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Update of the Flemish Cap multispecies model GadCap as part of the EU SC05 project: "Multispecies Fisheries Assessment for NAFO"

by

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ABSTRACT

Multispecies modelling is an essential part of the NAFO roadmap for an Ecosystem Approach to Fisheries management, connecting the "Ecosystem" tier with the "Single species" tier. Aware of the importance of continue moving forward in this direction, the EU DG-MARE launched in 2017 the project SC05 "Multispecies Fisheries Assessment for NAFO" with the intention of identifying the potential alternatives to implement an multispecies approach in NAFO, with the Flemish Cap as a case study. As part of this project the multispecies model GadCap, considering the Flemish Cap cod, redfish and shrimp interdependent dynamics over the period 1988-2012, has been improved and extended until 2016. This working document describes the improvements in relation to the version delivered in 2016, and present diagnostic figures to assess the fit of the model to the different databases. Finally, model estimates of population abundance, biomass as well as the predation and fishing mortality are presented.

INTRODUCTION

It is a common practice in the single species approach that natural mortality is assumed equal for all ages and constant over time. Under this assumption reference points and Harvest Control Rules HCRs are set and evaluated performing long term simulations within a Management Strategy Evaluation framework with a single species operating model. These HCR are guidelines which, in conjunction with the output of short term projections of population dynamic, allow the provision of scientific advice and facilitate agreements in the decision-making process. However, it has been widely demonstrated that natural mortality varies with age within a cohort and over time between cohorts as a result of different environmental pressures, very importantly species interactions like predation or competition.

Since natural mortality is one of the main elements determining productivity and hence the surplus production available for human exploitation, underestimates of natural mortality and especially its variability over time may lead to overestimation of productivity and overfishing. Due to the interdependent dynamic and productivity of interacting commercial stocks, a regime shift in the productivity of one stock induced by human or natural factors will affect the dynamic of the other stocks, but also the reference points that define their HCRs. All these issues cannot be assessed with a single species framework. A multispecies assessment approach considering exploited species as part of a complex system of interacting species would contribute to solve this problem by estimating predation mortality that can be used in the stock assessment, but also in short term single species models to provide catch advice, but also estimating multispecies based reference points and HCRs evaluated in MSE frameworks with a multispecies operating model.

The multispecies assessment and advice approach is implicit in the recently approved new NAFO convention as the "commitment to apply an ecosystem approach to fisheries management" and it is already addressed as part of the discussion on the Precautionary Approach Framework (PAF) and the development of the Ecosystem Approach roadmap. As part of this roadmap, NAFO is developing a 3-tiered hierarchical process to define sustainable exploitation levels (Tier 1: ecosystem sustainability, Tier 2: multispecies sustainability, Tier 3: stock sustainability). The second tier uses multispecies assessments to allocate fisheries production among commercial species, taking into account species interactions and the trade-off among fisheries (multispecies sustainability). The present study will be developed as part of this roadmap and within this three tiers framework.

With the aim of contributing to the development of an Ecosystem Approach to Fisheries in the NAFO area, the EU DG-MARE has launched the project SC05, "A Multispecies Fisheries Assessment for NAFO". The main purpose of this study is providing a comprehensive overview (from the economic and ecological perspective) on how multispecies assessments would fit into the scientific and decision-making processes within NAFO and develop specific analyses and techniques on a case study, the Flemish Cap, that result in potential practical implementations for the multispecies approach. As a first step an updated version of the multispecies model GadCap (Flemish Cap cod, redfish and shrimp multispecies Gadget model; Pérez-Rodríguez et al. (2017)) will be produced, by introducing new data sources and extending the time period covered. Some relevant technical elements, as well as a number of biological and ecological characteristics affecting the productivity and trade-offs between the stocks within the model will be improved. This will result in the release of an updated and improved version of the multispecies model GadCap that will be used to explore the provision of scientific advice for a multispecies approach in the Flemish Cap from different fronts. As a first output from GadCap, natural mortality at age (residual+ predation, M1+M2) will be estimated and make available to be used as alternative values of natural mortality in single species models stock assessment during the 3M cod benchmark (see Pérez-Rodríguez and González-Costas (2018)). Second a first configuration of an MSE framework with GadCap as operating model will be develop (i.e. a multispecies MSE), that will allow the estimation of multispecies reference points, and where traditional single species and potential new multispecies HCRs could be assessed from the precautionary and MSY perspectives. This study will also provide a first analysis of the implications of moving from single to multispecies assessment and management from the socio-economic perspective and the available techniques and models needed to assess the trade-offs resulting of the decisions taken from a multispecies approach to management.

In this working document, an updated and improved version of the multispecies model GadCap is presented. The main modifications introduced in the databases and the structure of the model are described. Finally the diagnostics and population estimates are presented.

MATERIAL AND METHODS

Updating model input databases

As indicated, the best model developed during the project GadCap[1] (Pérez-Rodríguez et al. (2017)) was taken as the starting point for the modelling exercise of SC05 project. The time period covered by this model was originally limited to the period 1988-2012. Accordingly, the first goal was extending until 2016 the time coverage of the commercial and survey databases supporting all the different likelihood components in the model. In addition, all these databases were reviewed to ensure, to the extent that it was possible, that the data employed in GadCap is comparable to the information used in the approved NAFO single species assessments for these stocks. In table 1 the different databases that have been updated are presented.

The updated databases are the key sources of information that support the core structure of GadCap. On one side the total annual commercial catches by the trawl fleets targeting for cod, redfish and shrimp and the gillnet fleet fishing for cod were updated. The seasonal distribution and the length composition of this catches have been also reviewed and extended until 2016. For cod and redfish fisheries these data have been provided by

[1] https://cordis.europa.eu/project/rcn/110232_en.html

the stock assessors and/or stock coordinators. For shrimp, due to the moratoria there is no trawl fishery since 2010 and hence, after confirmation by the stock assessor, annual catches were set to zero during the period 2010-2016 in the model. As part of the improvement of GadCap, in this project SC05 new data sources (total catch, distribution of effort by season and size distribution by season) describing the longline fishery on cod have been incorporated to the model. This fleet has become more important since 2012, and hence have been considered as part of the model improvement that will be explained in the next section.

The EU annual summer survey in the Flemish Cap is the other essential source of data, taking the role of tuning data, providing the model with a standardized perception about the state of the stock in terms of total biomass, abundance, age and size distribution. The total catch during the survey, abundance and biomass indexes and length distribution of the stock have been reviewed for the period 1988-2012 and updated until 2016 for all the three stocks. Due to the low catchability of one year old individuals, the recruitment index has not been calculated for shrimp. The indexes of abundance by age were only updated for cod. Part of these data was directly extracted from the EU Flemish Cap survey ARGO, although most of the information was provided by cod, redfish and shrimp stock assessors.

Apart from the population structure related data, the EU Flemish Cap survey provides also with biological and ecological information that is essential to properly model and assess the state and productivity of these three stocks, as well as the degree of their ecological interactions. During the EU Flemish Cap survey a length based stratified random sampling is conducted (Vázquez et al. 2013). The sampled individuals are aged, measured, weighted, sexed and their maturity state is determined. This data is available in the EU Flemish Cap survey ARGO. Accordingly all data related with key processes for stock productivity like growth, maturation or trophic interactions were reviewed for the period 1988-2012 and updated until 2016. As part of the update in the trophic interactions the stomach content databases (diet composition) for the different cod and redfish substocks have also being reviewed and extended up to 2016. The biomass of alternative prey to those directly modelled in GadCap have also been updated. The Continuous Plankton Recorder[2] (CPR) database, collected by the Sir Alister Hardy Foundation for Ocean Science, provided indices of biomass for copepods, hiperiids, chaetognaths and eufausiids in the Flemish Cap area over the period 1991-2015 (Figure 1). The biomass of other alternative prey like wolffishes, demersal fishes, mictofiids and pelagic fishes (Figure 2) was obtained from the biomass survey indices obtained from the EU summer survey.

The EU survey is also a platform to collect oceanographic data through a grid design of CTD casts. This CTD raw data was provided by the EU Flemish Cap survey coordinator, and were treated with Sea-Bird software[3] to produce a bottom water temperature database that allow estimating an annual average water temperature representative of the environmental conditions surrounding the modelled stocks. This data were reviewed and updated to 2016 (Figure 3).

Due to problems with right permissions, data directly or indirectly containing information about age and/or maturity state for cod and redfish after year 2013 couldn´t be finally used for this SC05 project. Accordingly, for years 2014 to 2016, growth and maturation had to be assumed the same than the observed/estimated in year 2013. This limitation is not expected to have a very large impact in the assessment of these stocks at this moment. However, if the problem of full access permission to the biological data is not solved, this may be a more serious issue in future years.

Improvement of GadCap model

The updated and revised databases were incorporated into the multispecies model GadCap presented by Pérez-Rodríguez et al. (2017). Some of these databases allowed extending the time coverage of the model until 2016, while other in addition allowed modifying the structure of the model, incorporating new fleets, improving the fit of certain biological processes such as growth or natural mortality, or exploring new ecological aspects, as it was done with the type III functional response in the relationship of prey consumption/prey abundance.

