. ICES 2018). The relative biomass of guilds within the ecosystem (i.e. the balance) may also provide a metric that is a proxy for change in dominance of ecosystem function due to the differing trophic pathways leading to each. Thompson et al. (2020) demonstrated an approach to determine feeding guilds based on stomach contents data. Potentially, these feeding guilds provide more informative measures of change in ecosystems than the simple separation of fish into their habitat-based assemblages (demersal and pelagic fish). For fish and elasmobranchs, we use a relatively simple set of guilds where we take a higher split in the classification tree than was used to generate the more highly resolved guilds by Thompson et al. (2020). These higher-level guilds are described as planktivores, benthivores and piscivores."

Depletion risks:

The risk of species depletion is studied in task 4.4 in order to establish limit reference points for indicators that can allow the ecosystem to revert to an unimpacted state when fishing pressure is eliminated.

The extent of depletion (D) of a single species (s) in any non-zero fishing effort scenario E was computed in relation to the unfished spawning stock biomass in the unfished scenario ($SSBs$,0) and used as a basis to infer risk as follows:

$$D_{s,E} = \begin{Bmatrix} 0 \;\; if \; SSB_{s,E} \geq SSB_{s,0} \\ \left(1 - \dfrac{SSB_{s,E}}{SSB_{s,0}}\right) otherwise \end{Bmatrix}$$

The grouped "Depletion Risk Within Guild" or "Depletion Risk Within Community" for the scenario is then derived from the weighted average of these species level impacts within the group for the SS species following application of the simple community risk metric of Thorpe and De Oliveira (2019). In this approach, the species depletion scores Ds,E are ranked in descending order and the maximum risk of 1 relates to a species depleted to zero SSB.

$$D_{G,E} = \frac{\sum_{s=1}^{S}(s^{-t}.D_{s,E})}{\sum_{s=1}^{S}(s^{-t})}$$

G : relevant group (guild, community)

E : fishing effort

s : rank order of the species. s=1 for the species with the maximum $D_{s,E}$

t = risk tolerance

If the risk tolerance is spread evenly across the community, *t* = 0. In contrast, if there is no tolerance of risk concentration and the community risk is considered to be equivalent to the most endangered stock, *t* = inf. SEAwise task 4.4 uses t =1, it heavily penalizes outcomes where the risks is loaded disproportionately onto a small number of stocks.

In the limit that the community risk defaults to the mean risk (first scenario). In the limit there is no tolerance of risk concentration and we consider the community risk as equivalent to the most endangered stock (*t* = inf).

<u>Indicator thresholds:</u>

The aim is to avoid a low biomass of any single species in the community, where low is considered to be an over-exploited depletion level of 30% of SSB0. This corresponds to the results obtained by Thorpe et al. (2015), indicating that in a multi-species system, the spawning biomass of each species when harvested at Maximum Sustainable Yield (MSY) is generally higher than 30% of its unexploited biomass (B0). Punt et al (2014) also find that a proxy for the spawning biomass of a species when fished at Maximum Economic Yield (B MEY) is expected to lie in the range of 50–60% of SSB0. Thus, when calculating the threshold for the community metric for each group or guild, we consider all member species that are not over-exploited to be maintained at 60% of SSB0, in contrast to the depleted stock at 30% of SSB0. Consequently, the species depletion score (Ds) is 0.7 for the depleted stock, whereas for all other species (maintained at higher SSB levels), the species depletion score is 0.4. Employing this approach, with a tolerance set to 1 (as outlined in Thorpe and De Oliveira, 2019), results in an upper limit of 0.53 for depletion risk in a community of 5 species, a limit of 0.50 for 10 species, and a limit of 0.46 for 100 species. For the set of models used in SEAwise task 4.4, these values range from 0.46 to 0.56, with the demersal fish community shows the lowest values.

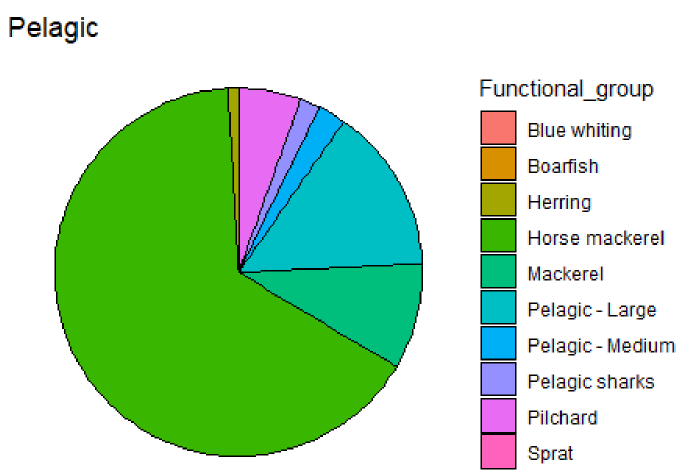
Community risk scores for the sustainability approach:

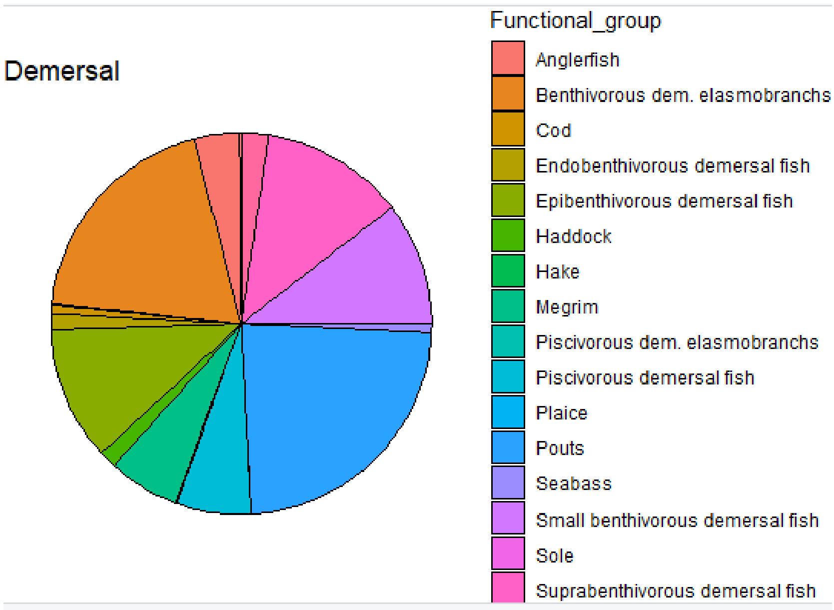
	Bay of Biscay EwE	Adriatic Sea EwE	Ionian Sea EwE	S. North Sea EwE	North Sea LeMANS	North Sea OSMOSE	Eastern Channel OSMOSE	Eastern Channel Atlantis
All	0.48	0.49	0.48	0.47	0.47	0.50	0.49	0.46
Demersal	0.49	0.50	0.49	0.47	0.48	0.51	0.51	0.46
Pelagic	0.50	0.50	0.50	0.52	0.52	0.56	0.53	0.53
Benthivores	0.51	0.53	0.52	0.50	0.50	0.56	0.56	0.49
Piscivores	0.50	0.52	0.50	0.48	0.49	0.53	0.51	0.47
Planktivores	0.52	0.51	0.51	0.47	0.51	0.54	0.56	0.56

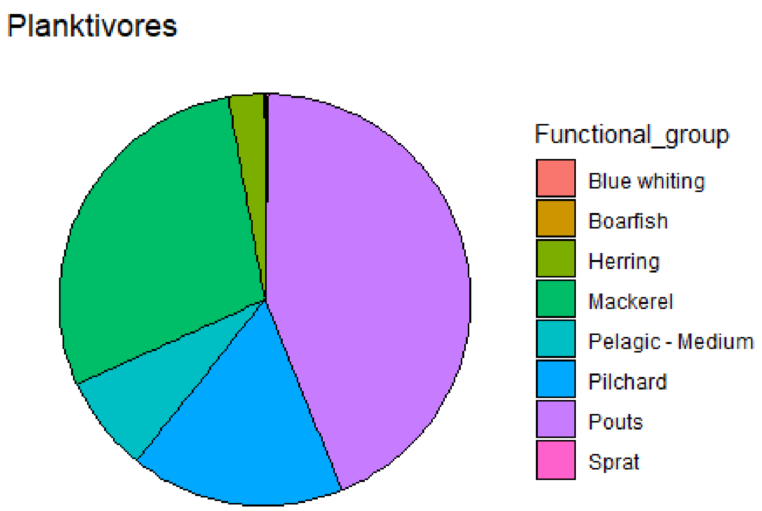
Appendix 6. – Calculation of Lmax and age max for each functional group

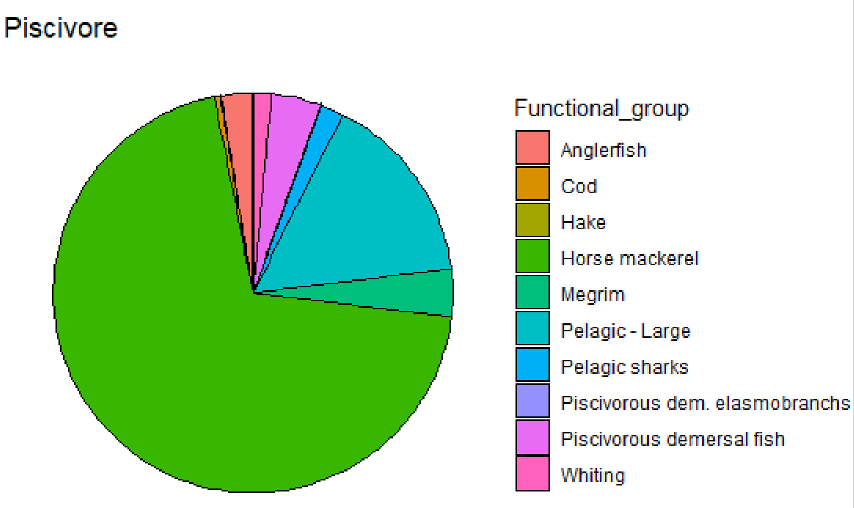
Lmax and maximum age were accessible for each species within the functional groups. For multispecies groups where the relative biomass of each species was provided in EVHOE, a weighted average is computed (on the 2011-2021 period to take into account recent evoultions). In cases where EVHOE data is unavailable, a simple mean is applied. This last situation applies to Large Pelagic fish, Medium Pelagic fish, Pouts, Endobenthivorous demersal fish, and Pisicvorous demersal elasmobranchs.

Appendix 7. – Composition on the demersal/pelagic and trophic guild groups in 2016

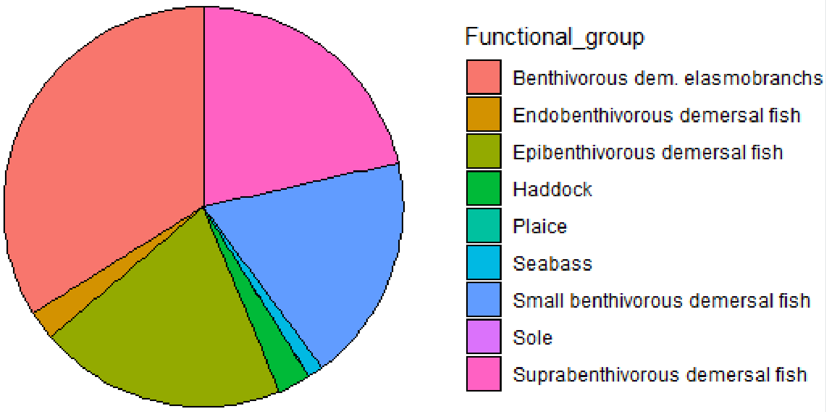



Demersal
Functional_group
Anglerfish
Benthivorous dem. elasmobranchs
Cod
Endobenthivorous demersal fish
Epibenthivorous demersal fish
Haddock
Hake
Megrim
Piscivorous dem. elasmobranchs
Piscivorous demersal fish
Plaice
Pouts
Seabass
Small benthivorous demersal fish
Sole
Suprabenthivorous demersal fish


Planktivores
Functional_group
Blue whiting
Boarfish
Herring
Mackerel
Pelagic - Medium
Pilchard
Pouts
Sprat


Piscivore
Functional_group
Anglerfish
Cod
Hake
Horse mackerel
Megrim
Pelagic - Large
Pelagic sharks
Piscivorous dem. elasmobranchs
Piscivorous demersal fish
Whiting

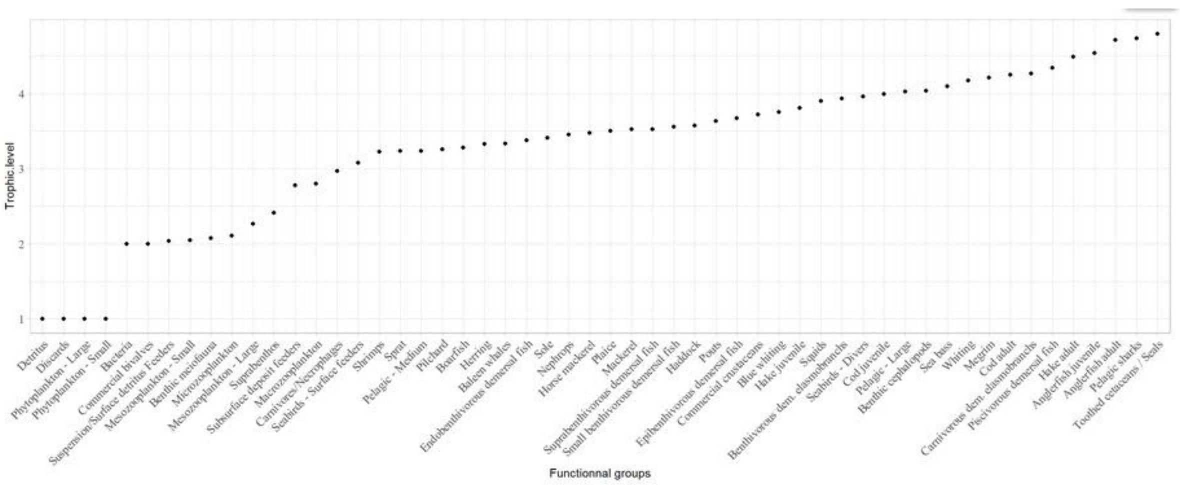
Benthivore



Appendix 8. – PREBAL diagnostics of Ecopath models (2014, 2015, 2016)

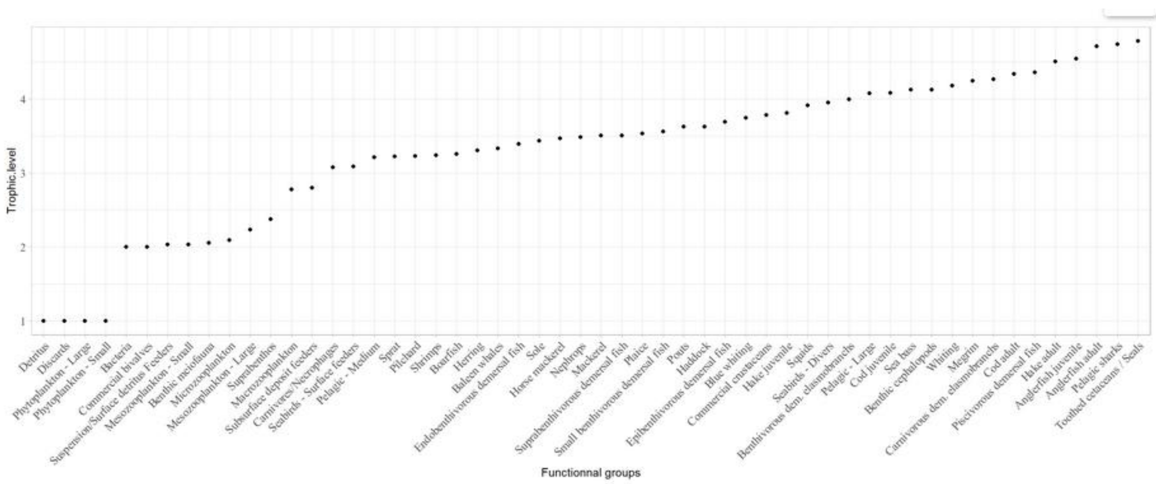
- Ecopath 2014

	Issues	Changes
1.	EE = -91 for seabirds 2 and >0 for seabirds 1	Setting seabirds EE at 0
2.	Whiting, Sprat, Pelagic Large, Detritus : EE > 1	Reduction in the cannibalism rate of Whiting in the diet matrix: from 0.0058 to 0.00245
3.	Sprat, Pelagic Large, Detritus EE> 1	Reduction in the cannibalism rate of Pelagic Large in the diet matrix: from 0.0757 to 0.0.557
4.	Sprat, detritus : EE > 1	Sprat C/B : from 7.196 to 6.9
5.	Sprat, detritus : EE >1	Sprat P/B : from 0.807 to 0.885
6.	Detritus : EE > 1	Reduction in benthic meiofauna : from 25.29 to 23.99
7.	Benthic meiofauna : EE>1	Reduction on the meiofauna predation by subsurface deposit feeders (0.704 to 0.686), increase in detritus consumption for SSDF (0.258 to 0.276).
8.	Sardine and herring P/Q < 0.1	Reduce Q/B for Sardine (8.281 to 4.888) and Herring (5.799 to 4.299)
9.	Whiting P/Q > 0.3	Increase Q/B : from 2.691 to 2.78