2 https://www.cprsurvey.org/

3 http://www.seabird.com/

Further modifications to the structure of the model have also been tried, such as the separation of the redfish in golden and beaked redfish, or testing the performance of the model with an annual structure instead of seasonal timesteps. In addition, alternatives to the current optimization process have also been explored, such as the paramin tool[4] and the new algorithms of optimizations introduced by the Centre of Supercomputation of Galicia (CESGA).

a) Improvements in the comercial and survey fleet components

Like other parameters of the model, the inclusion of new data in the optimization process allowed re-fitting the parameters of the initial conditions of the stocks. But very importantly, the parameters of the selectivity functions of the commercial fleets and also the scaling parameters (effort parameters) were also re-optimized. This is an especially important aspect since fishing is one of the main factors that determine the dynamics of the modelled stocks. The shape of the adjusted exploitation pattern (selectivity curve) together with the fishing effort determines the magnitude of the impact of fishing on the population. In the case of the three survey fleets for the three stocks, the parameters of the selectivity function and the scaling parameter have also been readjusted.

Since the re-opening of the cod fishery in 2010, Norway and the Faroe Islands have fished a very important part of their catches (some years up to 100%) using longline gear. Since these two countries accumulate around the 25-30% of the cod catches in Flemish Cap and fishes caught by this gear are usually larger than in the trawl fishery, it was considered of relevance including this fleet in the improved GadCap model. The data needed to model the selectivity and scaling parameters for the longline fleet were obtained from the catches reported by Norway and Faroe Islands for their respective longline fleets, as well as the size distributions obtained by the commercial fisheries sampling programs of these countries. Differences in the length distribution of trawl, gillnet and longline cod catches are shown for the year 1988, when data for all the three fleets was available (Figure 4).

In relation to the survey fleets, the selectivity and scaling parameters for all the three stocks have been re-optimized with the new reviewed and extended databases. The size distribution of shrimp survey catches have been reviewed and modified, using the best estimates provided by the stock assessor. In addition, new likelihood components have been included in the cod survey fleet: the mean weight at age (intended to improve the fit of the growth model) and the survey indices of abundance at ages 3 to 5. In comparison with the index of abundance at age 1, this indices at ages 3-5 have been included because of its capacity to allow higher flexibility in the when fitting annual recruitment.

b) Improvements in the biological processes

As part of the modifications introduced in GadCap (Pérez-Rodríguez et al. 2017), some of the biological processes that, along with fishing and predation, determine the productivity of the stocks and their size/age structure, have been reviewed and improved. The modelling of the maturation process for all the three stocks has also been revisited, introducing important modifications in the time structure. In addition, some more profound changes in the structure of GadCap have been explored.

a) Individual growth:

Gadget is a model based on an initial population structure and a growth model that determines how individuals grow over time. Fleet and predator selectivity functions are length based. Therefore, modeling of growth in GadCap is a process that needs a high dedication and effort.

In order to improve this element, for the cod stock, growth parameters have been adjusted annually instead of bi-anually as it was the case in the model version presented in Pérez-Rodríguez et al. (2017). In addition, the length at age infinite (L_{inf}) has also been adjusted annually, instead of a constant L_{inf} over time as it was assumed in the previous version of the model. Finally, a new likelihood component with the average weight by age has been included to improve the growth model fit. For redfish stock, a separate growth model has been fit for 3 periods: 1988-1992, 1993-1997, 1998-2016.

[4] https://github.com/Hafro/paramin

b) <u>Sexual maturation:</u>
The importance of achieving an accurate modelling of the maturation process is related with three elements very relevant within the functioning of GadCap:
1. When an individual matures the preference for the different prey in the model changes.
2. The relation SSB-recruitment is fit using the estimates of spawning biomass and recruits by year from the final model.
3. The importance of points 1 and 2 in the forward projections that will be employed to determine reference points and MSE.

In this new reviewed version the fit to the observed maturity ogives has been improved. For cod stock, the maturation models have been readjusted in GadCap, going from biannual to annual maturity ogives.

c) <u>Changes introduced in the ecological processes</u>
The revision of the ecological processes has been mostly related with the trophic interaction, but also the oceanographic conditions (bottom water temperature) and the residual natural mortality.

a) <u>*Review of parameters defining the interaction prey-predator*</u>
The extension of the stomach content database until 2016 has allowed the revision of two essential aspects that define the prey-predator relationships: the suitability parameters and the prey-predator size selectivity curves. The suitability parameters define the predator's preference for a given prey in comparison to others. The prey-predator size selectivity curve is the element of the consumption model within Gadget determining, in combination with the prey preference, the magnitude of the interaction of a predator of a given size with a prey of a given size. These parameters and maximum consumption sub-models have been readjusted with the extended stomach content database, and have been employed in the final model.

b) <u>Residual natural mortality</u>
The residual natural mortality for redfish and shrimp has been maintained as it was defined in Pérez-Rodríguez et al. (2017) and it is presented in the next section. However, for cod sub-stocks, new values of natural residual mortality have been used. These values have been estimated using alternative methods. In Pérez-Rodríguez and González-Costas (2018) the work developed to estimate the residual natural mortality is presented.

<u>*Model assemblage*</u>

<u>*Cod, redfish and shrimp single species model settings*</u>

As indicated in the previous section, a different model structure with and annual instead of a seasonal time step was tried. All the databases and the model structure were modified to support an annual time step in GadCap. However, the preliminary results obtained indicates that this model does not perform properly. There is a clear under-estimation of stock biomass for all populations. This is still in an early stage of development and accordingly, despite this model structure would reduce the optimization time, as well as the data adaptation requirements, it was decided to continue with the traditional time structure, with seasonal time steps.

Hence, all the three stocks were modeled over the period from 1988 to 2016, with a 3 month time step and the assumption of no migration and no differences all over the Flemish Cap in mortality (whether predation, fishing or residual mortality) or growth. For this reason a unique area was considered for all the three stocks. Other characteristics for each single-species model are outlined in tables 3, 4 and 5 for cod, redfish and shrimp respectively.

There exist important biological, ecological and fisheries reasons to separate the redfish species *Sebastes marinus*, *S. mentella* and *S. fasciatus* in golden (*S.marinus*) and beaked redfish (*S.mentella* and *S.fasciatus*). However, the separation of commercial catch between this two stocks requires strong assumptions, since commercial catches are not declared separated. In addition, in the EU survey total catch and length distribution were not split by redfish species with confidence until 1993, and species identification for individuals bellow

15 cm (1-3 years old) has not been still possible. This implies that very important assumptions have to be undertaken to separate redfish between beaked and golden redfish during the late and early 1990s and separate 1-3 year old individuals (<15cm) between beaked and golden redfish in the Flemish Cap survey database.

Due to these data limitations, the first option considered in this project SC05 was including all the three redfish species together in a single stock, as it was done in the EU Marie Curie project GadCap. Previous studies indicates similar mortality rates, diet composition and growth curves up to age 15 for all the three stocks (Saborido-Rey 1994). Most of the redfish population (for all the three species) is younger than 15 years old. Hence, all these arguments support that including the three species into one single stock, despite not being ideal, seems still reasonable. However, due to the important differences in age and length at maturation for male and female (see previous section), the redfish stock was split in male and female sub-stocks. It is still recognized (as it has been presented in the previous section) that a separation of redfish species in beaked and golden redfish would be desirable for a better assessment of redfish in the Flemish Cap. The first steps have been done to achieve this separation, but still more work is needed before a reliable model with golden and beaked redfish is available.

For Northern shrimp, sex separation was also considered but in a sequential way. Since this species is a protandrous hermaphrodite species (Bergström 2000), in the model, individuals are recruited as male, and after a reproductive period with this sex it changes to female primiparous, and later on to female multiparous.

Despite there is also a differential growth by sex in cod, females and males were modeled together in this version of GadCap. The reason is that survey length distribution data by sex is only available since 2010. Future versions of the model, when a higher number of years of data is available, may explore the possibility of splitting cod by sex.

Sex change in shrimp and maturation in all the three stocks were modeled internally (i.e. during the process of optimization of model parameters) with a logistic model based on length (Begley 2005). It has been reported that the maturation process in cod and shrimp (also for the sex change in shrimp) has experience notable variations over the study period 1988-2016. Due to the above mentioned importance of fitting precisely the maturation process in order to properly simulate the trophic interactions and the SSB-Recruitment relationship, the maturity parameters were hence estimated annually for cod. For shrimp 10 periods were considered. However, for redfish maturity change only one period was considered both for males and females. Sex change and maturation were modeled with a logistic model based on length:

$$P(l) = \frac{1}{1+e^{-4\propto(l_i-l_{50})}} \qquad (1)$$

where $P(l)$ is the probability of maturing (or changing the sex) at a given length l, l_i is the middle length of the length group i, l_{50} is the length at which 50% of the individuals become mature (or changing the sex in shrimp) in a given year, and α is a parameter to be estimated. It was assumed that all the three stocks mature or change from male to female in the last time step (4th time step) of the year.

As indicated in the previous section, due to limited access to all the data containing information about age and maturation for cod and redfish, maturity proportion by length for years 2014-2016 was assumed to be the same as that observed in 2013.

For all the three species the initial population was estimated as the number of individuals by age in year 1988. Recruitment was annually estimated for all the three stocks as the number of individuals at age 1 on 1st January. In the redfish stock, the estimated recruits were split into males and females assuming that 50% of individuals at age 1 belonged to each sex. The mean length and standard deviation at recruitment was fit every year for the cod stock, while for redfish four different periods 1988-1993, 1994-1997, 1998-2012 and 2013-2016 were considered; and for shrimp three periods were identified, 1988-2003 and 2004-2008 and 2009-2016. As part of the GADGET performing, the mean length and standard deviation at age 1 are used to produce the size distribution of recruits assuming a normal distribution.

The Von Bertalanffy growth model was used to define the growth curves for all the three species. As presented in the previous section, for cod the model was fit to the data annually, while for the redfish and shrimp stocks this model was fit separately for the same periods defined above for the mean length at recruitment. For each species the average standard deviation at age around the mean length was calculated externally for the whole time period. In gadget the mean growth in length during a time step is estimated for each length group using the fit Von Bertalanffy growth function. The length distribution around the mean was estimated according to the average standard deviation at age assuming a beta-binomial distribution. A unique length-weight relation was fit for all time steps and years. Due to limited access to biological data since 2014, the growth curve for years 2014-2016 was assumed to be the same as the fitted curve in 2013.

As explained in the previous sections, as an improvement in the GadCap model the commercial fleet targeting cod in the Flemish Cap was modeled as three different fleets: trawl, gillnet and longline. For redfish the pelagic and bottom trawl fishery were simplified to a unique trawl fishery due to the lack of information about total catches and size distribution by season in the pelagic fleet. The shrimp fishery was also considered for the redfish stock due to the important by-catch of juvenile redfish during the early-mid 1990´s, especially before the introduction of a sorting grid in 1995. The only fishing gear targeting the shrimp stock was the bottom trawl.

Instead of assuming that the declared catches were exact, some flexibility around the total catch was allowed for all the fleets considered in this study, including the survey fleet. Total catches were simulated in the model for each fleet and time step using the equation:

$$C_{sl} = ES_{sl}\Delta_t N_{sl} W_{sl} \qquad (2)$$

where C_{sl} is the catch in kg for a given species and length cell, E is the scaling factor for the part stock that is caught, Δ_t is the length of the time step, N_{sl} is the number of individuals and W_{sl} the mean weight of that species in the length cell. The parameter E was estimated annually for each commercial fleet, resembling the changes in effort over time. However for the survey fleets only one parameter was estimated for each species, in order to keep the effort constant over time. S_{sl} is defined by the suitability function and determine the proportion of the length group that will be caught by the fleet.

The suitability function employed in the model was variable depending on the fleet. The cod longline fleet and most trawl fleets in the model were assumed to fit to a logistic function of length, called in gadget the Exponential50 suitability function:

$$S(l) = \frac{1}{1+e^{-4\alpha(l_i - l_{50})}} \qquad (3)$$

where $S(l)$ is the proportion of the species at a given length l that is potentially caught by the fleet, l_i is the middle length of the length group I, l_{50} is the length at which 50% of the individuals are potentially fished, and α is a parameter to be estimated.

For the cod gillnet fleet, the redfish survey fleet and catches of redfish by the shrimp trawl fleet, the suitability curve was assumed to have a dome shaped relation with length. In gadget this is called the Andersen suitability function and is implemented for any prey-predator interaction:

$$S(l,L) = \begin{cases} p_0 + p_2 e^{\frac{-\left(ln\frac{L}{l} - p_1\right)^2}{p_4}} \; if \; ln\frac{L}{l} \leq p_1 \\ p_0 + p_2 e^{\frac{-\left(ln\frac{L}{l} - p_1\right)^2}{p_3}} \; if \; ln\frac{L}{l} \geq p_1 \end{cases} \qquad (4)$$

where $S(l, L)$ is the proportion of the species at a given length l that is potentially caught by the fleet. L denotes the length of the predator, which is a meaningless concept when the predator is a fleet and takes a constant value, the average length of the species. p_0, p_1, p_2, p_3 and p_4 are parameters to be estimated and define respectively the lowest suitability (assumed to be 0), the dispersion of the curve, the maximum suitability (assumed to be 1) and the shape of the left and the right slope.

With equations 2, 3 and 4, total catches (numbers and biomass) by time step, fleet and species are estimated and distributed by length. Due to the expected different pattern of exploitation for cod and redfish before and after the collapse of cod stock, the commercial fleets for these species were split into two different periods, 1988-1998 and 1999-2016. Consistently, two different sets of parameters for the suitability functions were fit.

The residual natural mortality, defined here as the natural mortality due to other factors than predation mortality was defined externally for redfish and shrimp (tables 4 and 5) and fixed during the model optimization. In previous studies a natural mortality of 0.5 for all ages was estimated as the most plausible value for the Flemish Cap shrimp (Skúladóttir 2004). Considering that natural mortality due to predation by cod and redfish is explicitly modeled here and added to the final mortality, a lower residual natural mortality was assumed for each age: 0.2 at age 1 and 0.1 for the remaining ages. In the Flemish Cap redfish, traditionally natural mortality has been assumed as 0.1 (Ávila de Melo et al. 2013). In this study, since predation by cod and cannibalism is explicitly modeled, a lower basic natural mortality of 0.05 was considered. With the intention of including the additional effect of predation by wolffishes and Greenland halibut, residual natural mortality values at ages 1-10 were set by multiplying 0.05 by the standardized EU survey biomass index of these predators over the study period. At ages 11-16, when the effect of predation by these predators is lower, a 0.05 residual natural mortality was assumed. For ages 17-25 residual values for natural mortality were taken from Efimov et al. (1986), representing the added mortality due to ageing in a long living species. For cod (table 3), residual natural mortality was fixed as 0.35 based in the results of the analysis presented in Pérez-Rodríguez and González-Costas (2018).

Assemblage of the multispecies model

Cod and redfish act as both predators and prey (Figure 5). Immature and mature cod prey on immature cod, redfish, shrimp and the non-modeled prey hyperiids, euphausiids, chaetognaths, wolffishes, demersal fish and other food. Meanwhile redfish preyed on immature redfish all shrimp substocks as well as the non-modeled preys: copepods, hyperiids, euphausiids, chaetognaths, pelagic fish and other food. Non-modeled preys were considered in the model to estimate the importance that the state of populations of these alternative prey has in the dynamic and interactions between the modeled stocks. The “other food” category represents all the remaining prey species not specified in this model and has as main function avoiding excessive and unrealistic predation mortality in the modeled prey.

The present model has not been designed for the consumption of any prey having any effect on growth and survival of predators. The exceptions to this are 1) the direct effect of cannibalism, which by affecting the dynamic of the prey it affects the survival of juvenile stages of the predator; 2) the indirect effect that the abundance of alternative prey has on the intensity of cannibalism.

Total consumption by length, both for cod and redfish, was estimated annually for each time step using a bioenergetic model (Temming and Herrmann 2009). In GADGET, these estimates were used to model maximum total consumption rate M_L (as kg/time step) by an individual predator as a function of length and water temperature as follows:

$$M_L = m_0 \Delta t e^{(m_1 T - m_2 T^3)} L^{m_3} \qquad (5)$$

Where M_L is the maximum consumption for a predator of length L; T is the water temperature; L is the predator length and m_0 m_1 m_2 and m_3 are parameters to be estimated.

No consumption rate studies were found for redfish species, and hence, it was assumed that the same parameters and model settings estimated by Temming and Herrmann (2009) for cod were assumed useful for redfish as well. The method developed by Temming and Herrman is based in assumptions about the relation of fish surface and metabolic rates, and the principle that annual food consumption is dependent on the magnitude of annual growth. Based on this, it can be concluded that this methodology can be applied to different species, with the main element that would need to be determined being the food conversion efficiency. It has been found that cod conversion efficiency is around 30% (Lemieux et al. 1999), while redfish (*Sebastes melanops*) conversion efficiency is usually between 15-20% (Boehlert and Yoklavich 1983). For this reason, in this project SC05, maximum consumption on redfish was estimated having into account this difference in conversion efficiency.

Next, gadget estimated the consumption of a given prey stock at length l by the predator stock of length L (Begley 2005).

$$C_p(l,L) = \frac{N_L M_L \psi_L F_p(l,L)}{\sum_p F_p(l,L)} \qquad (6)$$

$$F_p(l,L) = (S_p(l,L) E_p N_l W_l)^d \qquad (7)$$

$$\psi_L = \frac{\sum_p F_p(l,L)}{H\Delta_t + \sum_p F_p(l,L)} \qquad (8)$$

where $C_p(l,L)$ is the total consumption of prey p of length l by the whole predator population at length L, which is determined by N_L, the number of predator in length cell L; $F_p(l,L)$ the consumption of prey p of size l by an individual predator in the length cell L; and ψ_L the feeding level at predator length L. In addition to the sum of $F_p(l,L)$ for all prey species, ψ_L is dependent on the half feeding value H, the biomass of prey required for the predator consuming prey at a half the maximum consumption level. Due to the lack of information about this parameter it was assumed that the total prey consumption by both cod and redfish was independent of the amount of available food, and hence, the half feeding value H was set to zero. $F_p(l,L)$ depends on the suitability function S_p; the prey energy content E_p; N_l the number of prey at length and W_l the average weight of prey at length l. The parameter d determines the shape of the functional response of predator consumption to the abundance of the prey. In this model d was set as 1, a functional response type I.

For the modeled species, the suitability of a prey for a predator was set assuming a dome shape relation over prey length, the above mentioned Andersen function (equation 4). For a given predator size, there is a prey size for which suitability is maximum, and decreases at both sides. The maximum suitability, the relation between prey and predator size, as well as the asymmetry of this curve was set by the parameters: p_0, p_1, p_2, p_3 and p_4. For the non-modeled preys chaetognaths, hyperiids, copepods, euphausiids, wolffishes, demersal fish and pelagic fish a constant suitability function was assumed and hence, no variations with the predator-prey size ratio was considered.