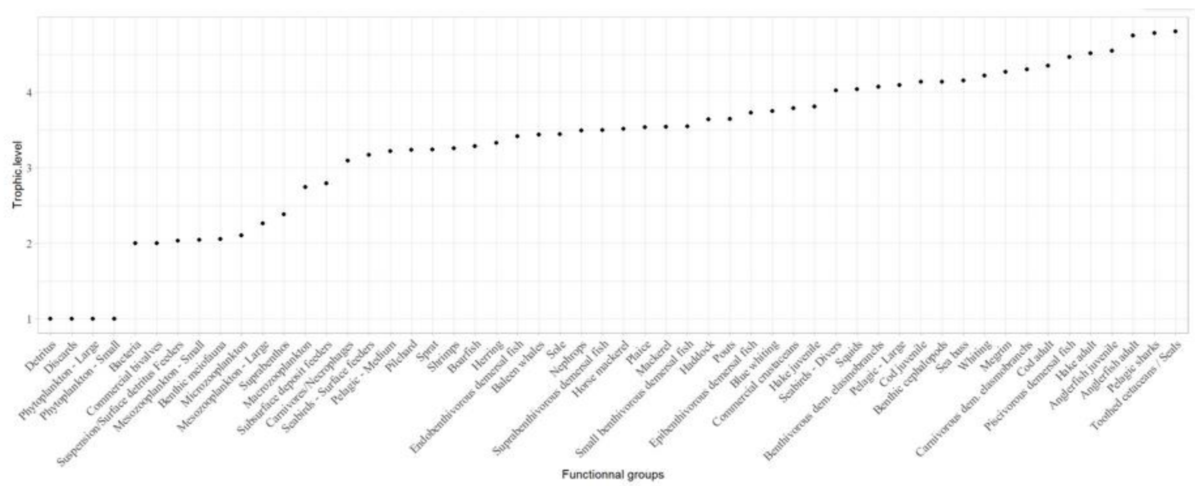
- Ecopath 2015

	Issues	Changes
1.	EE = -91 for seabirds 2 and >0 for seabirds 1	Setting seabirds EE at 0
2.	Whiting, Plaice, Sprat, Pelagic Large, Discards : EE > 1	Reduction in the cannibalism rate of Whiting in the diet matrix : from 0.00541 to 0.00441
3.	Plaice, Sprat, Pelagic Large, Discards EE> 1	Reduction in the cannibalism rate of Large Pelagic in the diet matrix from 0.071 to 0.0.5
4.	Plaice, Sprat, Discards EE>1	Decrease in Plaice biomass from 0.0645 to 0.0648
6.	Sprat, Discards : EE >1	Sprat P/B : from 0.759 to 0.765
7.	Discards : EE > 1	Changes in diet matrix for discards as prey: Nephrops from 0.00439 to 0.00450 and Carnivores Necrophages from 0.00182 to 0.00162
8.	Sardine and herring P/Q < 0.1	Reduce Q/B for Sardine (6.373 to 5.3) and Herring (4.997 to 4.4)



- Ecopath 2016

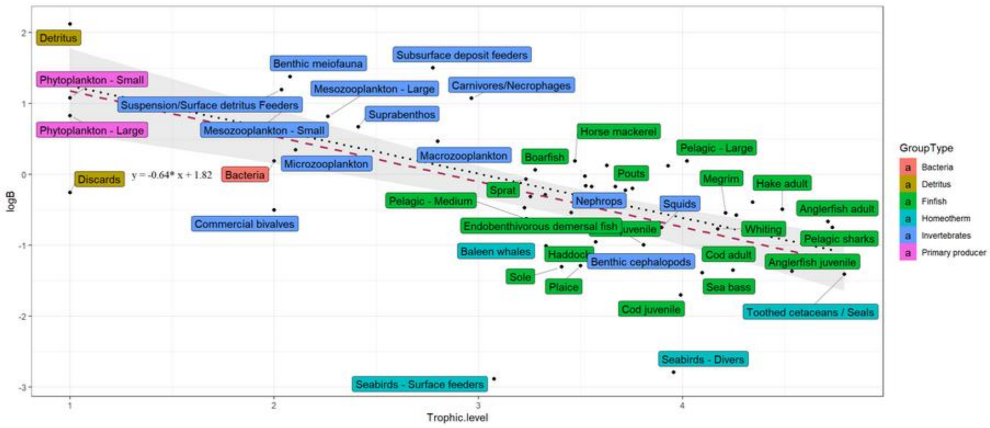
	Issues	Changes
1.	EE = -91 for seabirds 2 and >0 for seabirds 1	Setting seabirds EE at 0
2.	Whiting, Mackerell, Pelagic Large, Discards: EE > 1	Reduction in the cannibalism rate of Pelagic Large in the diet matrix : from 0.0682 to 0.0569
3.	Whiting , Mackerell, Discards EE> 1	Reduction in the cannibalism rate of Whiting in the diet matrix : from 0.0682 to 0.0569
4.	Mackerell, Discards : EE > 1	Decrease in Mackerell biomass : from 0.00539 to 0.00489
5.	Discards : EE >1	Changes in diet matrix for discards as prey: Nephrops from 0.00476 to 0.00599 and Carnivores Necrophages from 0.00198 to 0.00108
6.	Whiting P/Q > 0.3	Increase P/Q : from 2.894 to 2.945



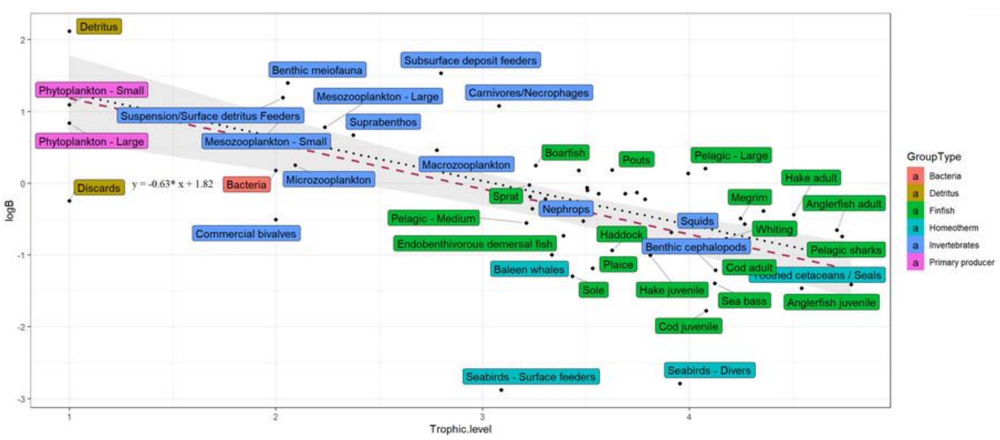
Biomass decomposition across trophic levels

The Biomass (in log scale) should decrease across trophic levels. The biomass should span 5-7 orders of magnitude according to Link **et al.** (2010). The slope of biomass decomposition across trophic levels should be around 5-10%.

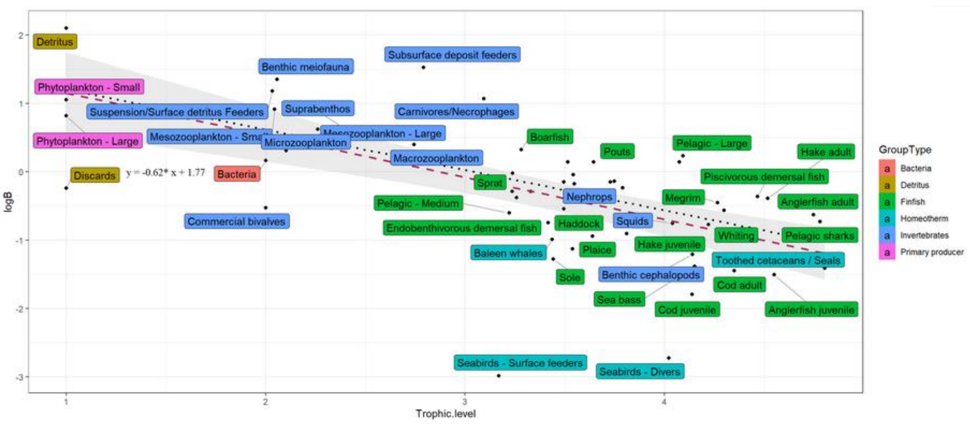
2014



2015



2016



The red dashed line is the regression line including all the group types apart from detritus. The black dotted line is the same regression line but excludes homeotherms

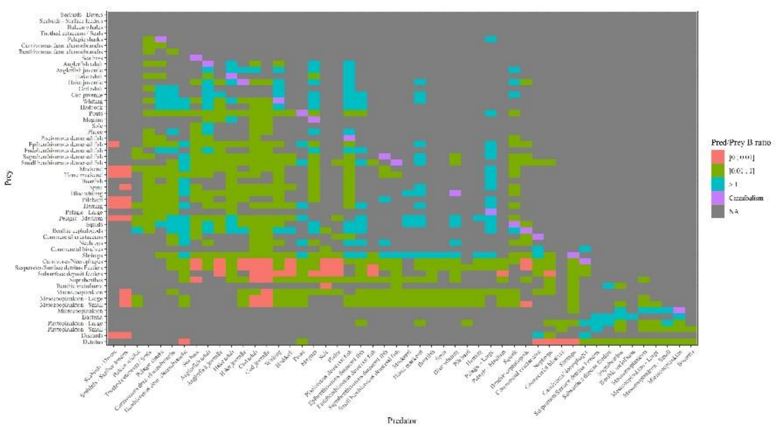
Biomass ratio

Biomass of preys should be higher than biomass of predators. (Link et al, 2010)

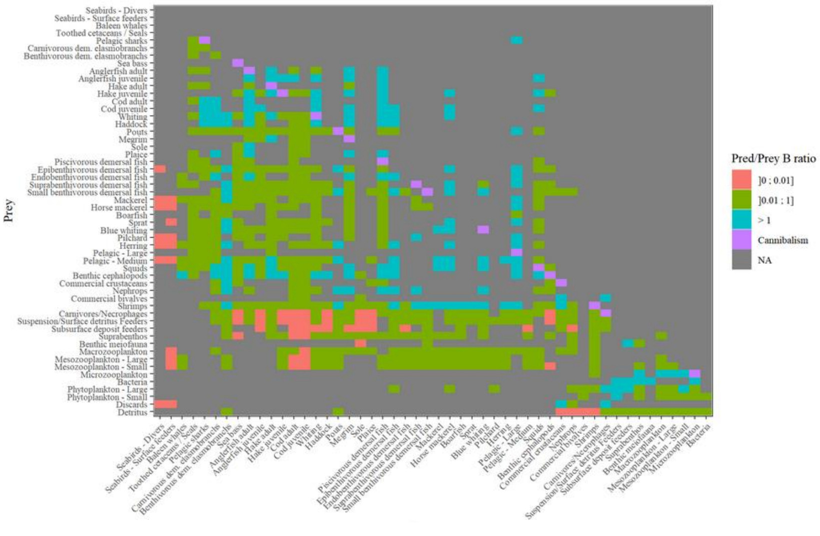
First, compared across taxa, total predator biomass should be less than that of their prey. If the ratio approaches 1, then there may possibly be too much predation pressure on the prey groups, indicative of some potential imbalances in system structure. Zooplankton feeding upon phytoplankton may be a reasonable exception to this diagnostic given the high productivity and low standing stock biomass of these primary producers. […]If this ratio is greater than 1, then it is highly likely that predation pressure is too excessive on a prey group, indicating that initial biomass estimates should be revisited.

If there are too many zeroes, it may be that predators are not feeding enough or the food web is at danger of being overly connected […]. If there are too few zeroes,it is possible that there is too much predation pressure on prey, predators may be feeding at too low of a trophic level (usually a holdover from diet data taken from the literature and not obtained within a particular ecosystem),or there is a high degree of omnivory (feeding at multiple trophic levels). (Link et al, 2010)

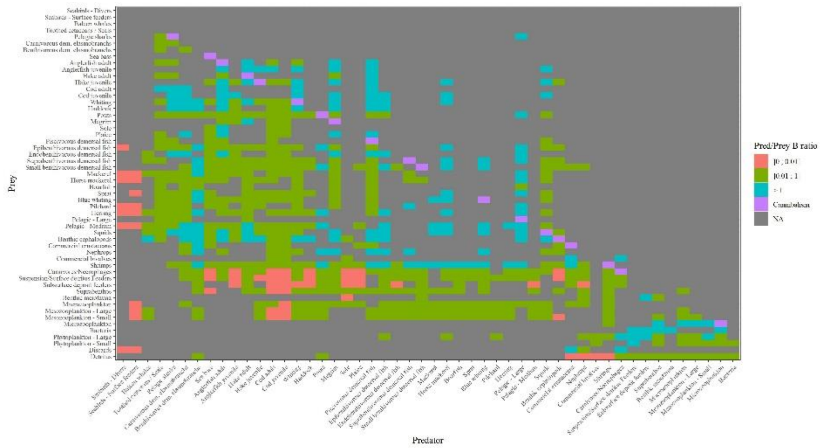
2014



2015



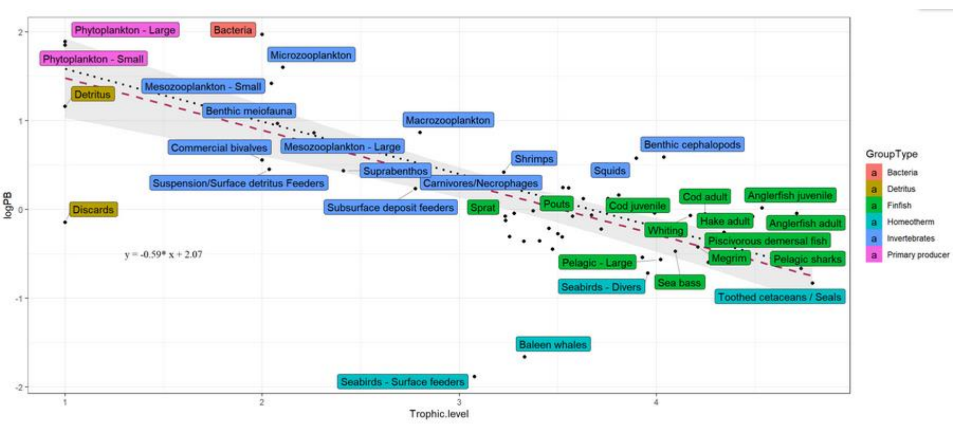
2016

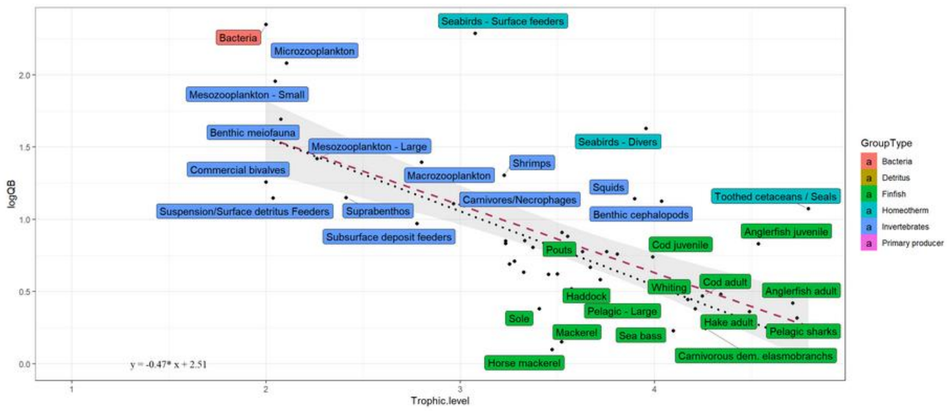


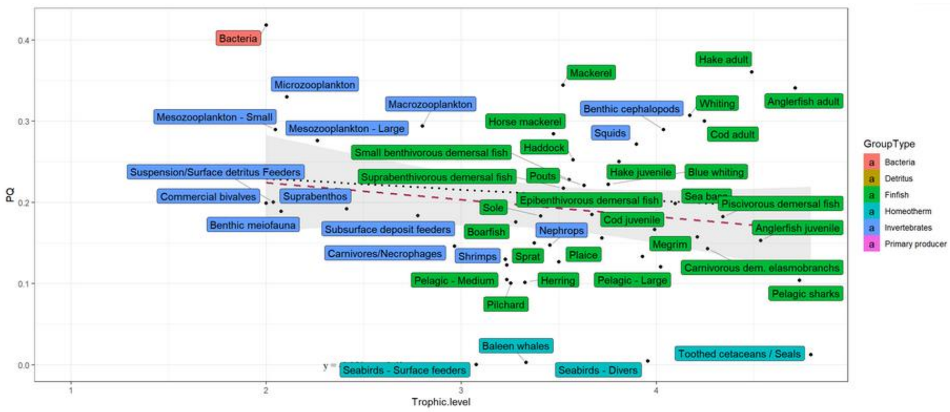
The red dashed line is the regression line including all the group types apart from detritus. The black dotted line is the same regression line but excludes homeotherms.

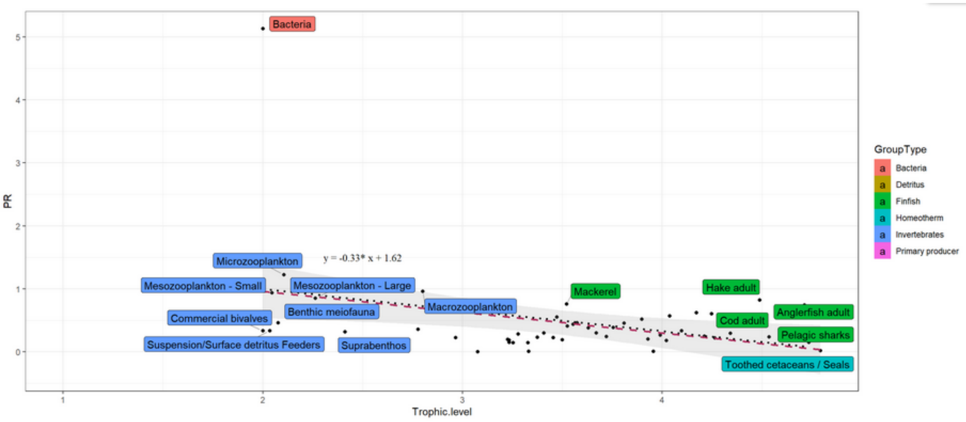
Vital rates

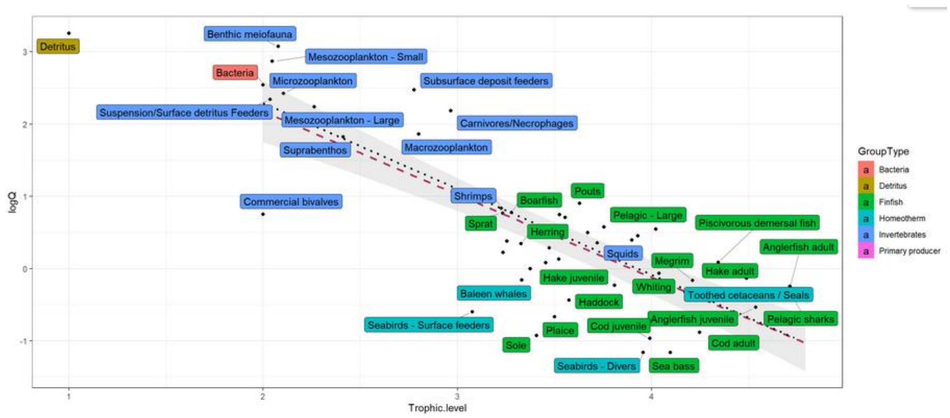
2014



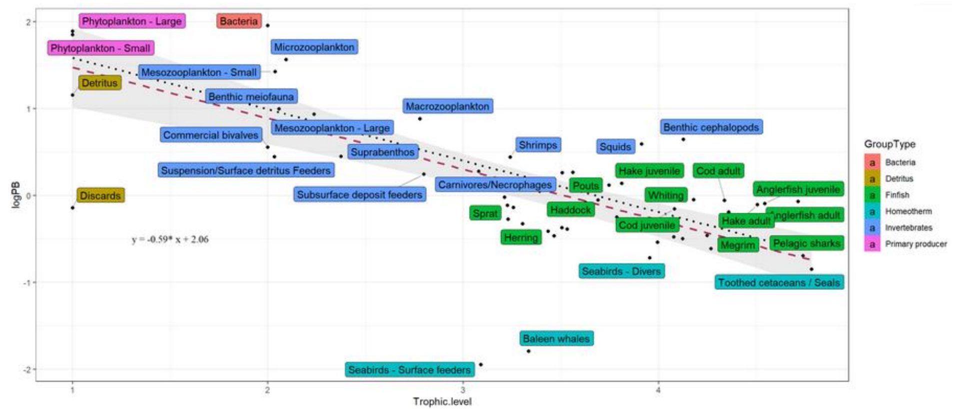

Seabirds - Surface feeders
Bacteria
Microzooplankton
Mesozooplankton - Small
Benthic meiofauna
Mesozooplankton - Large
Seabirds - Divers
Commercial bivalves
Shrimps
Macrozooplankton
Squids
Suspension/Surface detritus Feeders
Suprabenthos
Carnivores/Necrophages
Benthic cephalopods
Toothed cetaceans / Seals
Subsurface deposit feeders
Anglerfish juvenile
Pouts
Cod juvenile
Cod adult
Whiting
Haddock
Anglerfish adult
Pelagic - Large
Sole
Hake adult
Mackerel
Sea bass
Pelagic sharks
Carnivorous dem. elasmobranchs
Horse mackerel
y = -0.47* x + 2.51
logQB
Trophic.level
GroupType
Bacteria
Detritus
Finfish
Homeotherm
Invertebrates
Primary producer