Prey suitability is in gadget a relative index, set at 1 for the most preferred prey and decreasing in order to the lowest value for the less preferred one. Suitability values are representative of the importance of a prey in the diet related with its relative importance in the ecosystem. These parameters, as done for all the other parameters of the prey-predator size curve and the consumption model were estimated externally.

Parameter estimation and model validation

The new algorithms and methods of optimization developed by the Centre of Supercomputation of Galicia (CESGA) are being tested. As indicated in the previous section, this new methods seems to optimize much faster and with lower variability. However, there are still some elements that need to be reviewed, and hence, in the optimization of the final model selected at this moment the traditional algorithms available in Gadget have been used. The optimization routine consist of a two-stage iterative process combining a wide area search (Simulated Annealing) and a local search (Hooke and Jeeves) algorithm (Begley and Howell 2004). The iterative nature of the procedure is designed to try and arrive to a global rather than local solution. The model minimizes a total quasi-likelihood value, i.e. the result of a weighted sum of the score of all the components in the model. In this model different likelihood components were specified for each modeled stock: total commercial catch, survey index of biomass, size distributions of catches, age-length keys, maturity state, sex state (only shrimp) and diet composition. The optimal weight given to each likelihood component was estimated with the function gadget.iterative, of the R package Rgadget (https://github.com/rforge/rgadget), which follows the process described in Taylor et al. (2007). An exception to this were the weights given to all the commercial catch likelihood components, which were fixed at very high values with the intention of allowing some differences between observed and estimated catches, but simulating as much as possible the declared catches. A sensitivity test was conducted to confirm that an optimum was reached for all the parameters.

RESULTS and DISCUSSION

1.- Model fit

1.1.- Cod

The model estimated values of biomass and abundance survey indices (including the recruitment index proxy, or smaller than 25cm individuals), as well as catches in kg for the trawl and gillnet were very close to the observed values (Figure 6). The similarity obtained for the estimated and observed commercial catches (Figure 7) was due to the high weight assigned to these likelihood components. The estimated size distribution of catches showed also in general a high similarity with the observed distributions in the longline, gillnet and trawl commercial catches as well as in the survey fleet catches (Figures 8, 9, 10 and 11 respectively). The survey length distribution estimated by the model captured properly the observed size distribution (Figure 12), especially in those years of high abundance of recruits, like 1991, 2005-2006 and 2010-2012. The inclusion of a likelihood component with the average length by age contributed to improve the fit of the model to the observed length distribution in the survey, that was a problem in the previous GadCap version. The maturity ogives by length were fit by the model in an annual basis. The estimated proportion of mature individuals was in general very similar to that described by the observed maturity ogives since 1992 (Figure 13), with the exception of year 1994.

1.2.- Redfish

In the redfish stock, the model estimates were very similar to the observed indices of biomass, total abundance and abundance of individuals smaller than 12 cm length, as well as total redfish trawl fleet catches and shrimp trawl fleet by-catches (Figure 14). However, in this stock there was a higher deviation from the observed biomass indices in some years between 2005 and 2016. The size distribution of the redfish by-catch from the shrimp trawl fishery was well fitted by the model (Figure 15). With the exception of a few seasons in some years, the size distribution of catches from the redfish trawl fishery was also well simulated (Figure 16 and 17), like the EU survey fleet size distribution (Figure 18). The estimated curve of proportion of mature redfish by fish length, assumed constant for all years, was well fitted to the observed values (Figure 19).

1.3.- Shrimp

All the observed data for survey indexes of biomass and abundance, as well as the catches from the commercial fleet showed a very similar pattern, which were well fitted by the model (Figure 20). In years 2002, 2003 and 2005 there were higher differences especially in the index of abundance. However despite these higher differences it could be considered that the model fit properly the observed data. The size distribution of the survey fleet (Figure 21) despite was globally well fitted, showed some deviations from the observed values in years 1988-1989 and 2011-2015. This deviation was especially important in 2014. As it will be indicated in the next sections, this peak in small individuals in 2014 is result of a very high recruitment estimated in 2014, that is reflected in the estimated diet composition of cod. This increase in the diet composition was not observed. This recruitment did not have an impact on the population dynamic in later years, since in the 4th time step of year 2014 the high recruitment had been removed by predation. However, this is an issue that will be further explored. The observed size distribution for the commercial trawl fleet was in general well fit by the model (Figure 22). Since the data from the shrimp trawl fishery was thoroughly sampled by the Icelandic fleet, and this size distribution was very well fitted by the model, the deviation in the survey fleet size distribution was considered not having a bad effect in terms of the shrimp model perform. The estimated proportion of males, females primiparous and multiparous was fit from year 1994 onwards by means of optimizing the parameters that defined the female maturity and sex change ogives. These estimated proportions showed some difference in relation to the observed values (Figure 23), especially in the last years. This could be improved in the future, but at this moment is expected to be of low impact in the results since recruitment is not connected to the mature stock at this stage.

1.4.- Diet composition

The model estimated diet fit very closely the observed one, both for cod (Figure 24) and redfish (Figure 25). In both species the model represented important changes over the study period, with variations in the relative importance of all modeled and non-modeled preys. The proportion of shrimp exhibited an increasing trend since 1988 both in cod and redfish diets, and reached the highest values in the late 1990s and stayed at similar proportions until 2004-2005. Redfish was a relevant prey all over the study period for both small and large mature cod but it was especially since 2000 when its proportion in cod diet increased steadily until maximum values in 2009-2010. Cannibalism provided an important percentage to the diet of mature redfish those years when recruitment was high, like in the early 1990s and all over the period 2001-2007. In cod, cannibalism was also important and related to successful recruitments in late 1980s and early 1990s and 2010-2012. As indicated above, in 2014 there is a sudden increase in the estimated proportion of shrimp in the diet, especially for immature cod, although it can also be observed in immature redfish. This increase is not corresponded in the observed diet

2.- Model population and mortality estimates

2.1.- Cod, redfish and shrimp stock dynamic

Model estimates of annual recruitment at age 1 (Figure 26), total abundance (Figure 27) and total biomass by maturity and/or sex state (Figure 28) over the study period were highly variable. Cod recruitment was high in years 1991 and 1992, which was reflected in a subsequent rise in the immature and total stock abundance. However, this increase was followed by a steep decline in years 1993-1995, due to the lack of good recruitments and the reduction in the abundance of both immature and mature sub-stocks. Cod biomass remained at relative high values up to 1995, followed by a sharp decline until 1998, when the lowest value in the study period was reached. Over the period 1995-2004 estimates of cod recruitment were very low and consequently modeled stock abundance and biomass continued at minimum values over this period. However, in 2005 recruitment was above the average of the previous years and stayed at similar values until 2009, which produced an increase in the abundance of the immature and subsequently the mature sub-stocks. In the period 2010-2013 recruitment was very high, especially in year 2010 when the highest recruitment of the study period was estimated. The immature and total stock abundance reached the highest values since 1988 in these years, while the total biomass reached the highest value in 2014, with good year classes in both the mature stock stemming from cohorts 2005-2009 and the immature stock from recent recruitments (2010-2012). Since 2012 The biomass has stayed at high levels, although since 2014 it shows a marked decline.

Estimates of recruitment in the redfish stock were very high in the period 1990-1992 (Figure 3.2-33). This produced a marked increase in population abundance in 1991 (Figure 3.2-34), principally in immature individuals. However this increase was not reflected into total biomass (Figure 23), which showed a marked reduction in total biomass produced by the drop of the mature biomass and since 1990 also the immature sub-stock. After the increase in 1991-1992, the stock abundance showed a sharp decline due to the decrease in the immature stock, reaching the lowest values in the late 1990s. However, over the period 2001-2007 the model estimated a series of high annual recruitments, which were especially high in 2001, 2004, 2006 and 2007. These recruitments produced an increase of the stock abundance until 2007, when the highest value was attained. The increase in total stock biomass as result of these successful recruitments became more pronounced since 2003 due to the contribution of the immature sub-stock, and reached the highest value in 2009. Despite the mature sub-stock continuing the increasing trend in abundance, since 2007 total abundance declined sharply due to the reduction in the immature stock. The decline in total abundance was followed by the reduction of total stock biomass since 2010.

Despite being during the “burn in” period when caution is advised in interpreting the results, the model indicates that in 1988-1989 the shrimp stock experienced good recruitments (Figure 3.2-33) that produced the increase in the abundance of the male sub-stock in those years (Figure 3.2-34) and was the start of a growing trend in the stock biomass (Figure 3.2-35). However it was after 1993 that the highest recruitment values were estimated, in a series of successful cohorts that lasted until 2006. These high recruitments were reflected in the abundance of male, female primiparous and multiparous sub-stocks with a delay of c.a. two years from one sex-maturation stage to the next. The stock biomass showed a steady improvement until a maximum value in 2001, followed by a steady and continued decline that was not compensated by the high recruitments that kept the abundance at high values until 2004. This declining trend was mostly due to the reduction in the male sub-stock, however it was also observed in the primiparous and multiparous stocks. In 2016 the total biomass reached the lowest value since 1988.

2.2.- Instantaneous and harvest rates by source of mortality

The mortality rates by age due to fishing (F) and to predation by cod (M_{cod}) and/or redfish ($M_{redfish}$) were estimated for each modeled stock (Figures 29, 30 and 31). In cod, cannibalism was the main source of mortality at age 1 all over the study period (Figure 29), with the highest values in the early and late years. At age 2, cannibalism showed a similar pattern but in this case the highest values occurred in the last years, when the abundance of older and cannibalistic cod was higher. Since the reopening of the fishery in 2010, both M_{cod} and F had been similar at age 3 (close to 0.2). At age 4 and older, cannibalism was negligible and fishing accounted for most of annual mortality, which was extremely high before the collapse (F>1.5 at all ages in 1994). Since the reopening of the fishery in 2010, F at ages 4 and older stayed at relative low values in comparison with the levels of mortality during the 1990s. These high levels of cannibalism are in agreement with the observed in other areas at both sides of the Atlantic, with a high variability that has been related with fluctuations in recruitment (Bogstad et al. 1994, Fromentin et al. 2000, Lilly and Gavaris 1982, Neuenfeldt and Köster 2000, Tsou and Collie 2001).

In the redfish stock before 1996 the main cause of mortality for individuals younger than age 7 was predation by cod, with M_{cod} ranging from 0.1 to 0.3 (Figure 30). This range of ages were also affected by the shrimp trawl fishery in the period 1993-1995, with F=0.2 in average, that removed an important portion of the small population. Cannibalism was important in the early 1990s, but it was since 2000 when M_{red} showed an increasing trend from 0.07 to 0.36 in 2009 at age 1 and values above of 0.1 at age 2. For redfish older than age 9, the redfish trawl fleet was the main cause of mortality during the first part of 1990s, with values above 0.5 at most ages in years 1990-1992. After 1996, fishing mortality by the redfish trawl fleet decreased and stayed at very low levels despite the slight increase observed since 2007. From 2007-2010, M_{cod} became the most important source of mortality for all ages, with values above 0.2 for ages 2 to 9 and between 0.1 and 0.2 for ages 10 to 18. The exception to this was the age 1 redfish, for which M_{red} remained as the main cause of mortality. In agreement with these results, cannibalism in redfish has been reported before not just in the Flemish Cap (Albikovskaya and Gerasimova 1993), but also in other areas in the Northwest Atlantic including West Greenland (Pedersen and Riget 1993) or the Gulf of St. Lawrence (Savenkoff et al. 2006a), where it was responsible for 10-15% of total mortality. Equally, redfish predation by cod has been described in the Flemish Cap (Casas and Paz 1994, Lilly 1980, Pérez-Rodríguez and Saborido-Rey 2012) and other North Atlantic areas (Yagarina et al. 2011) as one of the most important sources of redfish mortality.

Other than the residual natural mortality, before the start of the shrimp fishery in 1993 the main source of mortality for shrimp was cod predation (Figure 31), with M_{cod} above 0.2 for ages 1-2, 0.2 for ages 3-4 and over 0.1 for ages 5 to 7. Since 1990 to 1995 M_{cod} declined steadily. Since 1993 until 1996 F raised to very high values (higher than 1) for ages 3 to 7. Since 1997 to 2005 F was lower for all ages, but it was still above 0.1 for age 2, 0.3 for age 3 and 0.6-1 for ages 5-7. Since 2006 fishing mortality showed a steady decline until 2011 when, with the moratoria, it became again zero. Since 2000, the estimated M_{red} showed an increasing trend for all ages, but especially at ages 1-3 (higher than 0.5 in 2009 for age 2 shrimp). M_{cod} increased steadily since 2005 for all ages and by 2012 was very similar to Mred.

CONCLUSIONS

The results presented here are able to disentangle the interconnected drivers of the abundance of the cod, redfish and shrimp stocks in the Flemish Cap. Overfishing, predation and cannibalism, and variable recruitment success have combined to produce strong swings in the biomass of all three stocks. The model has shown that predation was the explanation to most of the changes observed lately in the three main commercial species in the Flemish Cap. In shrimp, both predation by redfish and fishing have worked together driving the collapse of the shrimp stock, with the final contribution of predation by cod. The portion of large cod in the stock, especially since 2010, raised the predation mortality on redfish and seems to be the main factor inducing the decline of abundance and biomass in the last years. The model has also described that during those years of high recruitment cannibalism has been the main source of mortality both in juvenile cod and redfish, and has reduced significantly the expectative of increasing the biomass of the stock. In this regard, predation (including cannibalism) and fishing have co-occurred at age 3 in cod and most ages in redfish and shrimp in recent years. Additionally, the model has revealed the relevance of external prey groups like hyperiids and eupaussids for immature, small mature cod and redfish, the genus Anarhichas sp for large mature cod, and copepods for redfish. These results suggest that the potential decline of some of these alternative prey groups may have important consequences in the dynamic of the commercial species by changing predatory (and cannibalism) interactions.

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REFERENCES

Ávila de Melo, A., Petit, R., Pérez-Rodríguez, A., González Troncoso, D., Alpoim, R., Saborido-Rey, F., Pochtar, M., González-Costas, F., and Brites, N. 2013. An Assessment of Beaked Redfish (S. mentella and S. fasciatus) in NAFO Division 3M (With a Revised Approach to Quantify the Increase on Redfish Natural Mortality Determined by the Increase on Cod Predation Observed Over Recent Years, 2006-2012). NAFO SCR Doc. 13/024.

Begley, J. 2005. Gadget User Guide. *In* Marine Research Institute Report Series. p. 99.

Bergström, B.I. 2000. The biology of Pandalus. Advances in Marine Biology **38**(Journal Article): 55-256.

Boehlert, G.W., and Yoklavich, M.M. 1983. Effects of temperature, ration, and fish size on growth of juvenile black rockfish *Sebastes melanops*. Environmental Biology of Fishes **8**(1): 17-28.

Efimov, N.I., Savateeva, A.N., and Tretyak, V.L. 1986. On a feasible formal description of the natural mortality rate variation in relation to age of beaked redfish and capelin from the Northwest Atlantic. NAFO SCR Doc. 86/64.

Lemieux, H., Blier, P., and Dutil, J.D. 1999. Do digestive enzymes set a physiological limit on growth rate and food conversion efficiency in the Atlantic cod (*Gadus morhua*)? Fish Physiology and Biochemistry **20**: 293-303.

Pérez-Rodríguez, A., and González-Costas, F. 2018. Estimates of natural predation and residual mortality for the Flemish Cap cod NAFO SCR Doc. 18/XX.

Pérez-Rodríguez, A., Howell, D., Casas, J.M., Saborido-Rey, F., and Ávila-de Melo, A. 2017. Dynamic of the Flemish Cap commercial stocks: use of a gadget multispecies mdoel to determine the relevance and synergies between predation, recruitment and fishing. Can. J. Fish. Aquat. Sci. **74**: 582-597.

Saborido-Rey, J.F. 1994. El género Sebastes Cuvier, 1829 (Pisces, Socorpaenidae) en el Atlántico Norte: identificación de especies y poblaciones mediante métodos morfométricos; crecimiento y reproducción de las poblaciones en Flemish Cap, Universidad Autónoma de Madrid, Madrid (Spain).

Skúladóttir, U. 2004. Yield per recruit of shrimp (*Pandalus borealis*) at Flemish Cap. NAFO SCR Doc. 04/90.
Temming, A., and Herrmann, J.P. 2009. A generic model to estimate food consumption: linking von Bertalanffy's growth model with Beverton and Holt's and Ivlev's concepts of net conversion efficiency. Can. J. Fish. Aquat. Sci. **66**: 683-700.

Vázquez, A., Casas, J.M., and Alpoim, R. 2013. Protocols of the EU bottom trawl survey of Flemish Cap. NAFO SCR Doc. 13/021.

FIGURES

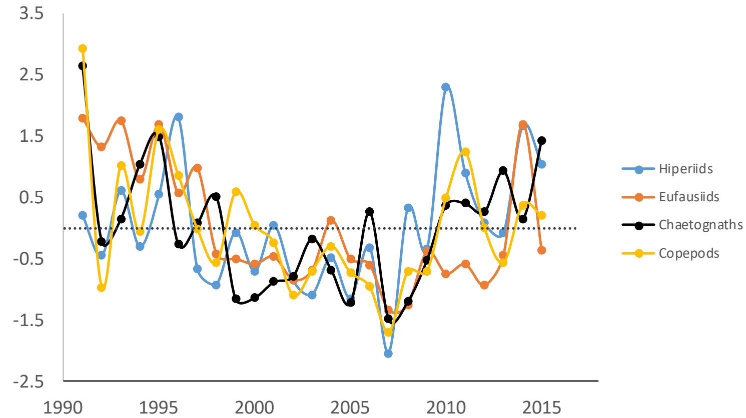

Fig. 1 Standardized abundance index of hyperiids, copepods, eufausiids and chaetognaths in the Flemish Cap area over the period 1991-2015. This index has been obtained from the Continous Pankton Recorder sampling program[1].