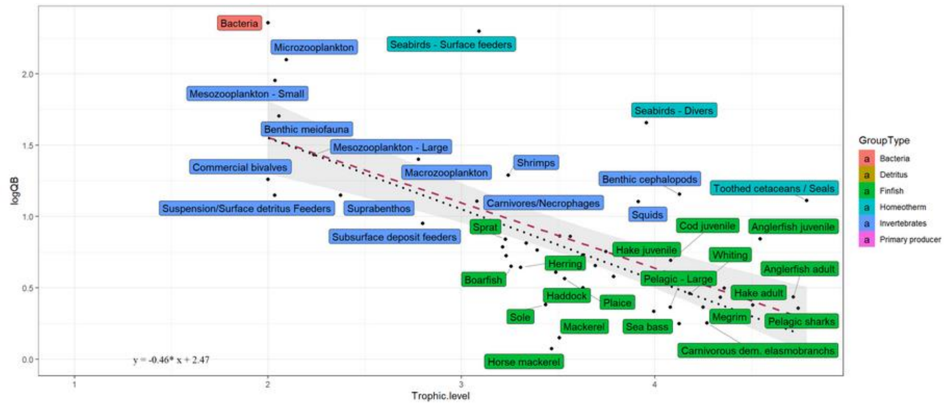

Bacteria
Hake adult
Mackerel
Microzooplankton
Anglerfish adult
Macrozooplankton
Benthic cephalopods
Whiting
Mesozooplankton - Small
Mesozooplankton - Large
Horse mackerel
Squids
Cod adult
Haddock
Small benthivorous demersal fish
Suspension/Surface detritus Feeders
Hake juvenile
Blue whiting
Suprabenthivorous demersal fish
Pouts
Commercial bivalves
Suprabenthos
Epibenthivorous demersal fish
Piscivorous demersal fish
Sole
Cod juvenile
Benthic meiofauna
Anglerfish juvenile
Subsurface deposit feeders
Boarfish
Nephrops
Megrim
Carnivores/Necrophages
Shrimps
Sprat
Plaice
Carnivorous dem. elasmobranchs
Pelagic - Medium
Herring
Pelagic - Large
Pelagic sharks
Pilchard
Baleen whales
Toothed cetaceans / Seals
Seabirds - Surface feeders
Seabirds - Divers
PQ
Trophic.level
GroupType
Bacteria
Detritus
Finfish
Homeotherm
Invertebrates
Primary producer

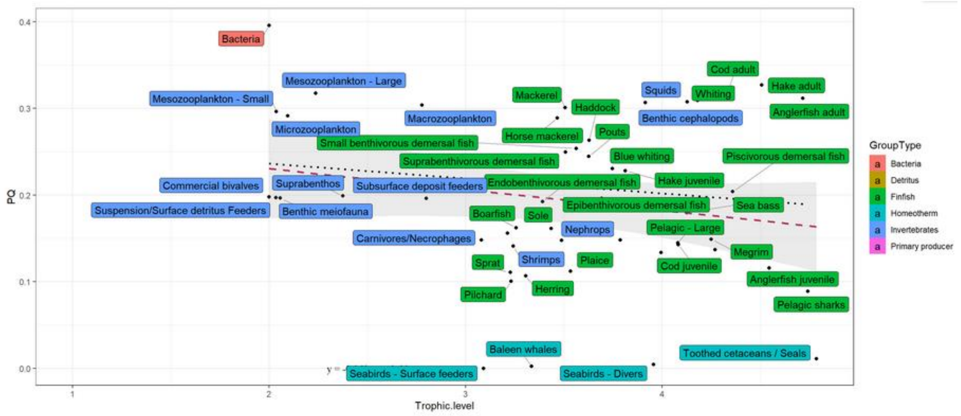

Bacteria
Microzooplankton
y = -0.33* x + 1.62
Mesozooplankton - Small
Mesozooplankton - Large
Mackerel
Hake adult
Macrozooplankton
Benthic meiofauna
Anglerfish adult
Commercial bivalves
Cod adult
Pelagic sharks
Suspension/Surface detritus Feeders
Suprabenthos
Toothed cetaceans / Seals
PR
Trophic.level
GroupType
Bacteria
Detritus
Finfish
Homeotherm
Invertebrates
Primary producer

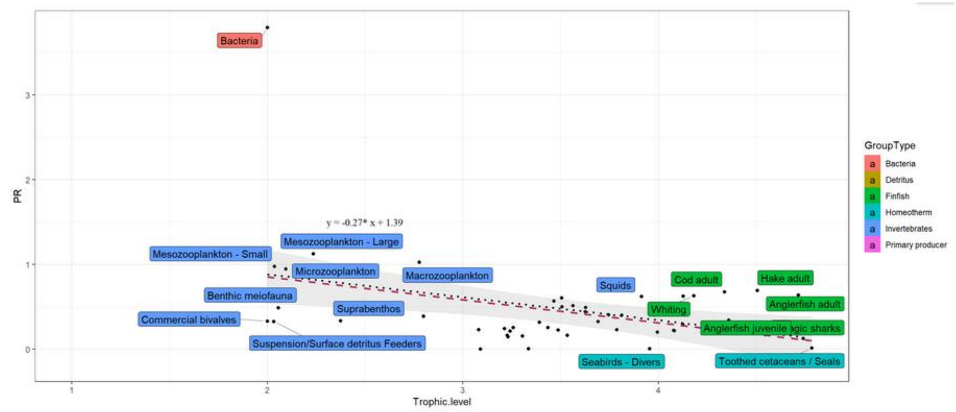

Detritus
Benthic meiofauna
Mesozooplankton - Small
Bacteria
Microzooplankton
Subsurface deposit feeders
Suspension/Surface detritus Feeders
Mesozooplankton - Large
Carnivores/Necrophages
Suprabenthos
Macrozooplankton
Pouts
Commercial bivalves
Shrimps
Boarfish
Pelagic - Large
Sprat
Piscivorous demersal fish
Herring
Anglerfish adult
Squids
Megrim
Hake adult
Hake juvenile
Whiting
Baleen whales
Toothed cetaceans / Seals
Haddock
Seabirds - Surface feeders
Anglerfish juvenile
Pelagic sharks
Cod juvenile
Plaice
Sole
Cod adult
Seabirds - Divers
Sea bass
logQ
Trophic.level
GroupType
Bacteria
Detritus
Finfish
Homeotherm
Invertebrates
Primary producer

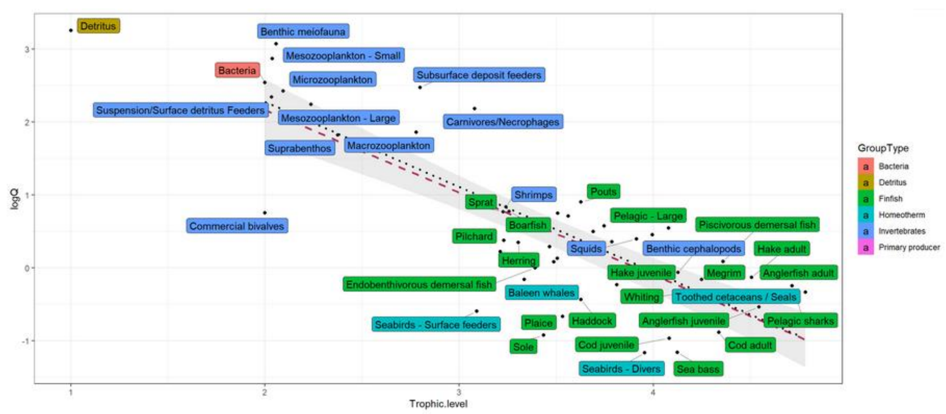
2015


Phytoplankton - Large
Bacteria
Phytoplankton - Small
Microzooplankton
Mesozooplankton - Small
Detritus
Benthic meiofauna
Macrozooplankton
Mesozooplankton - Large
Commercial bivalves
Benthic cephalopods
Shrimps
Squids
Suprabenthos
Suspension/Surface detritus Feeders
Hake juvenile
Cod adult
Carnivores/Necrophages
Pouts
Anglerfish juvenile
Discards
Subsurface deposit feeders
Whiting
Haddock
Sprat
Anglerfish adult
Hake adult
Cod juvenile
Herring
Megrim
Pelagic sharks
y = -0.59* x + 2.06
Seabirds - Divers
Toothed cetaceans / Seals
Baleen whales
Seabirds - Surface feeders
logPB
Trophic.level
GroupType
Bacteria
Detritus
Finfish
Homeotherm
Invertebrates
Primary producer

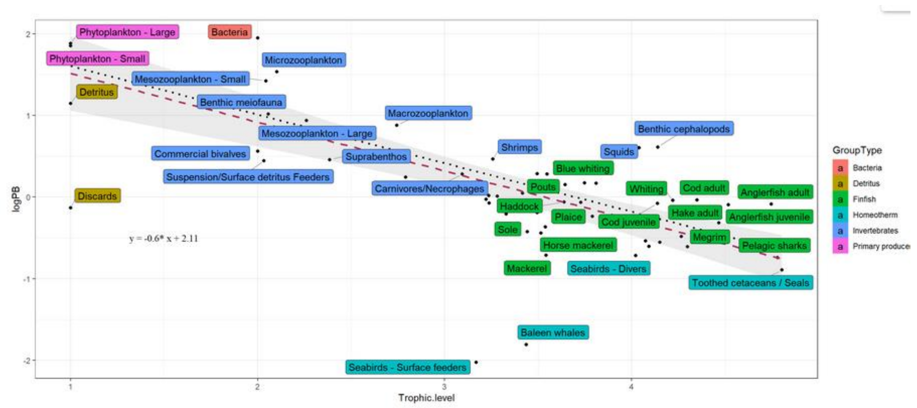

Bacteria
Seabirds - Surface feeders
Microzooplankton
Mesozooplankton - Small
Seabirds - Divers
Benthic meiofauna
Mesozooplankton - Large
Shrimps
Commercial bivalves
Macrozooplankton
Benthic cephalopods
Toothed cetaceans / Seals
Carnivores/Necrophages
Suspension/Surface detritus Feeders
Suprabenthos
Squids
Sprat
Cod juvenile
Anglerfish juvenile
Subsurface deposit feeders
Hake juvenile
Whiting
Herring
Anglerfish adult
Boarfish
Pelagic - Large
Hake adult
Haddock
Plaice
Megrim
Sole
Pelagic sharks
Mackerel
Sea bass
Carnivorous dem. elasmobranchs
y = -0.46* x + 2.47
Horse mackerel
logQB
Trophic.level
GroupType
Bacteria
Detritus
Finfish
Homeotherm
Invertebrates
Primary producer

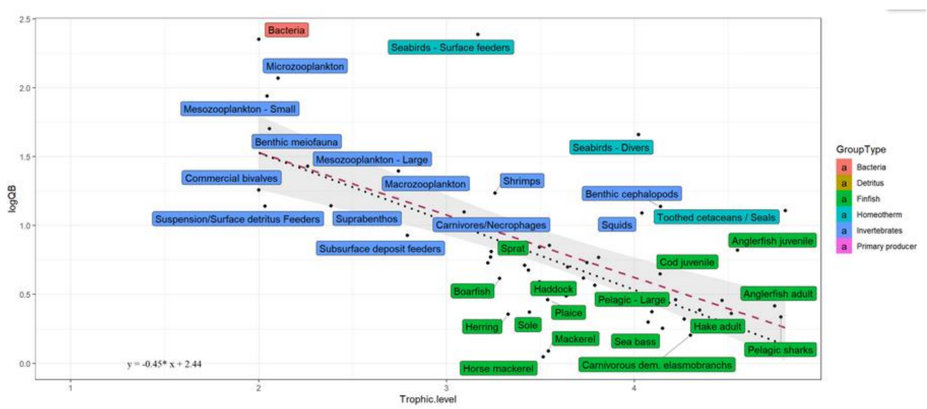

Bacteria
Cod adult
Mesozooplankton - Large
Squids
Whiting
Hake adult
Mesozooplankton - Small
Mackerel
Haddock
Macrozooplankton
Benthic cephalopods
Anglerfish adult
Microzooplankton
Horse mackerel
Pouts
Small benthivorous demersal fish
Blue whiting
Piscivorous demersal fish
Suprabenthivorous demersal fish
Commercial bivalves
Suprabenthos
Endobenthivorous demersal fish
Hake juvenile
Subsurface deposit feeders
Epibenthivorous demersal fish
Sea bass
Suspension/Surface detritus Feeders
Benthic meiofauna
Boarfish
Sole
Nephrops
Pelagic - Large
Carnivores/Necrophages
Megrim
Sprat
Shrimps
Plaice
Cod juvenile
Anglerfish juvenile
Herring
Pilchard
Pelagic sharks
Baleen whales
Toothed cetaceans / Seals
Seabirds - Surface feeders
Seabirds - Divers
PQ
Trophic.level
GroupType
Bacteria
Detritus
Finfish
Homeotherm
Invertebrates
Primary producer

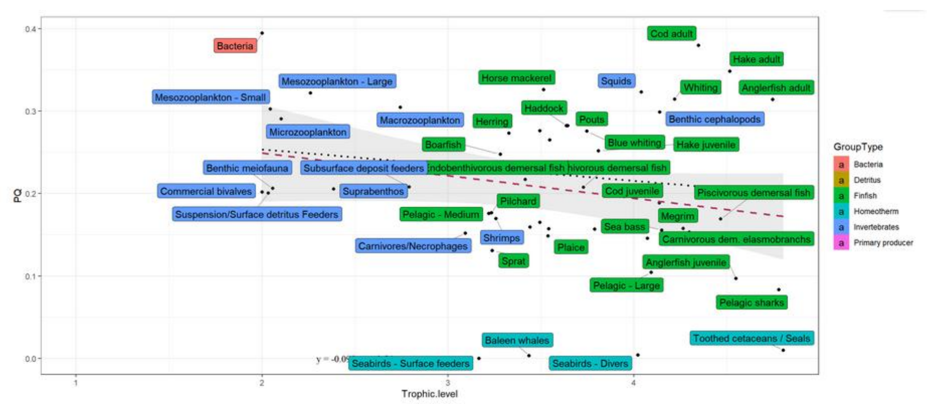

Bacteria
y = -0.27* x + 1.39
Mesozooplankton - Large
Mesozooplankton - Small
Microzooplankton
Macrozooplankton
Squids
Cod adult
Hake adult
Benthic meiofauna
Whiting
Anglerfish adult
Suprabenthos
Commercial bivalves
Anglerfish juvenile
Suspension/Surface detritus Feeders
Seabirds - Divers
Toothed cetaceans / Seals
PR
Trophic.level
GroupType
Bacteria
Detritus
Finfish
Homeotherm
Invertebrates
Primary producer

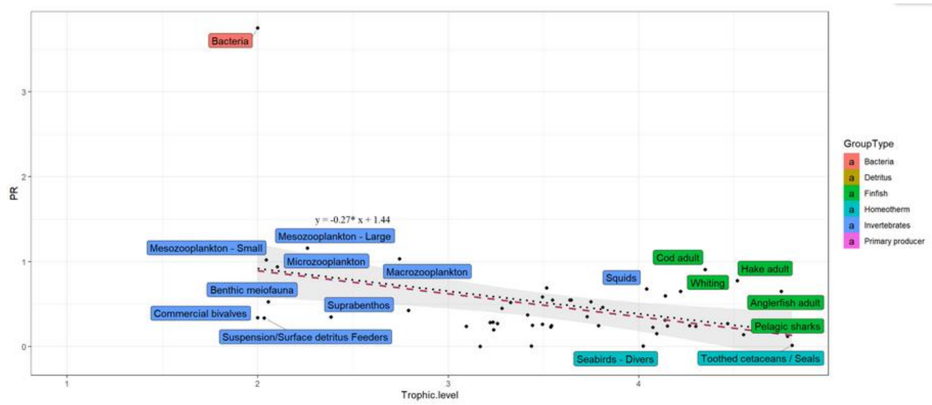

Detritus
Benthic meiofauna
Mesozooplankton - Small
Bacteria
Microzooplankton
Subsurface deposit feeders
Suspension/Surface detritus Feeders
Mesozooplankton - Large
Carnivores/Necrophages
Suprabenthos
Macrozooplankton
Sprat
Shrimps
Pouts
Commercial bivalves
Boarfish
Pelagic - Large
Piscivorous demersal fish
Pilchard
Squids
Benthic cephalopods
Hake adult
Herring
Hake juvenile
Megrim
Anglerfish adult
Endobenthivorous demersal fish
Baleen whales
Whiting
Toothed cetaceans / Seals
Seabirds - Surface feeders
Plaice
Haddock
Anglerfish juvenile
Pelagic sharks
Sole
Cod juvenile
Cod adult
Seabirds - Divers
Sea bass
logQ
Trophic.level
GroupType
Bacteria
Detritus
Finfish
Homeotherm
Invertebrates
Primary producer