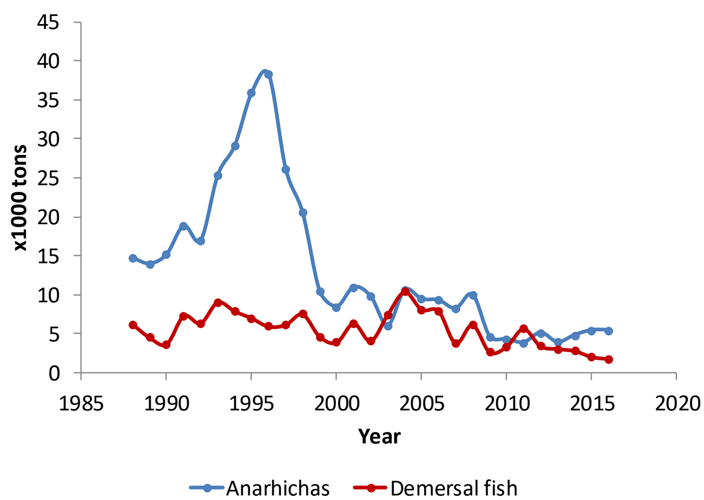

Fig. 2. EU Survey index of biomass in the Flemish Cap area over the period 1988-2016. This index was obtained by the swept area method used in the Flemish Cap (Vázquez et al. 2013)

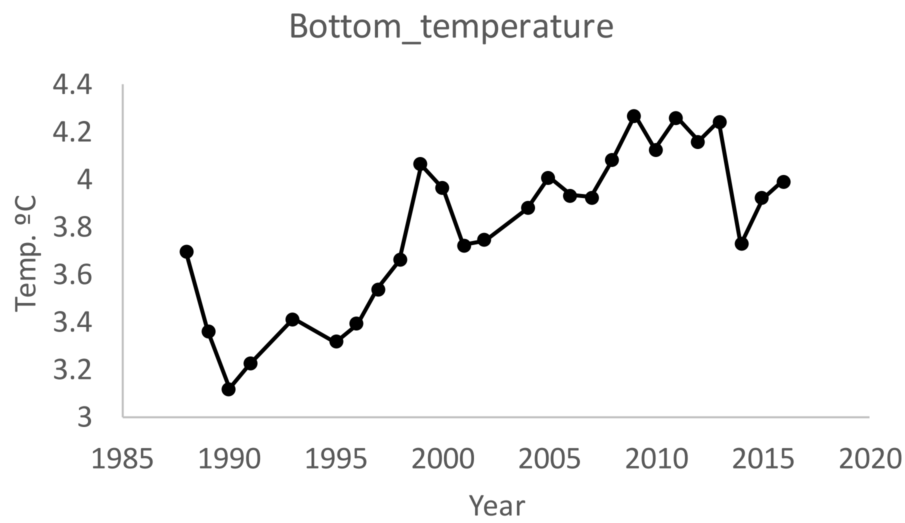

Fig.3. Bottom water temperature in the Flemish Cap during the EU summer bottom trawl survey.

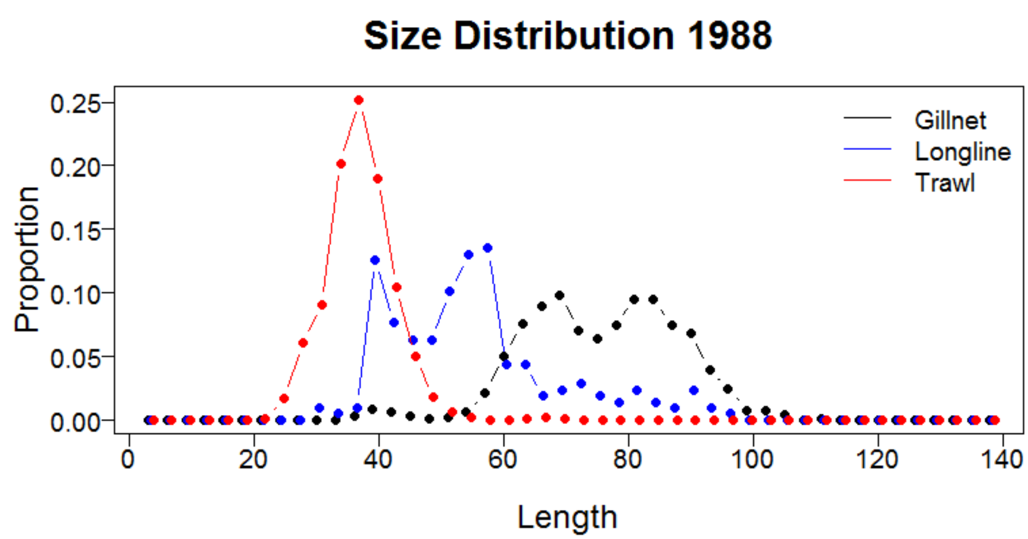

Fig. 4. Size distribution of catches in Gillnet, Longline and Trawl fleets in 1988. Data obtained from the 1989 Research Report of NAFO (https://www.nafo.int/Library/Documents/Scientific-Council-SC/Scientific-Council-SC-SCSs/1989-scientific-council-summary-scs-documents) .

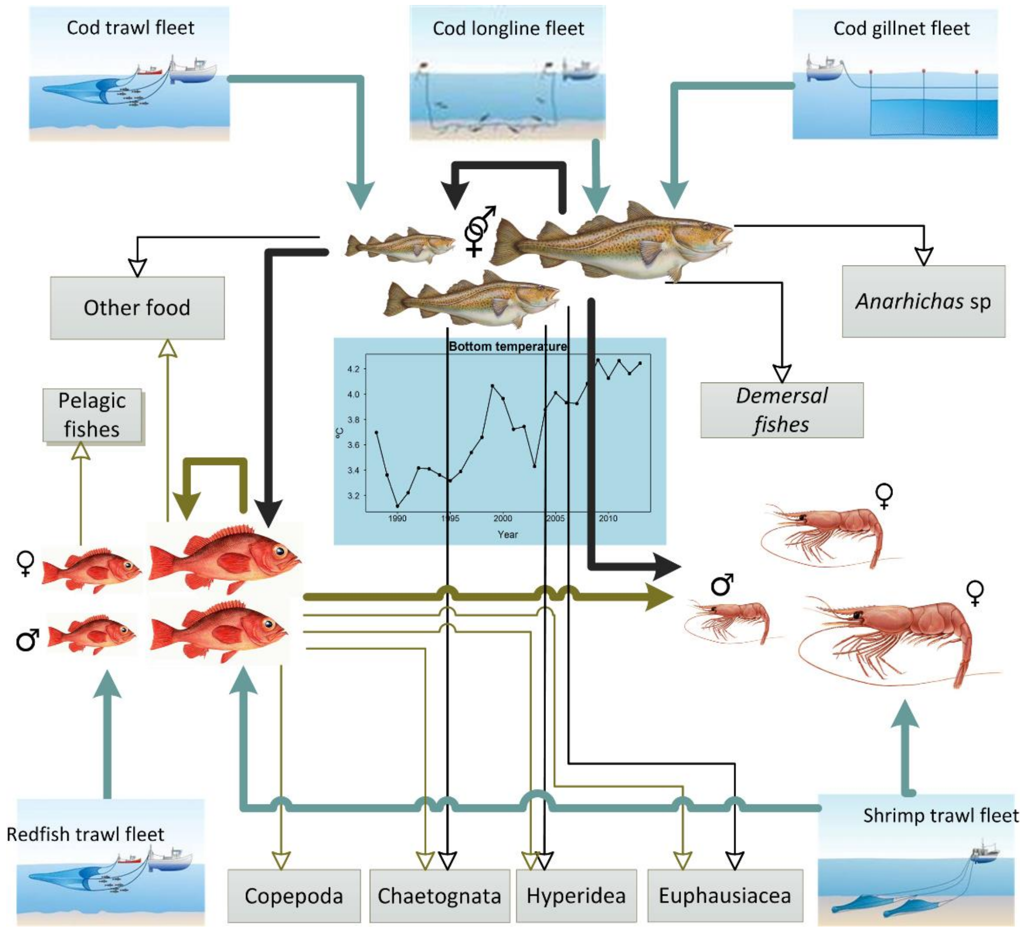

Fig. 5. Species interactions modeled in this study. Cod, redfish and shrimp are fully dynamically modeled, whereas species/prey groups in grey text boxes are incorporated as time series or constant values. The fleets fishing each species are also represented, as well as the effect of water temperature in total consumption.

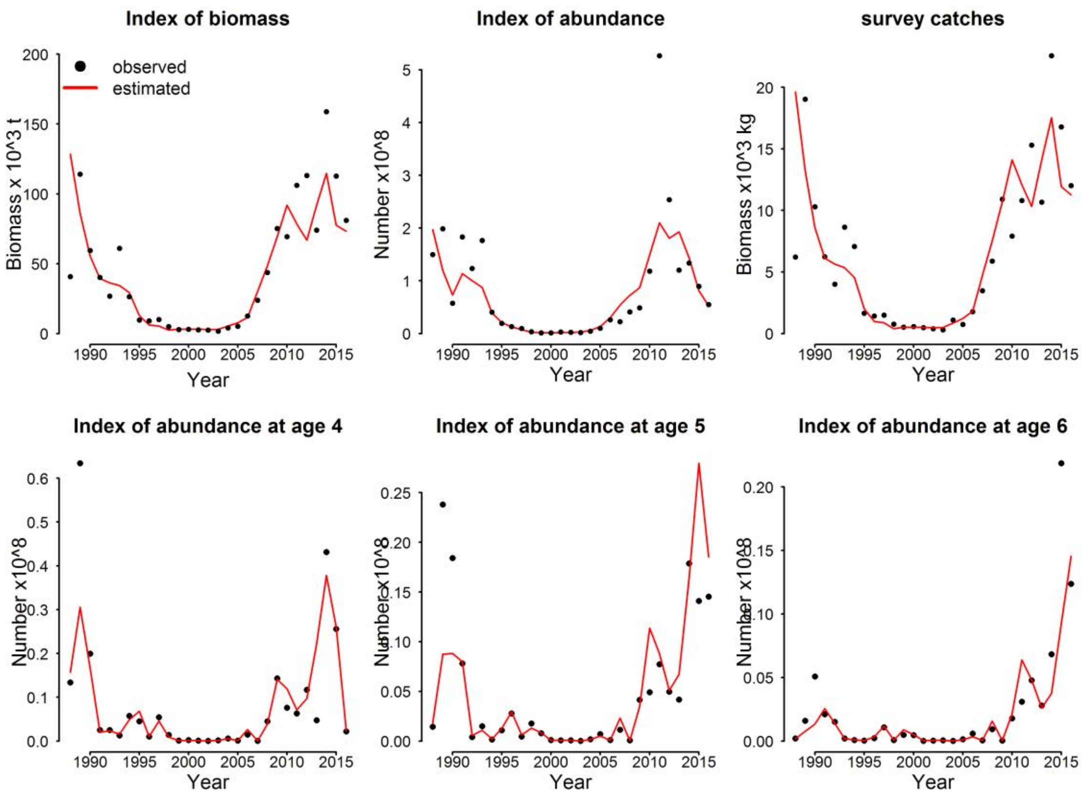

Fig. 6. Cod survey indexes of biomass, abundance and abundance of individuals at ages 4, 5 and 6. Total cod catches in tones during the EU Flemish Cap survey are also shown. Red lines are the estimated values with GADGET versus black points which represent the observed data.

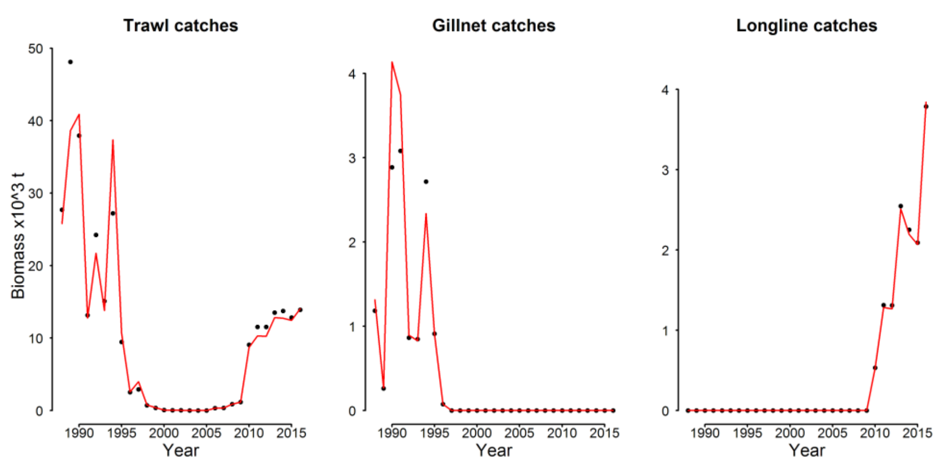

Fig. 7. Total cod catches in tones by the international trawl, longline and gillnet fleets. Red lines are the estimated values with GADGET versus black points which represent the observed data.

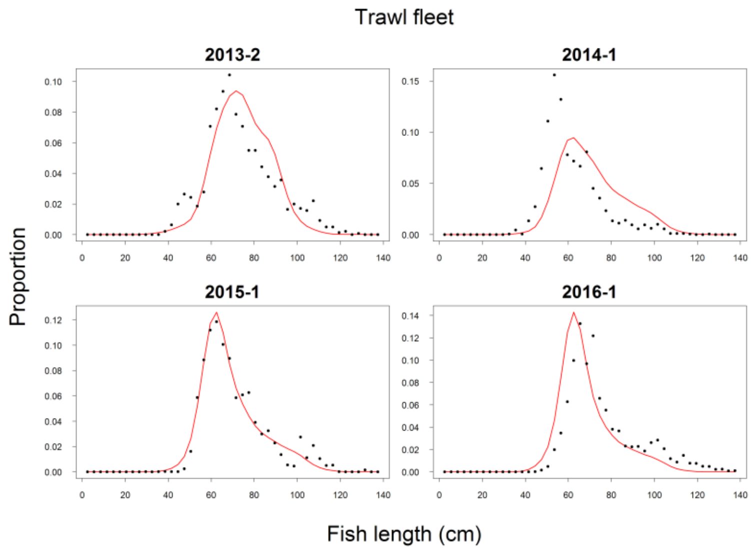

Fig. 8. Size distribution (in proportion relative to 1) of cod catches by the longline fleet. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 refers to winter of 1988). Red lines are the estimated values versus black points which represent the observed data.

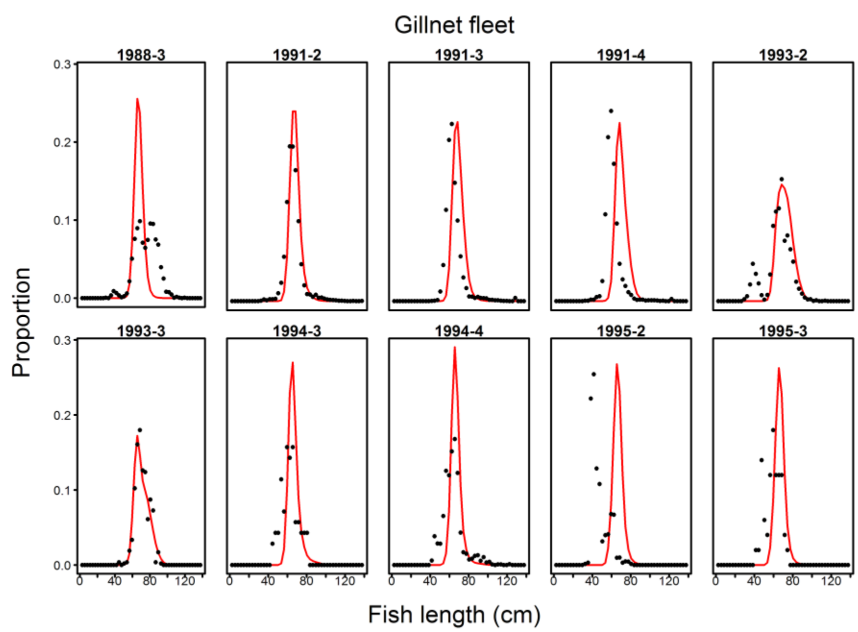

Fig.9. Size distribution (in proportion relative to 1) of cod catches by the gillnet fleet. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 refers to winter of 1988). Red lines are the estimated values versus black points which represent the observed data.

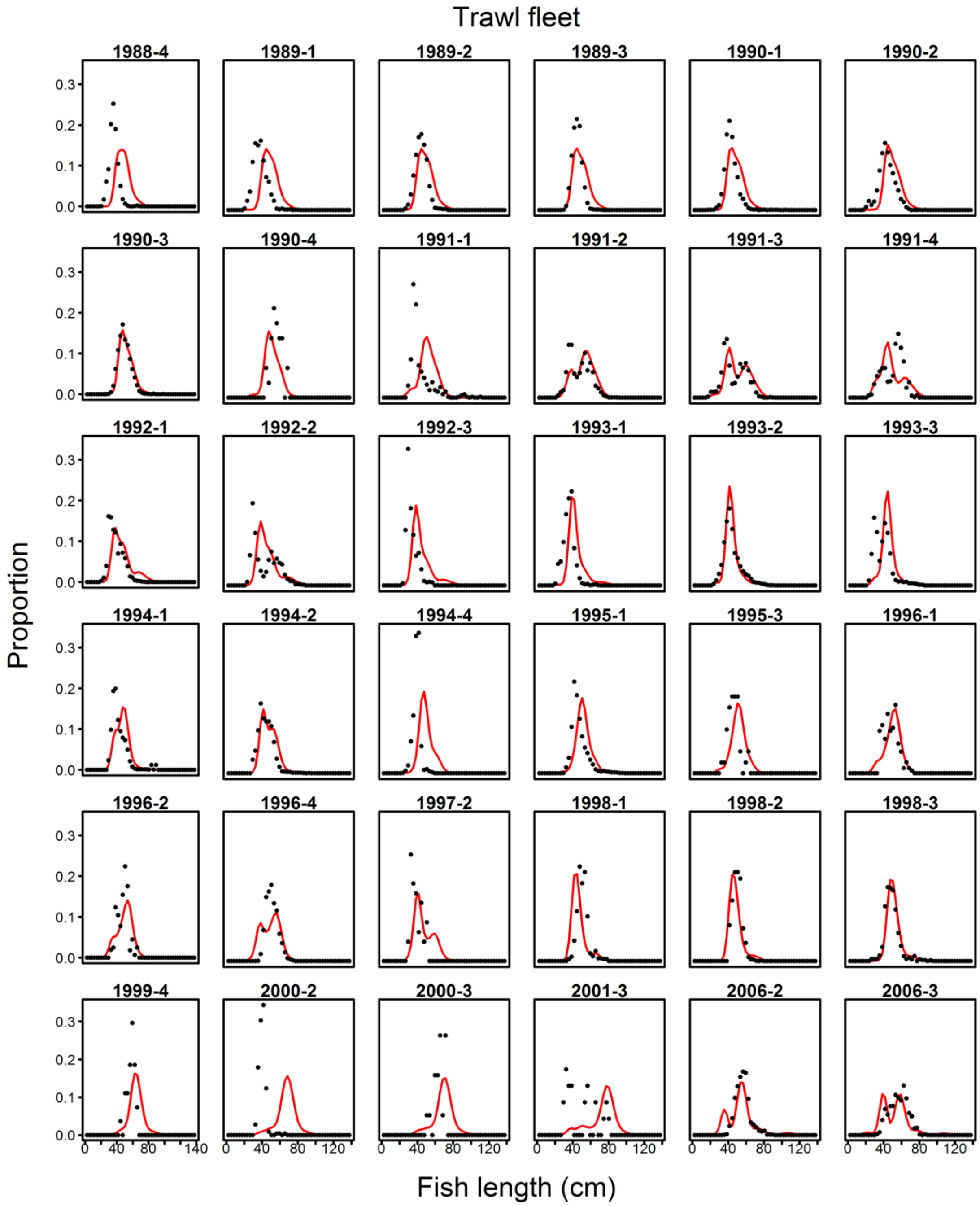

Fig.10. Size distribution (in proportion relative to 1) of cod catches by the commercial trawl fleet over the years 1988-2006. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 refers to winter of 1988). Red lines are the estimated values versus black points which represent the observed data.