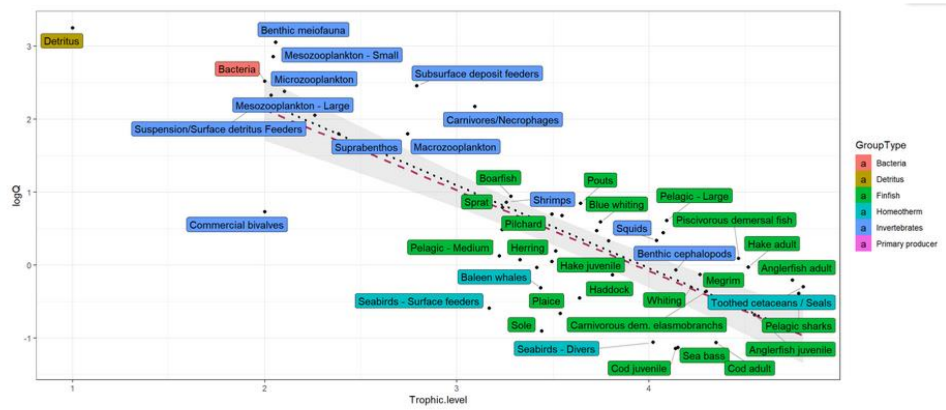
2016


Phytoplankton - Large
Bacteria
Phytoplankton - Small
Microzooplankton
Mesozooplankton - Small
Detritus
Benthic meiofauna
Macrozooplankton
Mesozooplankton - Large
Benthic cephalopods
Commercial bivalves
Suprabenthos
Shrimps
Squids
Suspension/Surface detritus Feeders
Blue whiting
Carnivores/Necrophages
Pouts
Whiting
Cod adult
Anglerfish adult
Discards
Haddock
Plaice
Cod juvenile
Hake adult
Anglerfish juvenile
Sole
Megrim
y = -0.6* x + 2.11
Horse mackerel
Pelagic sharks
Mackerel
Seabirds - Divers
Toothed cetaceans / Seals
Baleen whales
Seabirds - Surface feeders
logPB
Trophic.level
GroupType
Bacteria
Detritus
Finfish
Homeotherm
Invertebrates
Primary producer


Bacteria
Seabirds - Surface feeders
Microzooplankton
Mesozooplankton - Small
Benthic meiofauna
Seabirds - Divers
Mesozooplankton - Large
Commercial bivalves
Macrozooplankton
Shrimps
Benthic cephalopods
Suspension/Surface detritus Feeders
Suprabenthos
Carnivores/Necrophages
Squids
Toothed cetaceans / Seals
Anglerfish juvenile
Subsurface deposit feeders
Sprat
Cod juvenile
Boarfish
Haddock
Anglerfish adult
Pelagic - Large
Plaice
Herring
Sole
Hake adult
Mackerel
Sea bass
Pelagic sharks
y = -0.45* x + 2.44
Horse mackerel
Carnivorous dem. elasmobranchs
logQB
Trophic.level
GroupType
Bacteria
Detritus
Finfish
Homeotherm
Invertebrates
Primary producer


Cod adult
Bacteria
Hake adult
Mesozooplankton - Large
Horse mackerel
Squids
Whiting
Anglerfish adult
Mesozooplankton - Small
Haddock
Macrozooplankton
Herring
Pouts
Benthic cephalopods
Microzooplankton
Boarfish
Blue whiting
Hake juvenile
Benthic meiofauna
Subsurface deposit feeders
Endobenthivorous demersal fish
Commercial bivalves
Suprabenthos
Cod juvenile
Piscivorous demersal fish
Pilchard
Suspension/Surface detritus Feeders
Pelagic - Medium
Megrim
Sea bass
Shrimps
Carnivores/Necrophages
Plaice
Carnivorous dem. elasmobranchs
Sprat
Anglerfish juvenile
Pelagic - Large
Pelagic sharks
Baleen whales
Toothed cetaceans / Seals
Seabirds - Surface feeders
Seabirds - Divers
PQ
Trophic.level
GroupType
Bacteria
Detritus
Finfish
Homeotherm
Invertebrates
Primary producer





Appendix 9. – Selection of fleets

- High discard rate fleets

The selection was based on the new grouping of fleets in the model by Potier et. al, in prep. The corresponding old fleets were then matched.

Data on discards by fleet are taken from the FDI from 2016 to 2020. Fleets with a discard rate for all species combined above the third quantile are selected as high-discard-rate fleets. The same is done for fleets with high discard rates of elasmobranchs in particular, this concerns the groups Pelagic sharks, Benthivorous demersal elasmobranchs, Piscivorous demersal elasmobranchs.

High discard rate fleets all species

ESP DEF OTB
FRA MOL OTB
FRA CRU OTT
UKM MOL DRA
UKM CRU OTB OTT
UKM MOL OTB OTT
IRL CRU tr
IRL DEF GNT
UKM MOL OTB OTT
IRL CRU tr
IRL DEF GNT
IRL DEF tr
OTH DEF TBB
FRA DEF tr

High discard rate fleets elasmobranchs

ESP DEF OTB
FRA MOL OTB
FRA CRU OTT
FRA DEF tr
UKM CRU OTB OTT
UKM MOL OTB OTT
UKM DEF tr
OTH DEF TBB
UKM DEF dorm
UKM SPF GNT
UKM DEF tr

ESP DEF OTB
FRA MOL OTB
FRA CRU OTT
FRA DEF tr
UKM CRU OTB OTT
UKM MOL OTB OTT
UKM DEF tr
OTH DEF TBB
UKM DEF dorm
UKM SPF GNT
UKM DEF tr

- High/low trophic level fleets

Fleets are differentiated according to the average trophic level of their catch. The limit between high and low trophic levels is set at 3.5, the new limit for predators.

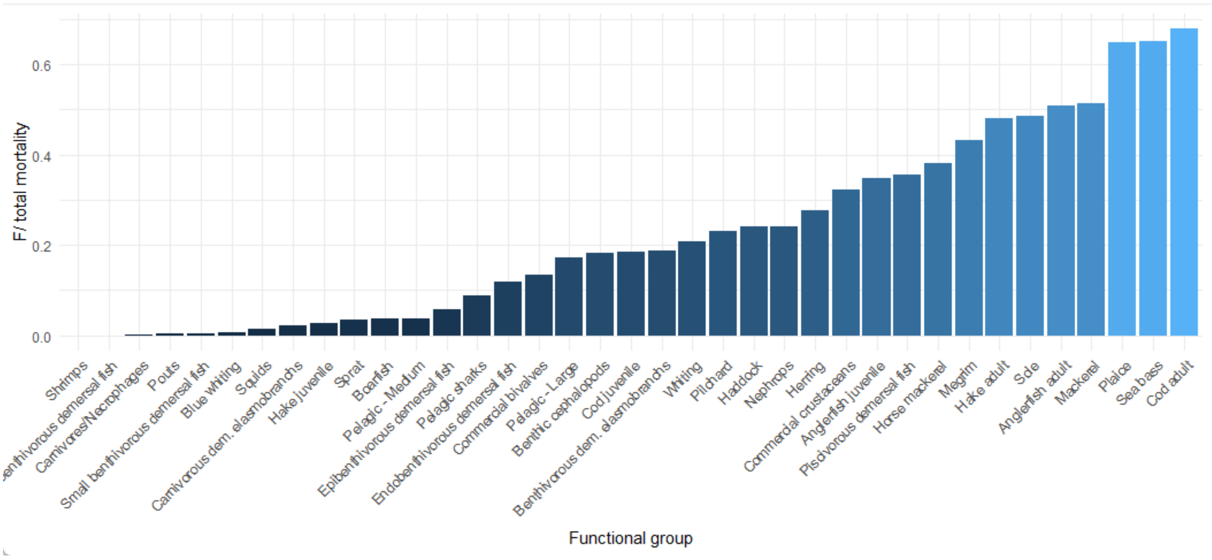
Low TL	High TL
FRA SPF PS	ESP DEF lines
FRA MOL FPO	ESP LPF lines
FRA MOL DRA	ESP DEF OTB
IRL SPF PTR OTM	FRA DEF dorm
IRL MOL DRA	FRA MOL OTB
OTH SPF OTM	FRA SPF OTM
OTH CRU FPO	FRA CRU GNT DRA
UKM SPF PTR OTM	FRA CRU OTT
UKM SPF GNT	FRA LPF PTR
UKM MOL FPO	FRA DEF tr
UKM MOL DRA	IRL DEF GNT
UKM LPF lines	IRL CRU FPO
	IRL CRU tr
	IRL LPF PTR
	IRL DEF tr
	OTH LPF SEN
	OTH DEF TBB
	UKM DEF dorm
	UKM MOL OTB OTT
	UKM CRU FPO
	UKM DEF tr

Appendix 10. – Description of the fleets (Potier, 2021)

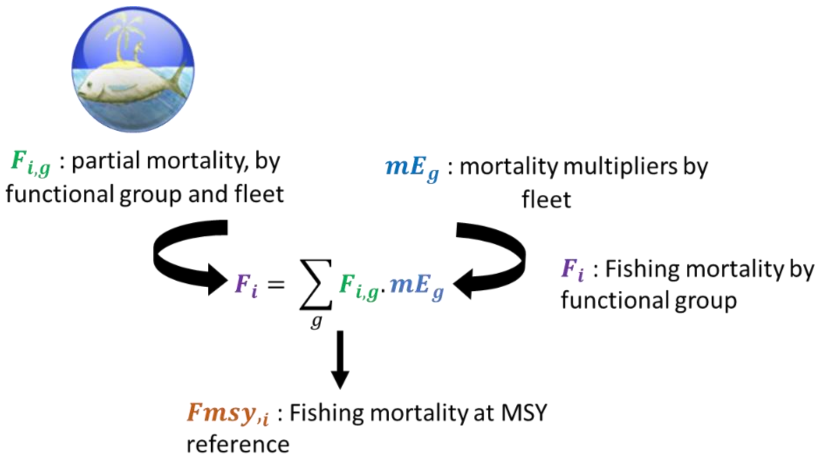
Fleet code	Country	Mainly exploited functional groups	Target species assemblages	Main fishing gears
ESP DEF lines	Spain	Hake	Demersal fish	Lines
FRA DEF dorm	France	Hake, piscivorous demersal fish, seabass, anglerfish, benthivorous demersal fish		Passive fishing gears: lines and nets
IRL DEF GNT	Ireland	Piscivorous demersal fish and hake		Nets
UKM DEF dorm	UK	Piscivorous demersal fish, hake, mackerel		Passive fishing gears: lines, nets
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
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
FRA SPF PS	France	Sardine, herring	Small pelagic fish	Purse seine
UKM SPF GNT	UK	Sardine		Gillnets
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
FRA MOL FPO	France	Necrophagous carnivores	Mollusks	Pots, traps
UKM MOL FPO	UK	Necrophagous carnivores, SSDF*		Pots, traps
FRA MOL DRA	France	Commercial bivalves	Mollusks	Dredges
IRL MOL DRA	Ireland			Dredges
UKM MOL DRA	UK			Dredges
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

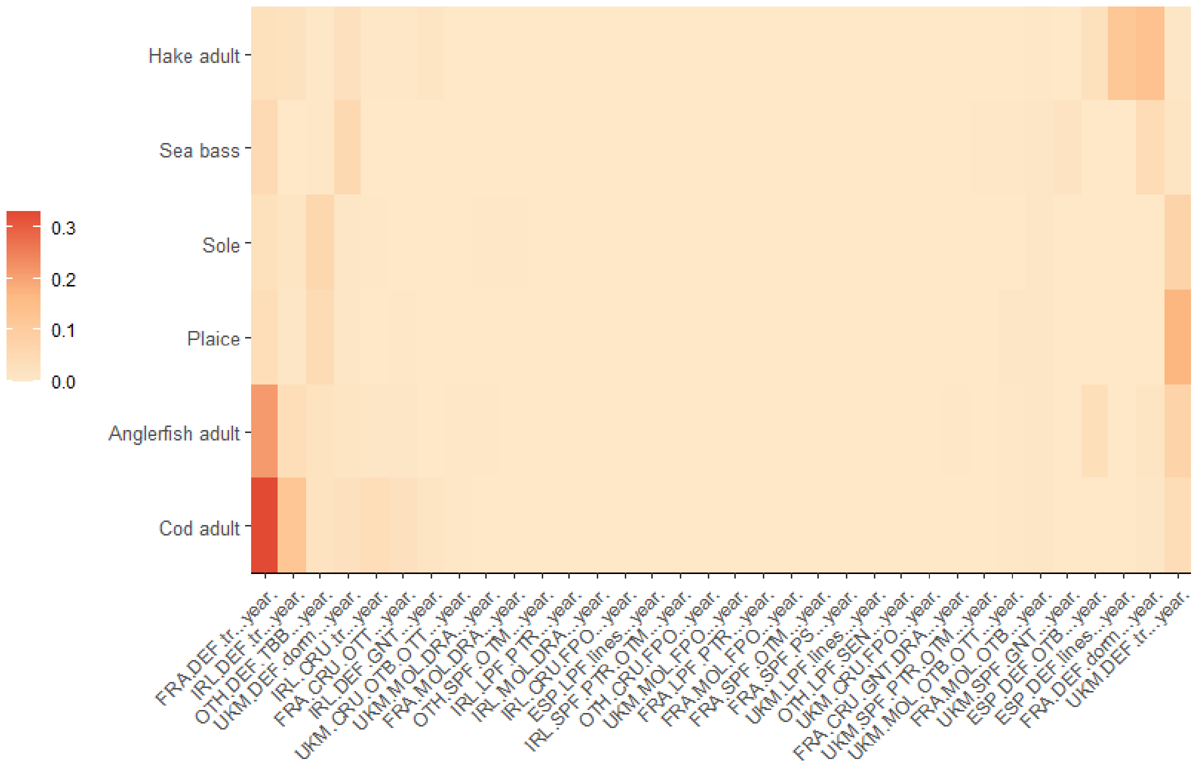
ESP LPF lines	Spain	Large pelagic fish, pelagic sharks	Large pelagic fish	Lines
FRA LPF PTR	France	Large pelagic fish		Pair trawls
IRL LPF PTR	Ireland	Large pelagic fish		Pair trawls
OTH LPF SEN	Others	Large pelagic fish, mackerel, horse mackerel		Seines
UKM LPF lines	UK	Large pelagic fish		Lines
ESP 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

Appendix 11. – Fishing mortality on total mortality for functional groups in the Ecopath 2016 model



Appendix 12. –Bayesian estimation of mF





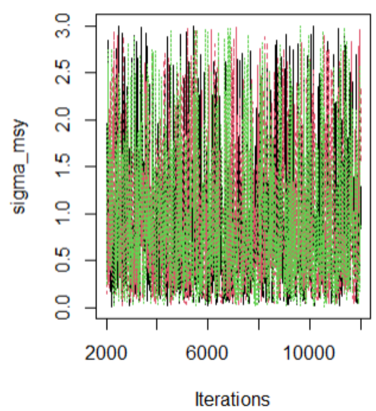
<u>Model:</u>

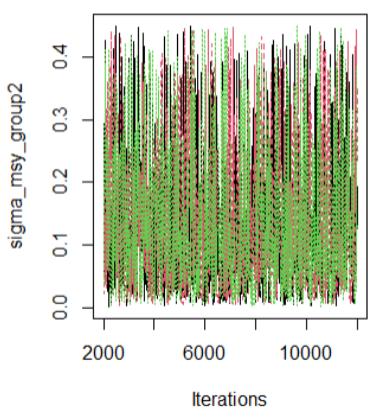
#Parameter / Prior

for (t in 1:(n_fleet)){

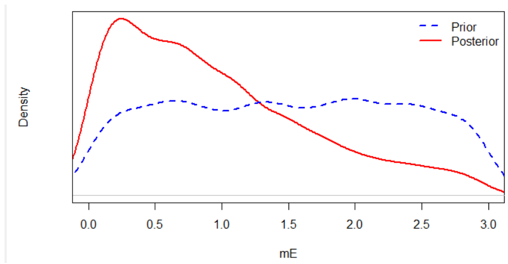
```
  mE[t] ~ dunif(0,4)}
# State Equation
for (i in 1:(n_esp)){
  for (g in 1:(n_fleet)){
    F2[i,g] <- mE[g]*(Fcurrent[i,g])  }}
for (i in 1:(n_esp)){
F[i] <- sum(F2[i,]) }


# Observation equations
sigma_msy ~ dunif(0,3)
tau_msy <- 1/sigma_msy
for (t in esp1){
  Fm[t] <- F[t]
  Fmsy[t] ~ dlnorm(log(Fm[t]), tau_msy)
}
sigma_msy2 <- 0.2*sigma_msy
tau_msy2 <- 1/sigma_msy2
for (t in esp2){
  Fm[t] <- F[t]
  Fmsy[t] ~ dlnorm(log(Fm[t]), tau_msy2)
}
#end
}
```

Results:

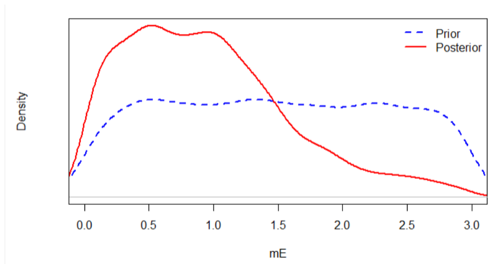




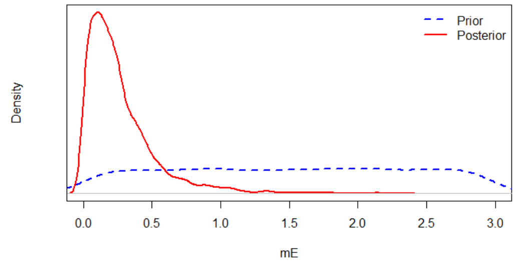
ESP DEF lines



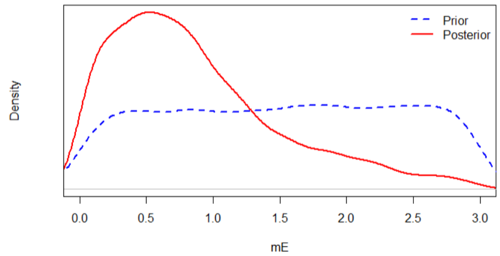
FRA DEF dorm



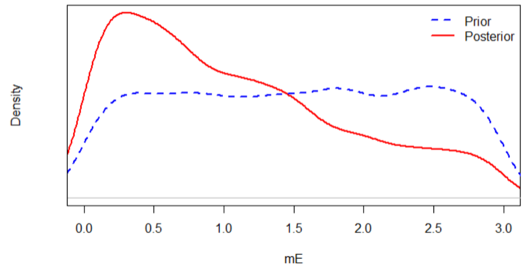
FRA DEF tr



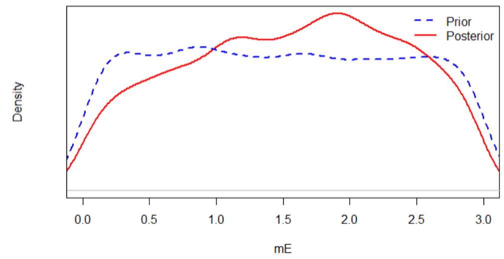
IRL DEF tr



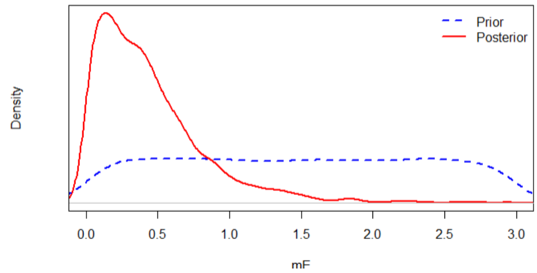
ESP DEF OTB

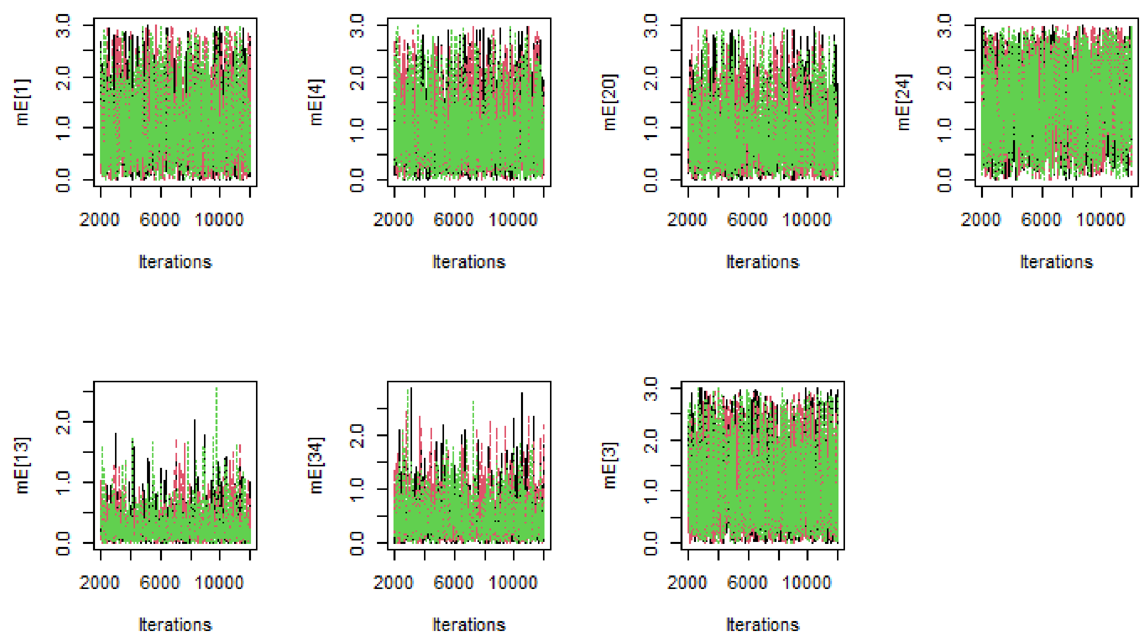


OTH DEF TBB



UKM DEF tr

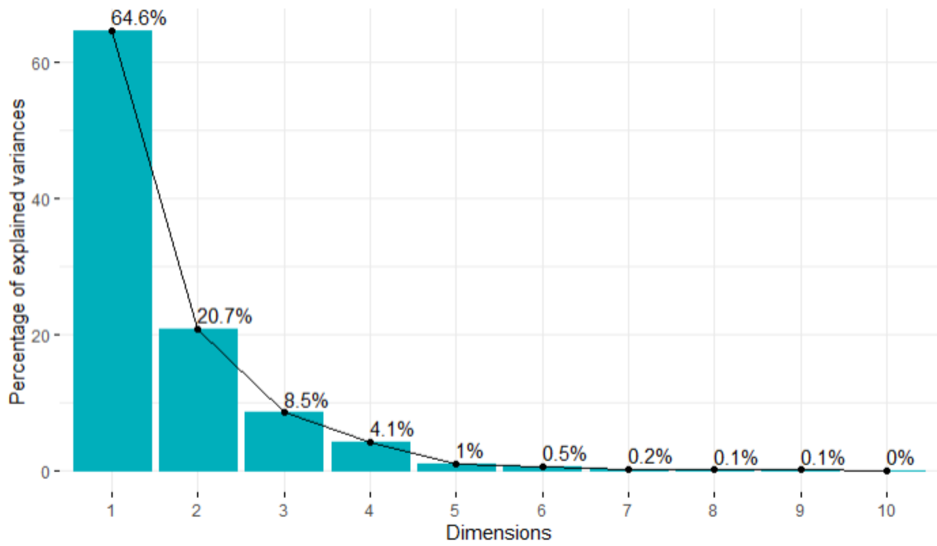


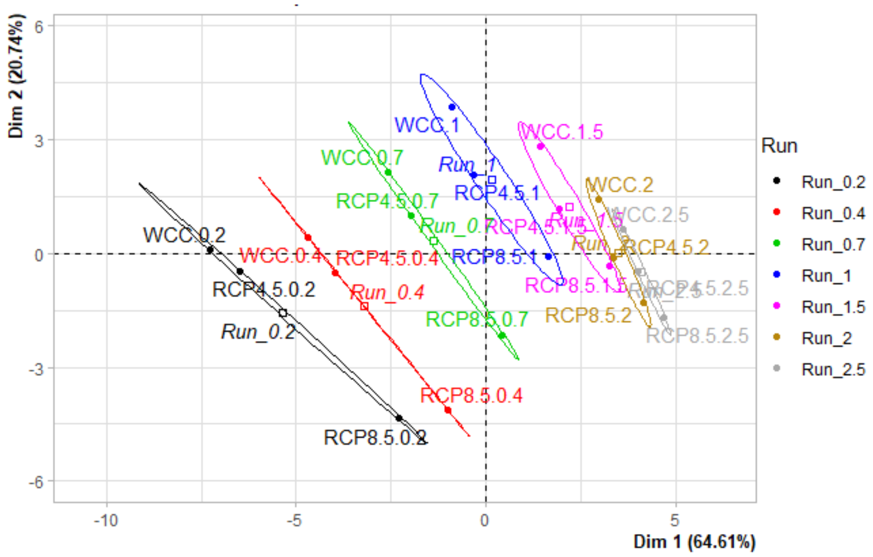


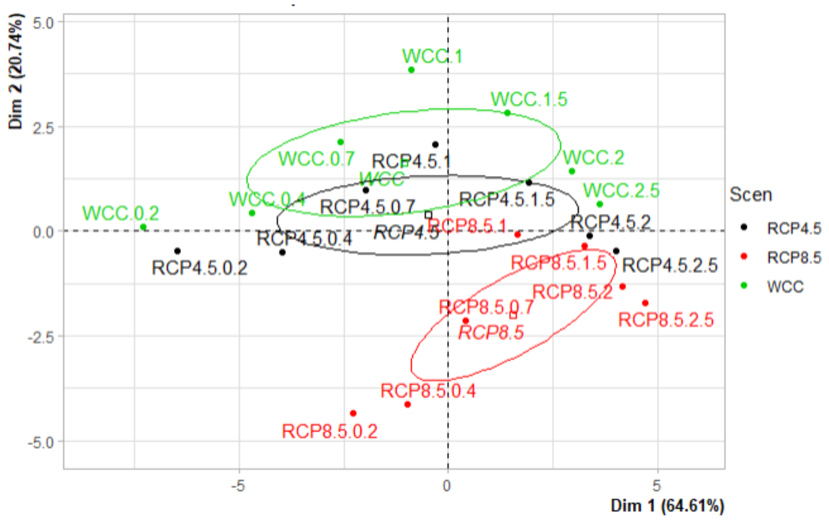
<u>Discussion:</u> The median value of the estimated mF for each fleet was taken. Except for two fleets, the model has difficulty in converging on a precise mF value and the estimated mF range is fairly wide. Nevertheless, based on the data, the model is still able to detach itself from the a priori uninformative distribution.

Appendix 13. – ACPs results

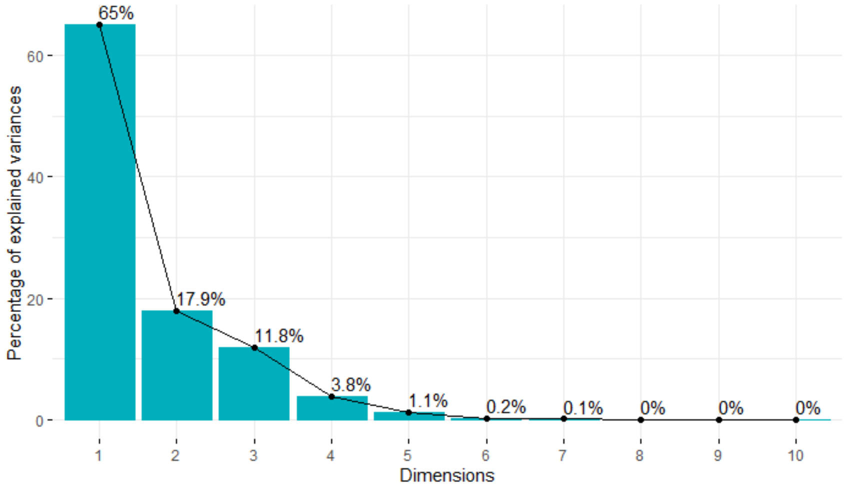
Biomass indicators:

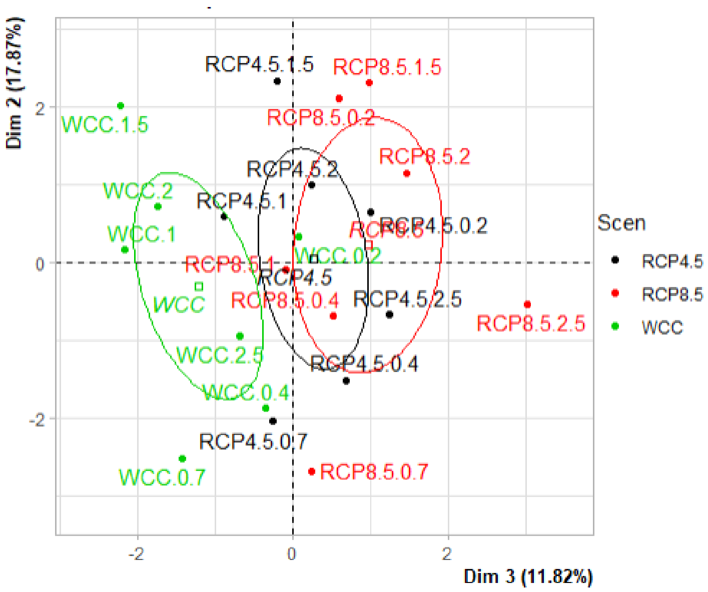


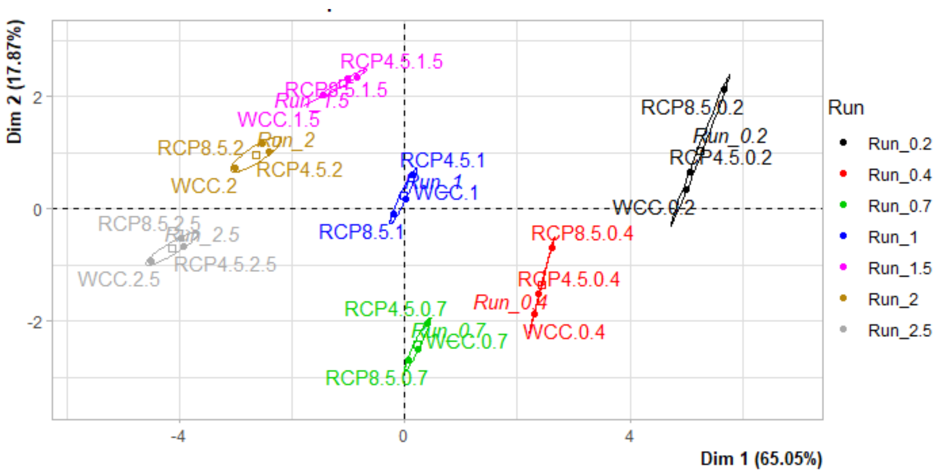




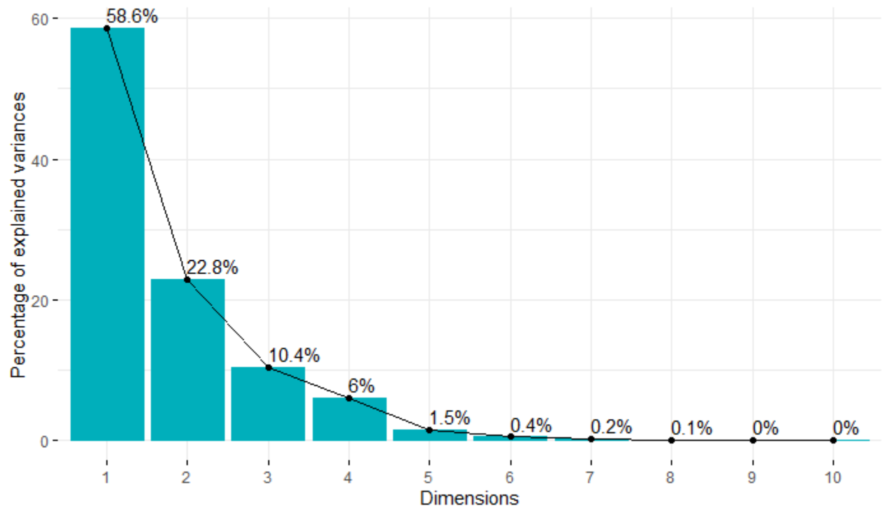
Trophic indicators:

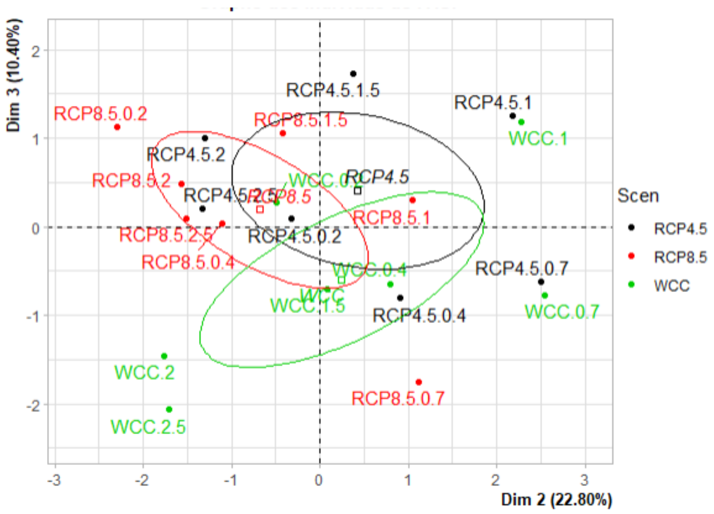


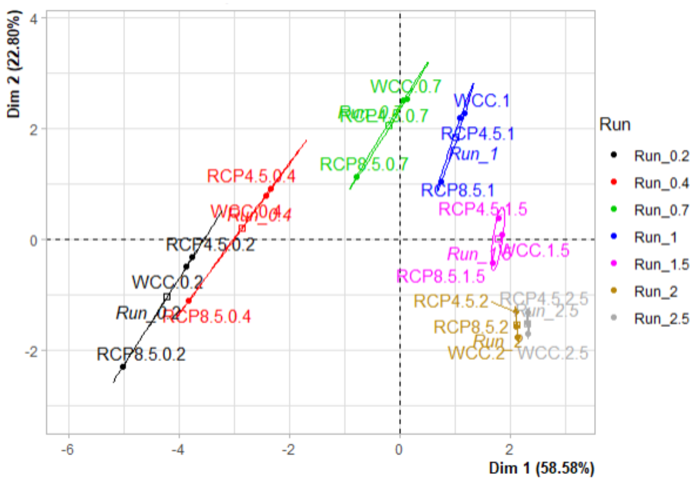




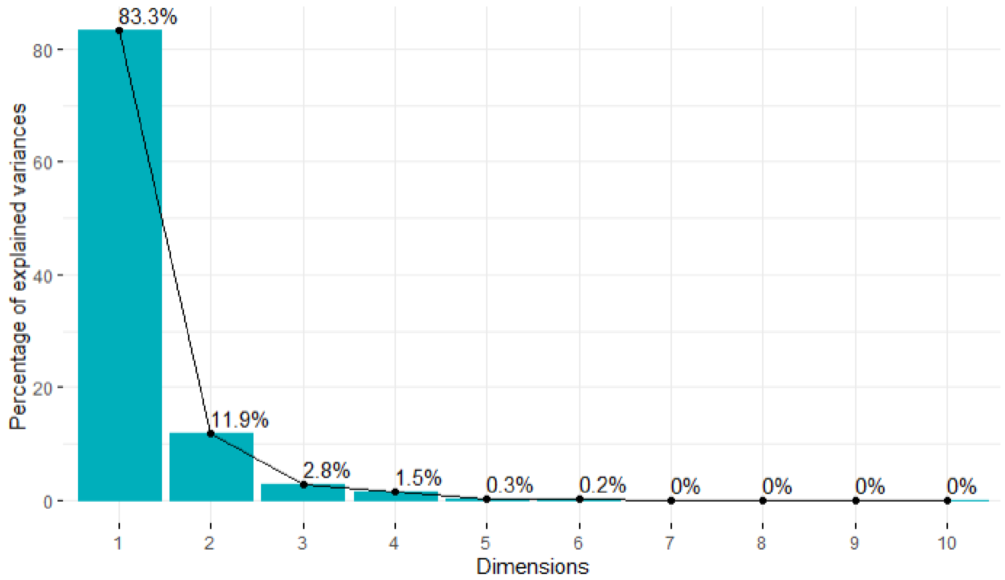
Community structure indicator:

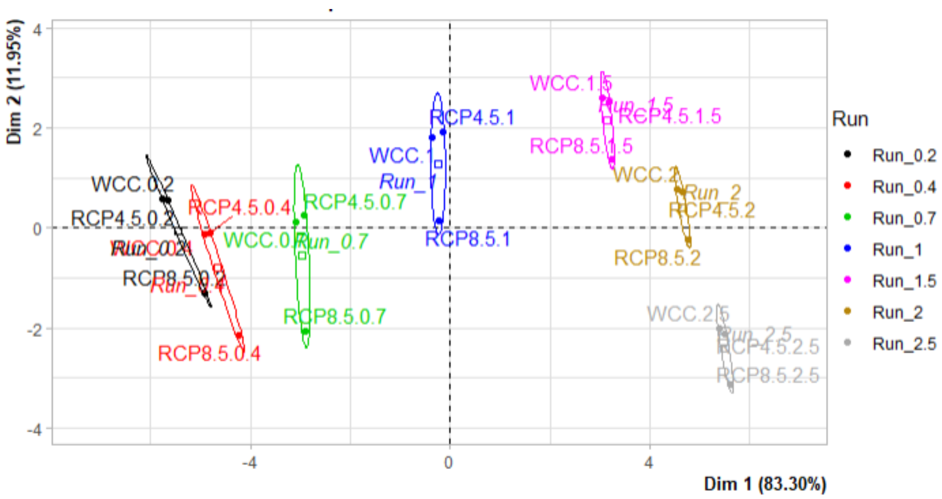


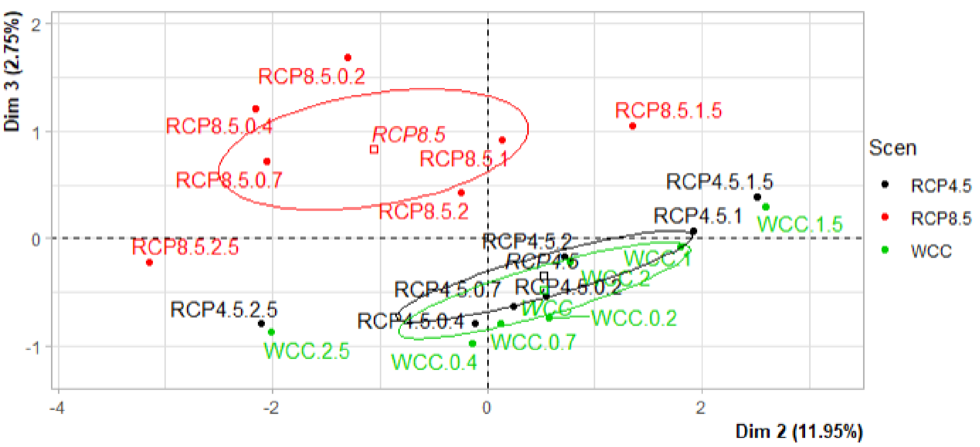




Trait-based indicators:

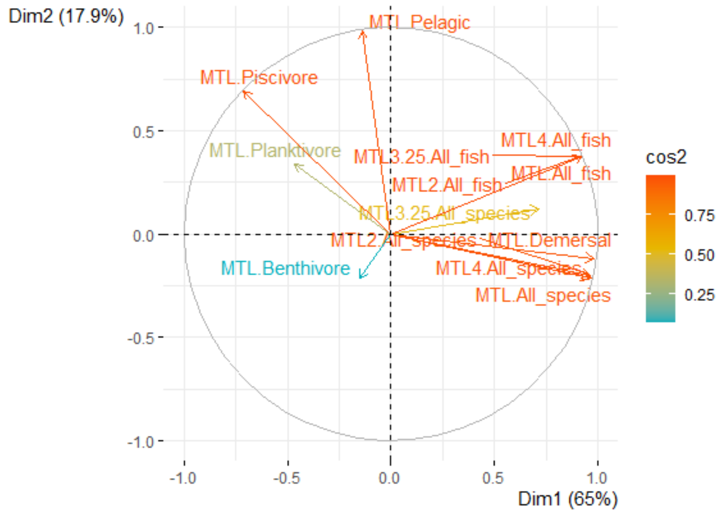


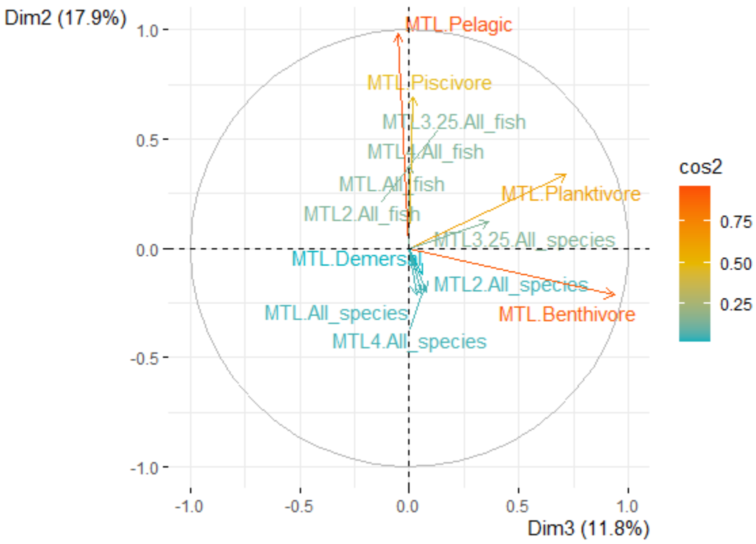




Appendix 14. - Description of the PCAs

- Trophic indicators





The first two dimensions of analysis explain 83 **%** of the total dataset inertia. It can be worth to look at the third dimension too, as it explains more than 10% of the total variance (12%). The illustrative variable mF explains significantly 99 % of the variability on the first dimension. The individuals corresponding to a fishing multiplier of 0.2 have higher coordinates on the dimension on average and those with the multiplier of 2.5 lower. MTL_demersal, MTL_all_species with a cut-off of 2 and 4, and MTL_all fish with a cut-off of 2,3.25,4 are positively correlated variables. The MTL of piscivores is highly negatively correlated. Fishing intensity scenarios explain 93% of the variability on the second dimension. This dimension separates individuals with medium fishing multipliers. Those with fishing multipliers of 1.5 have higher coordinates on average and those of 0.7 have lower. MTL of pelagics and MTL of piscivores are the two variables highly positively correlated. To investigate sensitivity to fishing intensity, the first dimension is more interested. MTL of planktivores and benthivores are not well projected in the first plan.

Climate change scenarios explain 54% of the variability on the third dimension, i.e 6.3% on the total dataset. Individuals corresponding to RCP 8.5 scenario have higher coordinates on the third axis and those corresponding to constant climatic conditions have lower. Two variables are positively significantly correlated, MTL_benthivore and MTL_planktivore have a better quality of projection on the plan corresponding to dimension 2 and 3 (and even 1 and 3).

- **Community structure indicators**

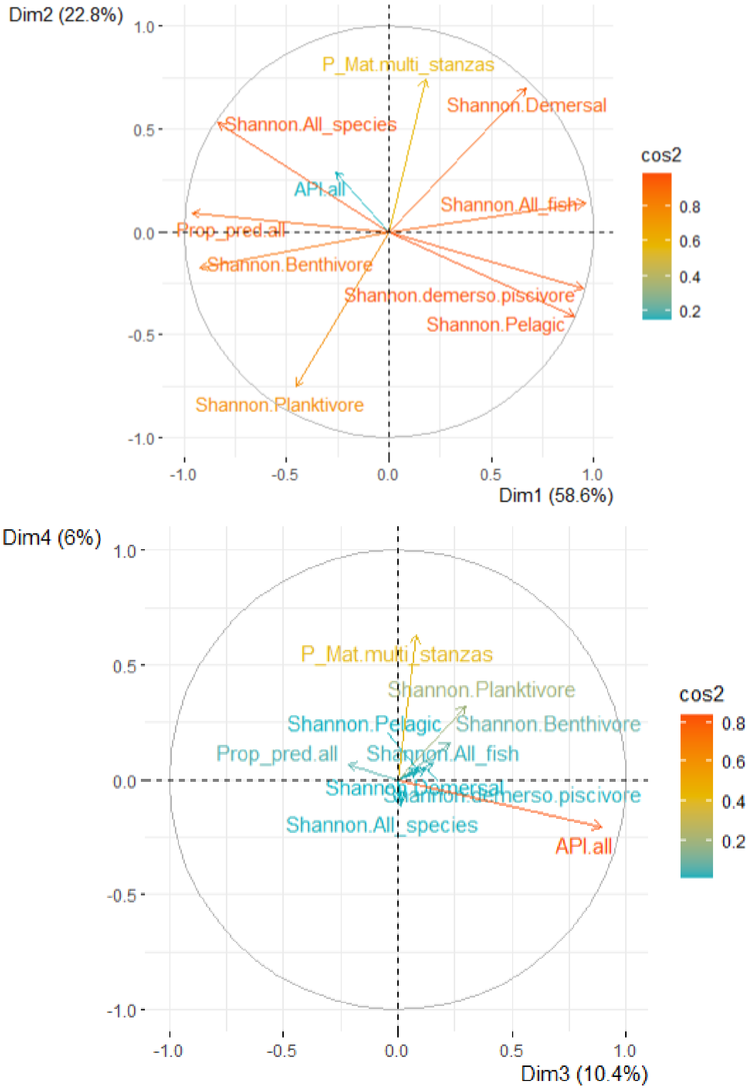
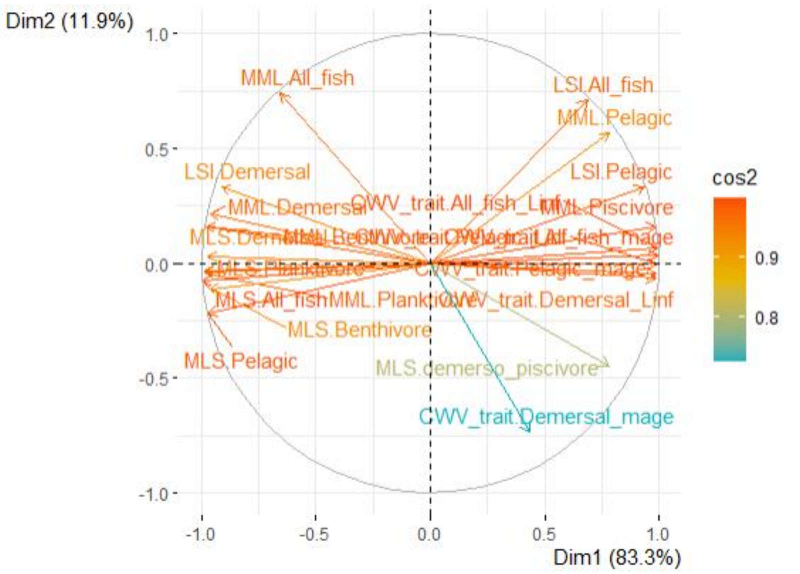


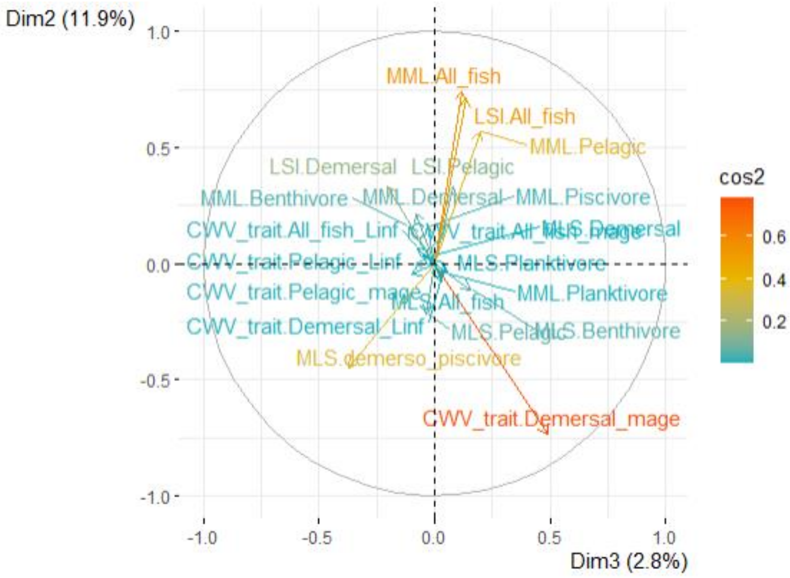
Figure 5. – Variable correlation diagram, PCA analysis with community structure indicators

The first plan explained 81% of the total dataset inertia. The third dimension is just above 10%. The illustrative variable mF explains significantly 97 % of the variability on the first dimension and 84% on the second. The first dimension is linked to individuals with low fishing multipliers, those having 0.2 and 0.4 fishing multipliers have lower coordinates. Shannon indice of all fish, piscivores, pelagics, demersals are highly positively correlated (from 0.96 to 0.66). The proportion of predators, Shannon of benthivores, of all species are highly negatively correlated (from -0.96 to -0.83) and Shannon_planktivore is also negatively correlated (-0.45). The second dimension is linked to medium fishing multipliers, individuals with fishing multipliers of 0.7 and 1 have on average positive coordinates on this axis. The third dimension is only positively correlated to API.
Climate change scenarios are linked to the fourth dimension, they represent only 3.3% on the total variability of the dataset and separate RCP 8.5 with negative coordinates and constant climatic condition with positive ones The proportion of immature fish is positively correlated with the dimension so negatively correlated with climate change scenario. The worst climatic scenario is, the

less immatures fish there are in the three multi-stanzas group. The community structure indicators are correlated to fishing, but not notably to climate change, with the exception of the proportion of immature fish.

- **Trait-based indicators**



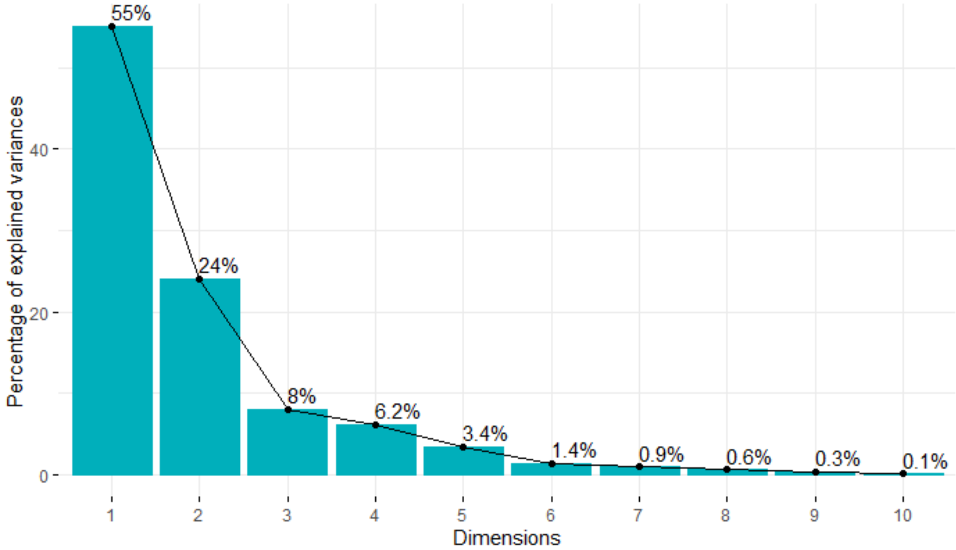


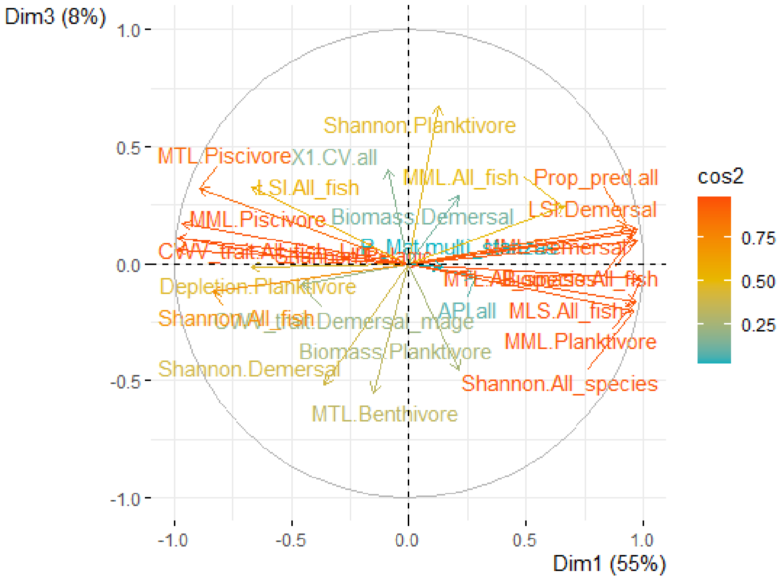
The first dimension explains 83,3% of the total dataset inertia by its own. The second dimension explains 11,9% and the third 2.8%. The illustrative variable mF explains significantly 99,8 % of the variability on the first dimension. Individuals with high fishing mortality multipliers (2.5 and 2) have positive coordinates on average and those with 0.2 and 0.4 mF fishing multipliers have negative ones. All the CWV, community weighted variance (Linf and age max) are highly positively correlated with the first axis (0.997 to 0.98), like MML of pelagics and piscivores, the MLS of piscivores and the LSI all fish (0.98 to 0.69). All the others MML and MLS are negatively correlated, with LSI_demersal too (from -0.995 to -0.65).

The second dimension separates individuals with fishing multipliers of 1.5 with positive coordinates on average and fishing multipliers of 2.5 and RCP 8.5 with negative ones. MML all fish, LSI all fish and MML_pelagic are positively correlated (from 0.74 to 0.57) and the CWV_age_max for demersals and

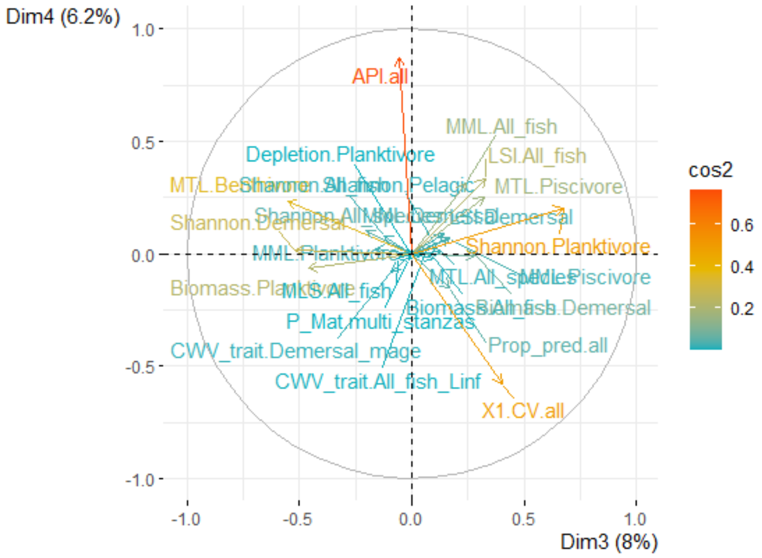
MLS_piscivore are negatively correlated (-0.74 and -0.45). The third dimension is only linked to climate change scenario (60%) and only significantly correlated with CWV_age_max_demersal.

Appendix 15. – ACP results for all pre-selected indicators

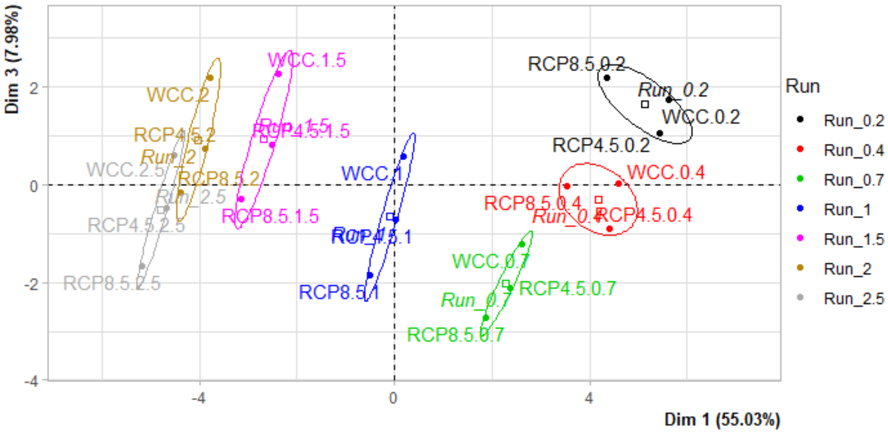


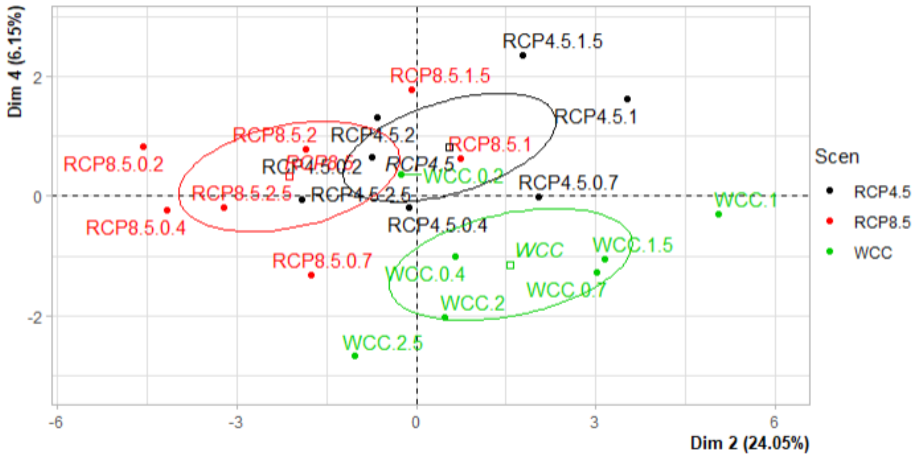


Dim3 (8%)
Shannon.Planktivore
MTL.Piscivore
X1.CV.all
MML.All_fish
Prop_pred.all
LSI.All_fish
MML.Piscivore
Biomass.Demersal
LSI.Demersal
Depletion.Planktivore
Shannon.All_fish
CWV_trait.Demersal_mage
API.all
MLS.All_fish
Biomass.Planktivore
MML.Planktivore
Shannon.Demersal
Shannon.All_species
MTL.Benthivore
Dim1 (55%)
cos2
0.75
0.50
0.25



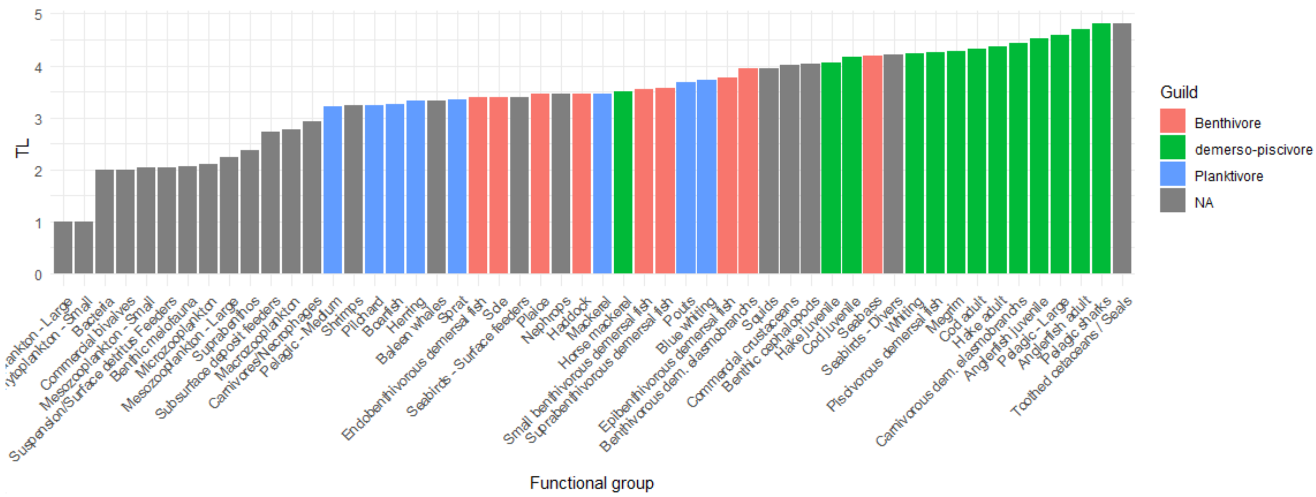
Dim4 (6.2%)
API.all
MML.All_fish
Depletion.Planktivore
LSI.All_fish
MTL.Piscivore
Shannon.Demersal
Shannon.Planktivore
MTL.All_species
Biomass.Planktivore
MLS.All_fish
P_Mat.multi_stanzas
Biomass.Demersal
CWV_trait.Demersal_mage
Prop_pred.all
CWV_trait.All_fish_Linf
X1.CV.all
Dim3 (8%)
cos2
0.6
0.4
0.2

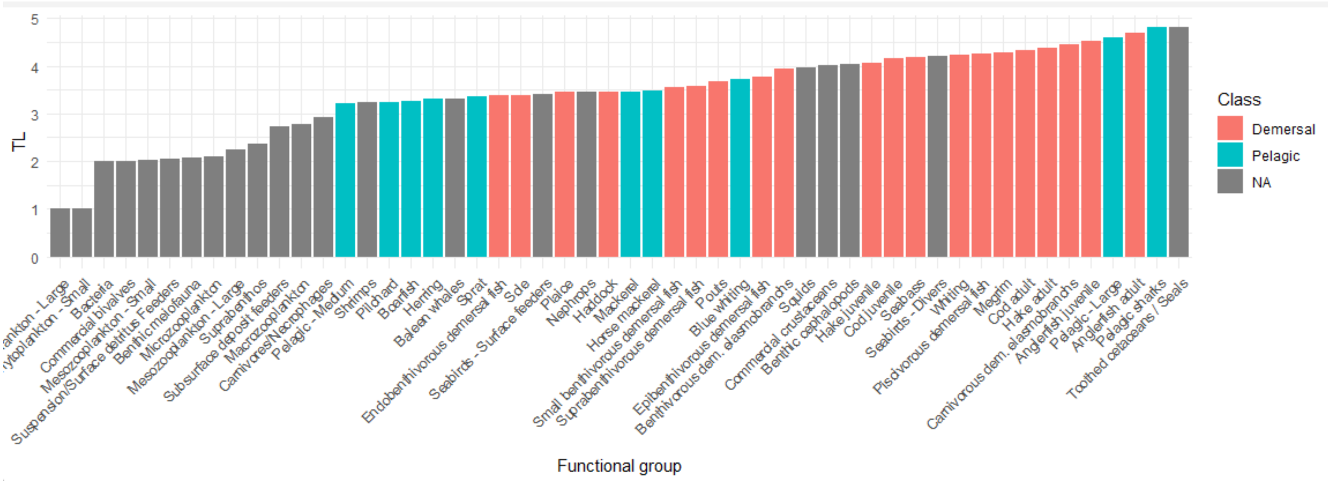




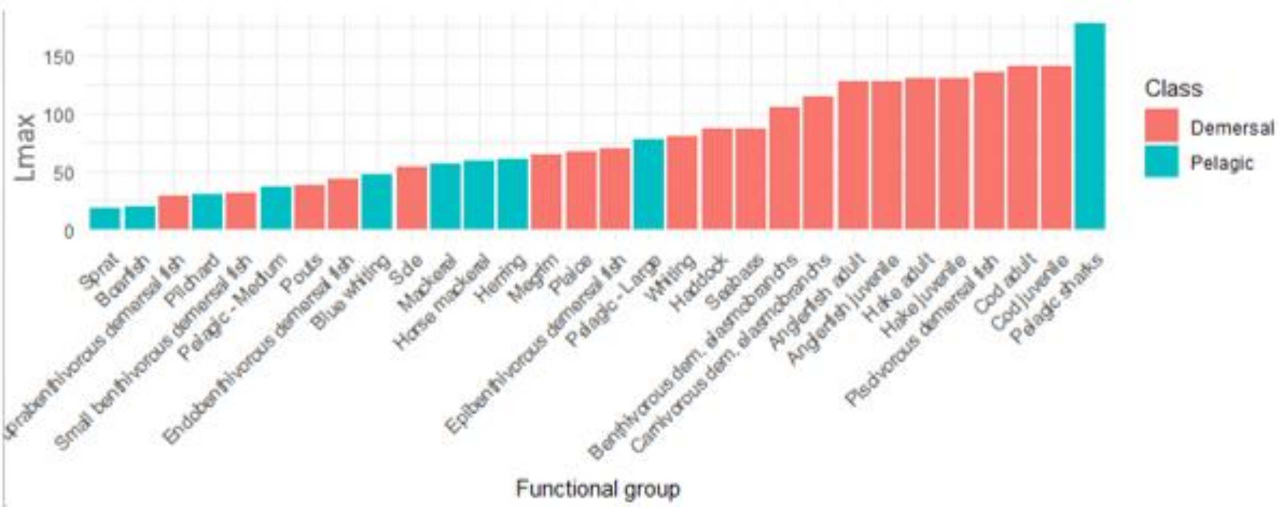
Appendix 16. – Composition in size, trophic level and age maximum of the functional groups

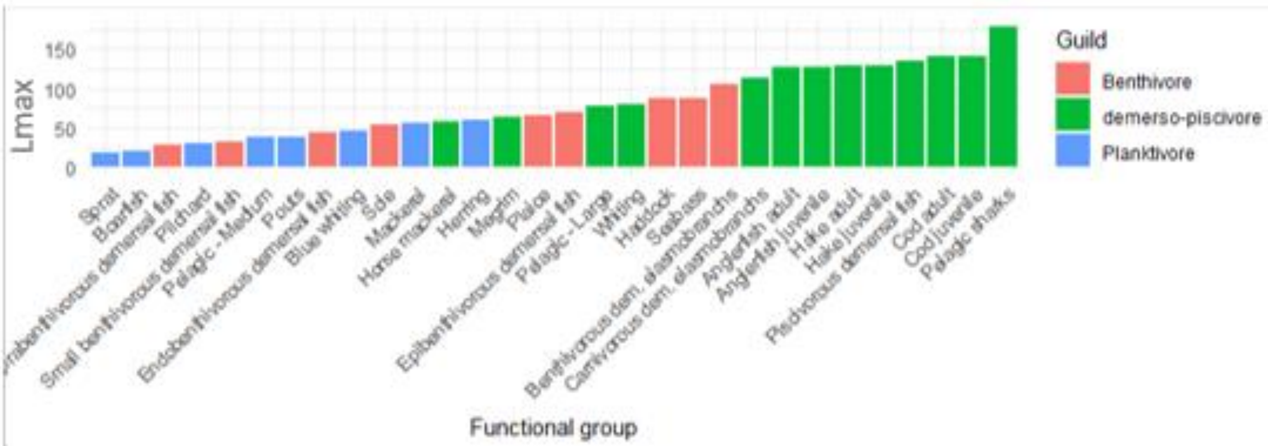
Trophic level



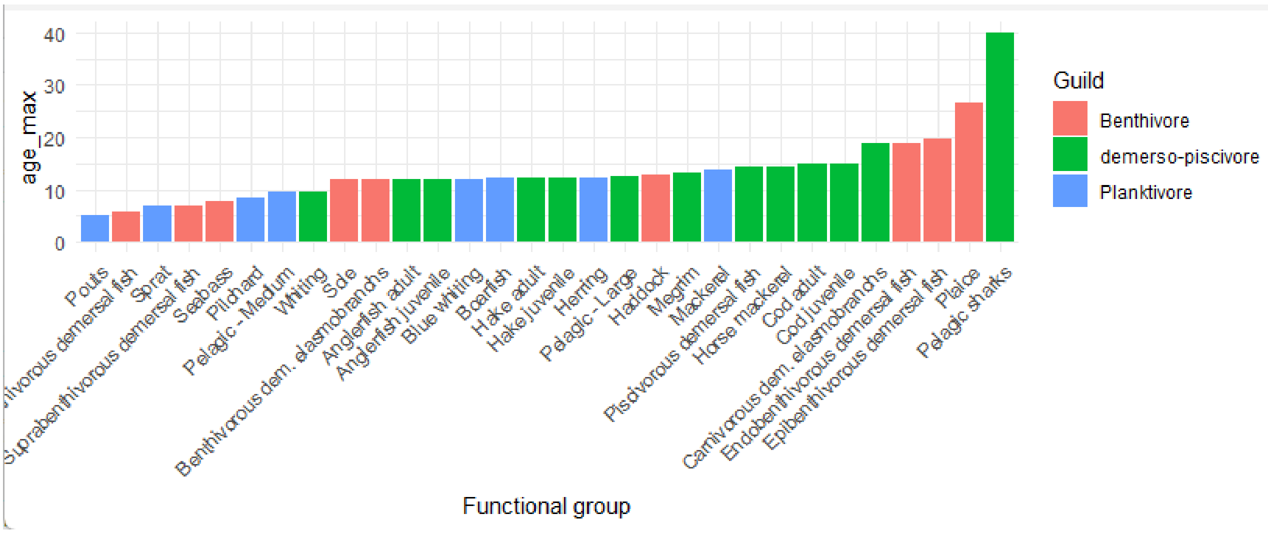


Lmax



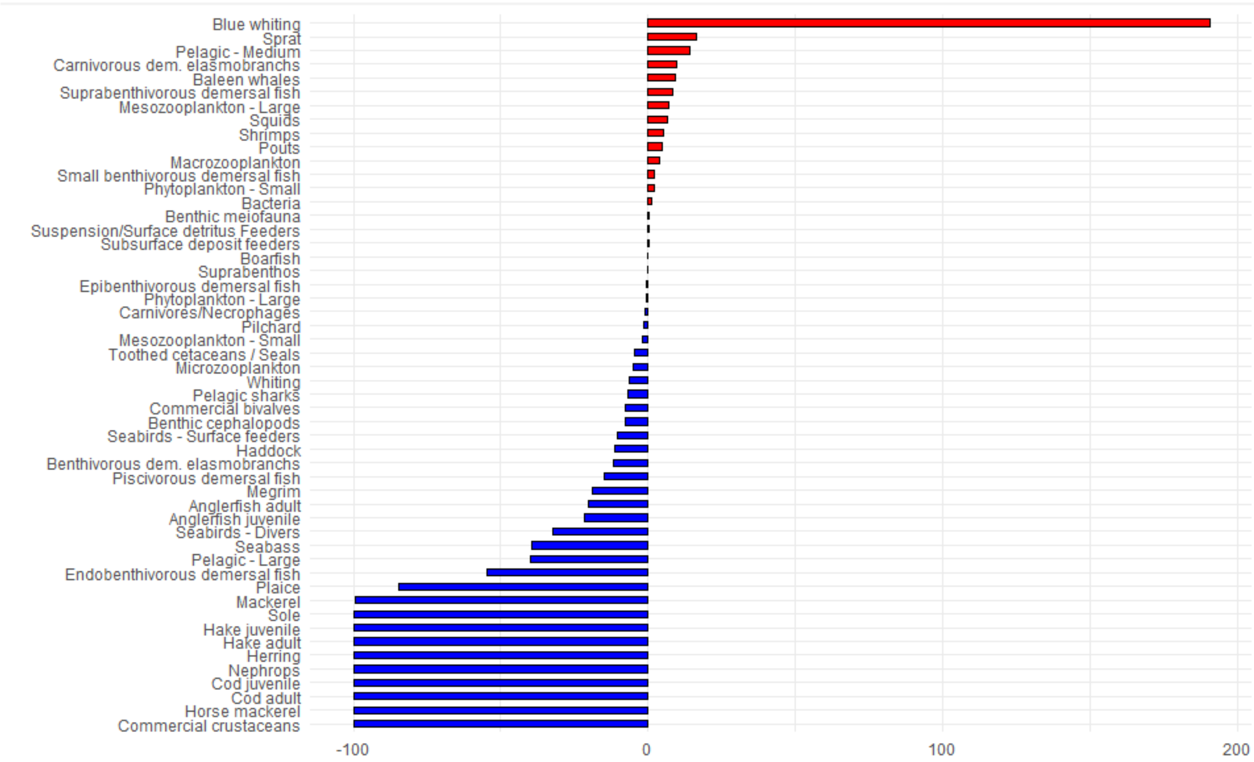


Age maximum :



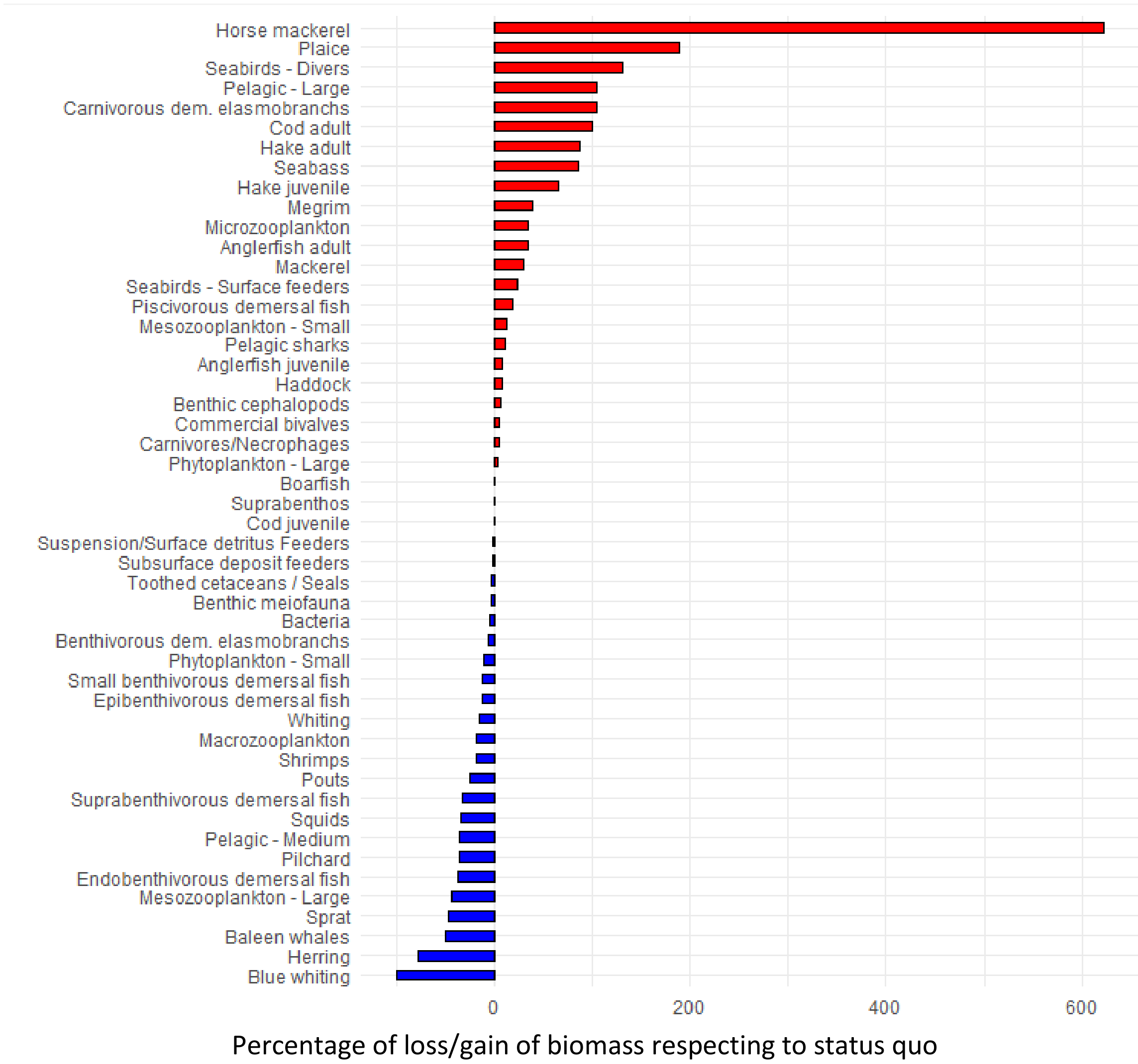
Appendix 17. – Sensibility of the functional groups to fishing

2100 after a fishing mortality multiplier of 2



Percentage of loss/gain of biomass respecting to status quo

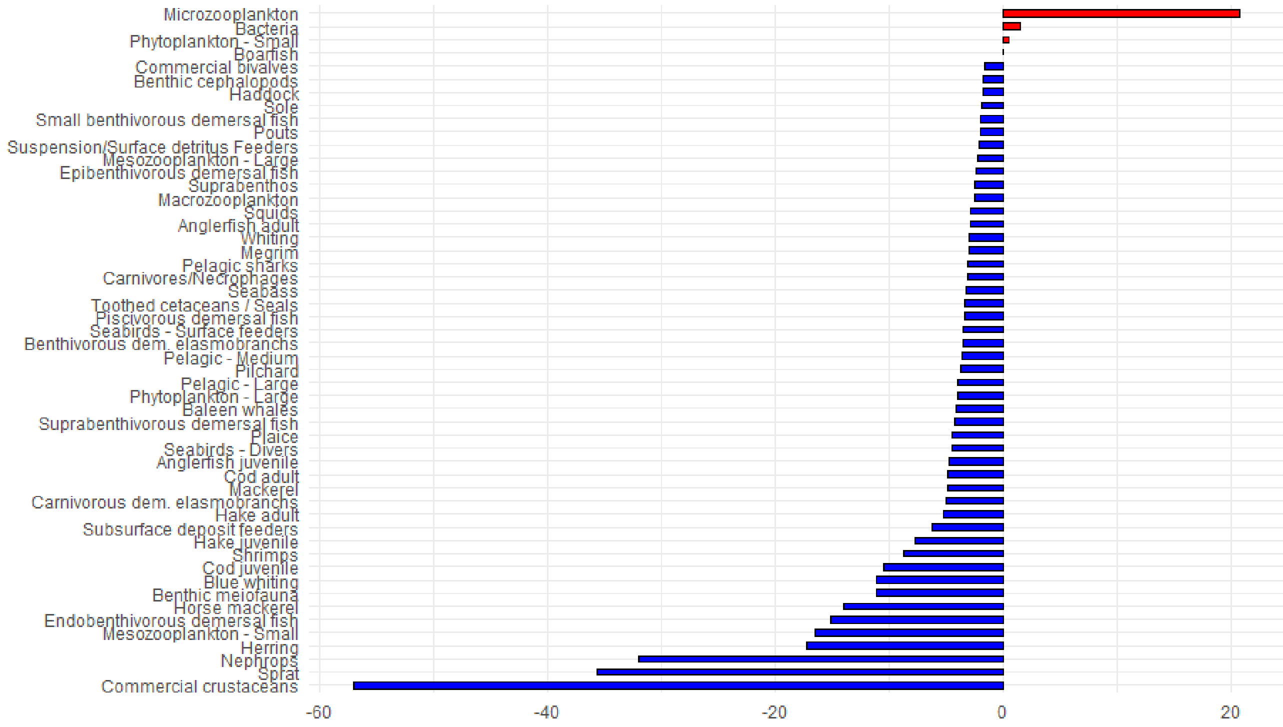
2100 after a fishing multiplier of 0.2



Sole, commercial crustaceans and nephrops have very high values

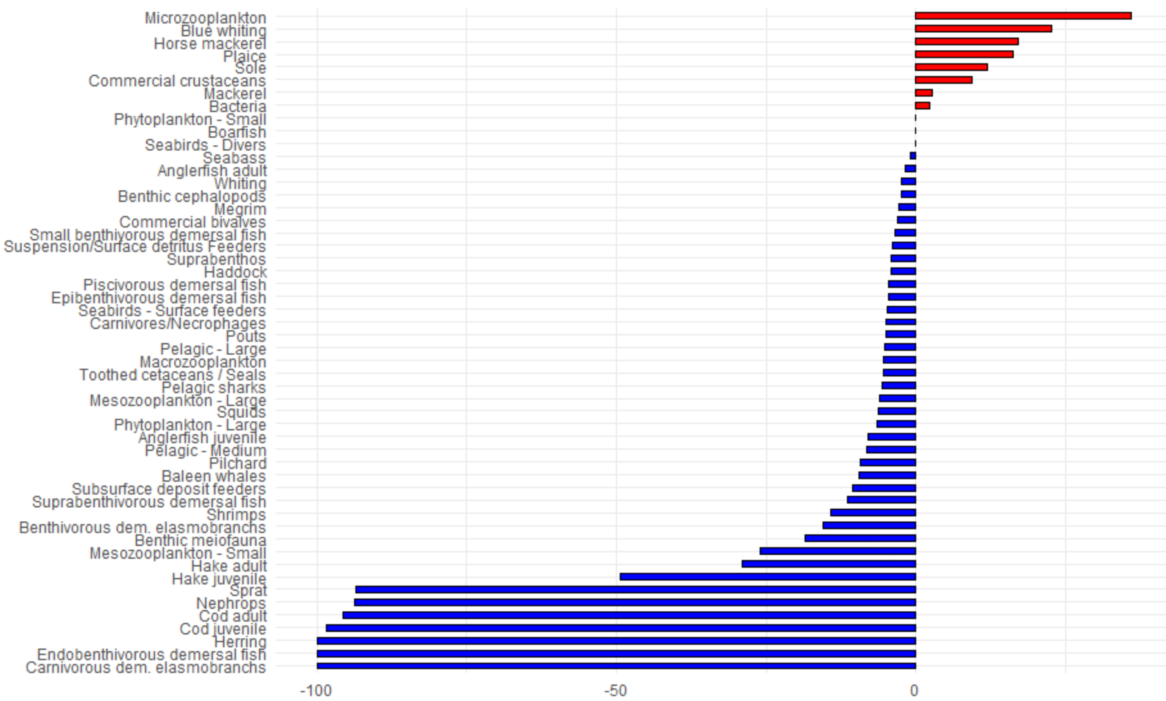
Appendix 18. – Sensibility of the functional groups to climate change

2100 in RCP 4.5



Percentage of loss/gain of biomass respecting to constant conditions

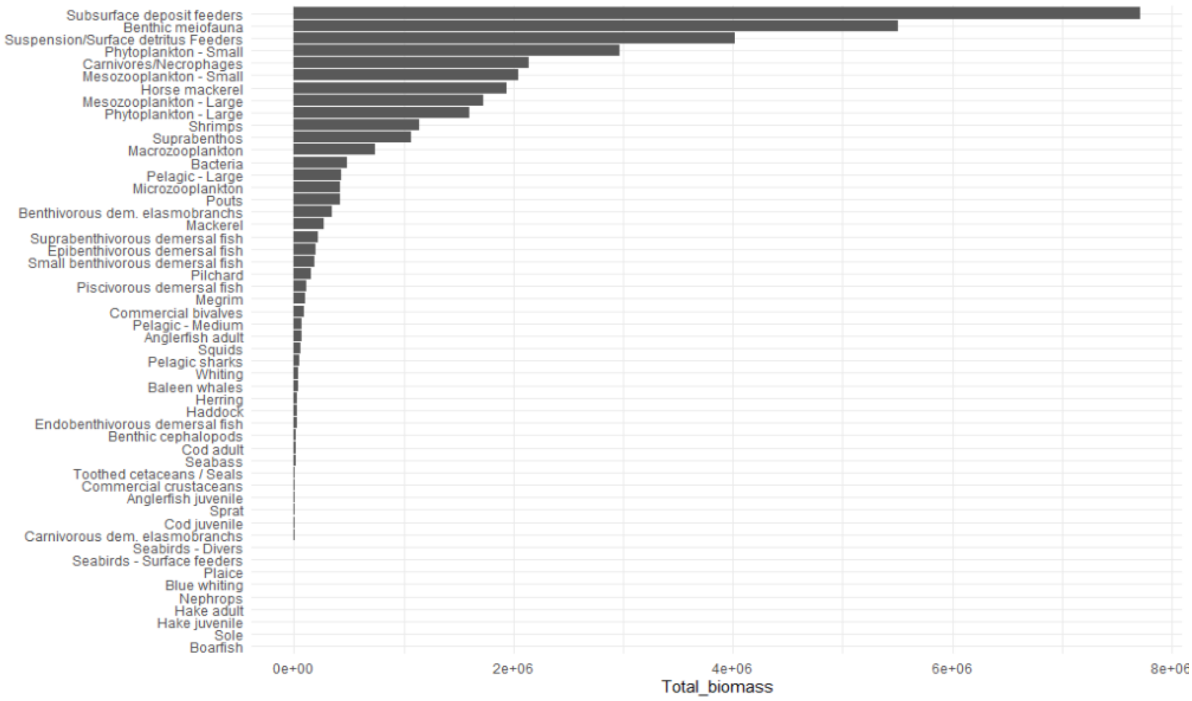
2100 in RCP8.5



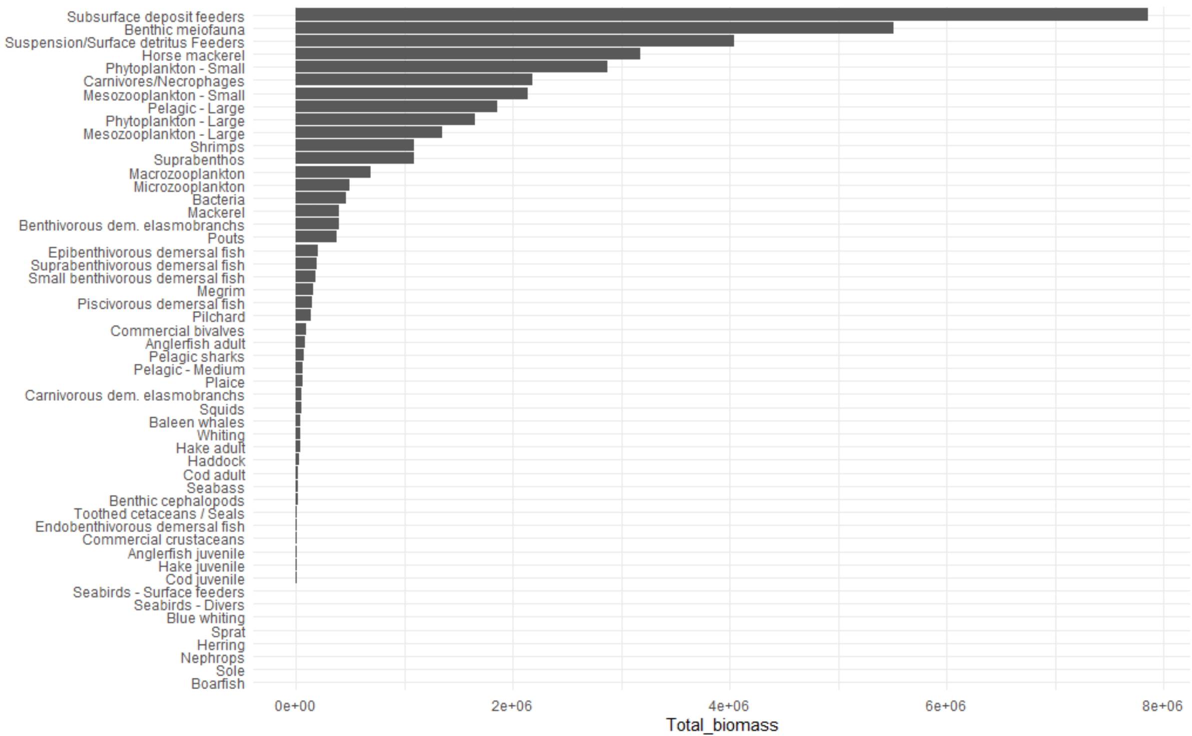
Percentage of loss/gain of biomass respecting to constant conditions

Appendix 19. – Biomass repartition

Biomass repartition in 2016



Biomass repartition in 2100 with RCP4.5 and F=0.4



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Spécialité : Sciences Halieutiques et Aquacoles
Spécialisation / option : REA
Enseignant référent : Olivier Le Pape</td></tr>
<tr><td colspan="3">Auteur(s) : Patricia BELLOEIL

Date de naissance* : 17/03/2000</td><td rowspan="3">Organisme d'accueil : Institut Agro
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<tr><td>Nb pages : 40</td><td colspan="2">Annexe(s) : 41</td></tr>
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<tr><td colspan="4">Titre français : Analyser les effets conjoints du changement climatique et de la pêche en mer Celtique : vers la sélection d’indicateurs d’impact sur le fonctionnement et la productivité des écosystèmes

Titre anglais : Analysing the joint effects of climate change and fishing in the Celtic Sea: towards the selection of impact indicators on ecosystem functioning and productivity</td></tr>
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Résumé (1600 caractères maximum) :

L'approche écosystémique des pêches est essentielle en mer Celtique pour préserver un écosystème productif face au changement climatique. Cette étude vise à identifier des indicateurs pertinents pour évaluer les impacts de la pression de pêche et du changement climatique. La pression de pêche inclut l'intensité, la sélectivité et un RMD optimisé. Les indicateurs, analysés à diverses échelles, sont calculés via des simulations Ecosim pour divers scénarios. L'état et la dynamique (via la recovery) de l’écosystème sont étudiés. Des Analyses en Composantes Principales permettent d’explorer les corrélations et redondances d'indicateurs entre pêche et climat. La biomasse de poissons, l’indice de Shannon des pélagiques et la Community Weigthed Variance sur Linf se démarquent comme indicateurs sensibles à la pêche. La proportion d'immatures, l’indice de deplétion des planktivores et la Community Weigthed Variance sur l'âge maximum des demersaux réagissent le plus aux scénarios climatiques. La biomasse d'espèces, l’indice de Shannon des planctivores et demersaux, le Large Species Index des démersaux et la proportion de prédateurs sont sensibles aux effets cumulés de climat et pêche. Les indicateurs de biomasse et d’evenness varient avec la gestion des pêches. L'intensité de pêche impacte significativement la recovery face au climat. Les indicateurs dépendent du modèle, cette étude révèle des ajustements nécessaires pour certains groupes. Éliminer les groupes problématiques change les sensibilités, notamment pour l'Apex Predator Index et la proportion de prédateurs.

Abstract (1600 caractères maximum) :

Ecosystem-Based Fishery Management is necessary in the Celtic Sea to keep healthy and productive ecosystem in a climate change context. This study aims to identify relevant indicators to assess the impacts of fishing pressure and climate change. Fishing pressure encompasses intensity and selectivity, optimized msy scenarios. Indicators can be analysed at different scales (trophic guilds). Ecosim (EwE) simulations were used to calculate indicators under various fishing and climate scenarios. Both ecosystem state and dynamics are investigated, including recovery. Principal Component Analyses were employed to explore indicator correlations with fishing and climate change, as well as redundancy among indicators. Biomass of all fish, shannon indice of pelagics and Community Weighted Variance in Linf for all fish emerge as sensitive fishing indicators. The proportion of immatures, Community Weighted Variance in maximum age of demersals and depletion of planktivores are most sensitive to climate change. Biomass of all species, shannon indice of planktivores and demersals, predator proportion and Large Species Index of demersals are sensitive to combined climate change and fishing effects. Biomass and evenness indicators react differently to fishing management scenarios. Fishing intensity significantly impacts recovery compared to climate change. Indicators are model-dependent, this study highlights necessary parameter adjustments for certain groups. Eliminating problematic groups changes sensitivities, particularly for Apex Predator Index and predator proportion.

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

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