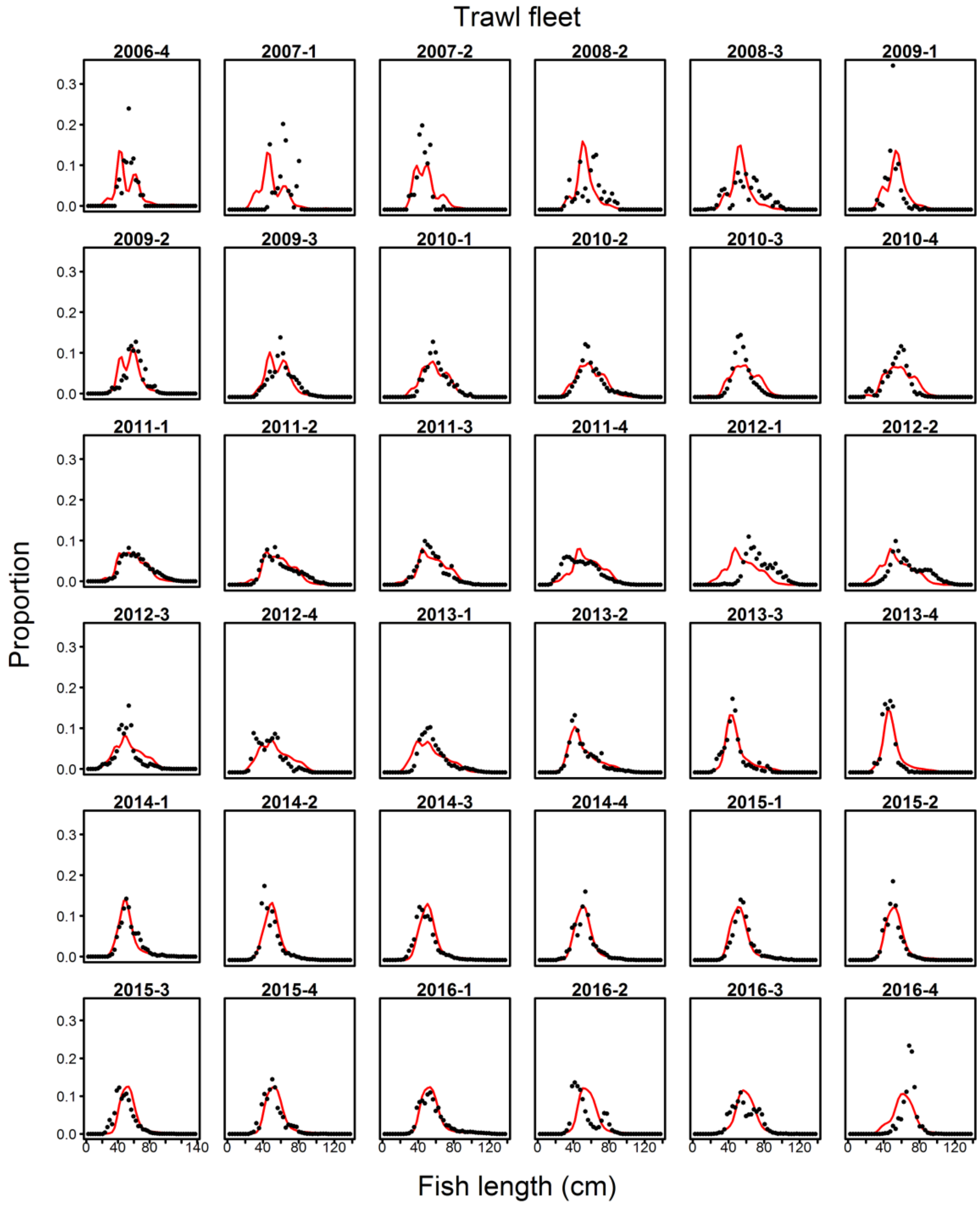

Fig. 11. Size distribution (in proportion relative to 1) of cod catches by the commercial trawl fleet over the years 2006-2016. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 refers to winter of 1988). Red lines are the estimated values versus black points which represent the observed data.

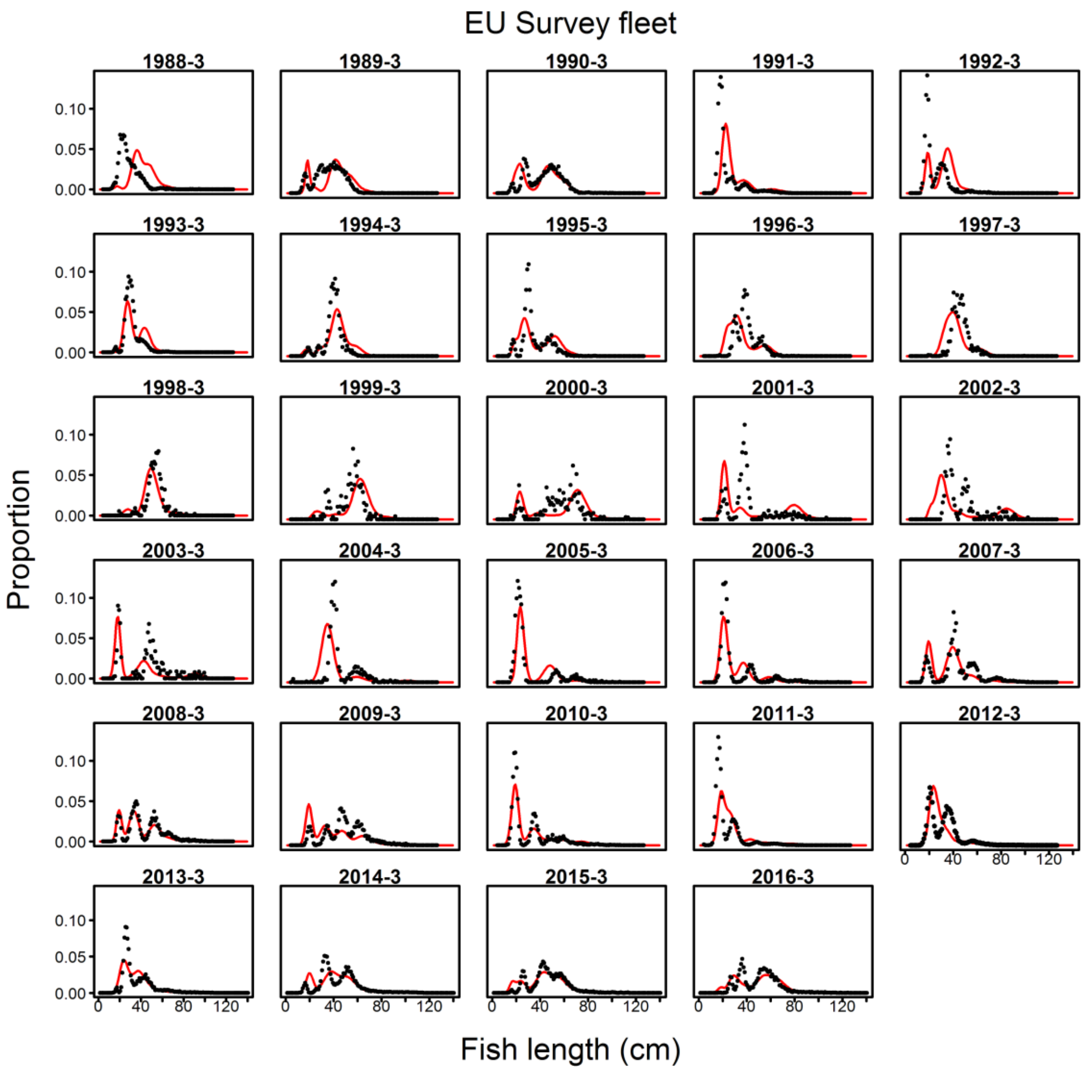

Fig. 12. Size distribution (in proportion relative to 1) of cod catches by the EU survey fleet. The label in each subpanel represents the year (Years: 1988 to 2016). For this fleet the season is always 3 (summer), when the survey takes place. Red lines are the estimated values versus black points which represent the observed data.

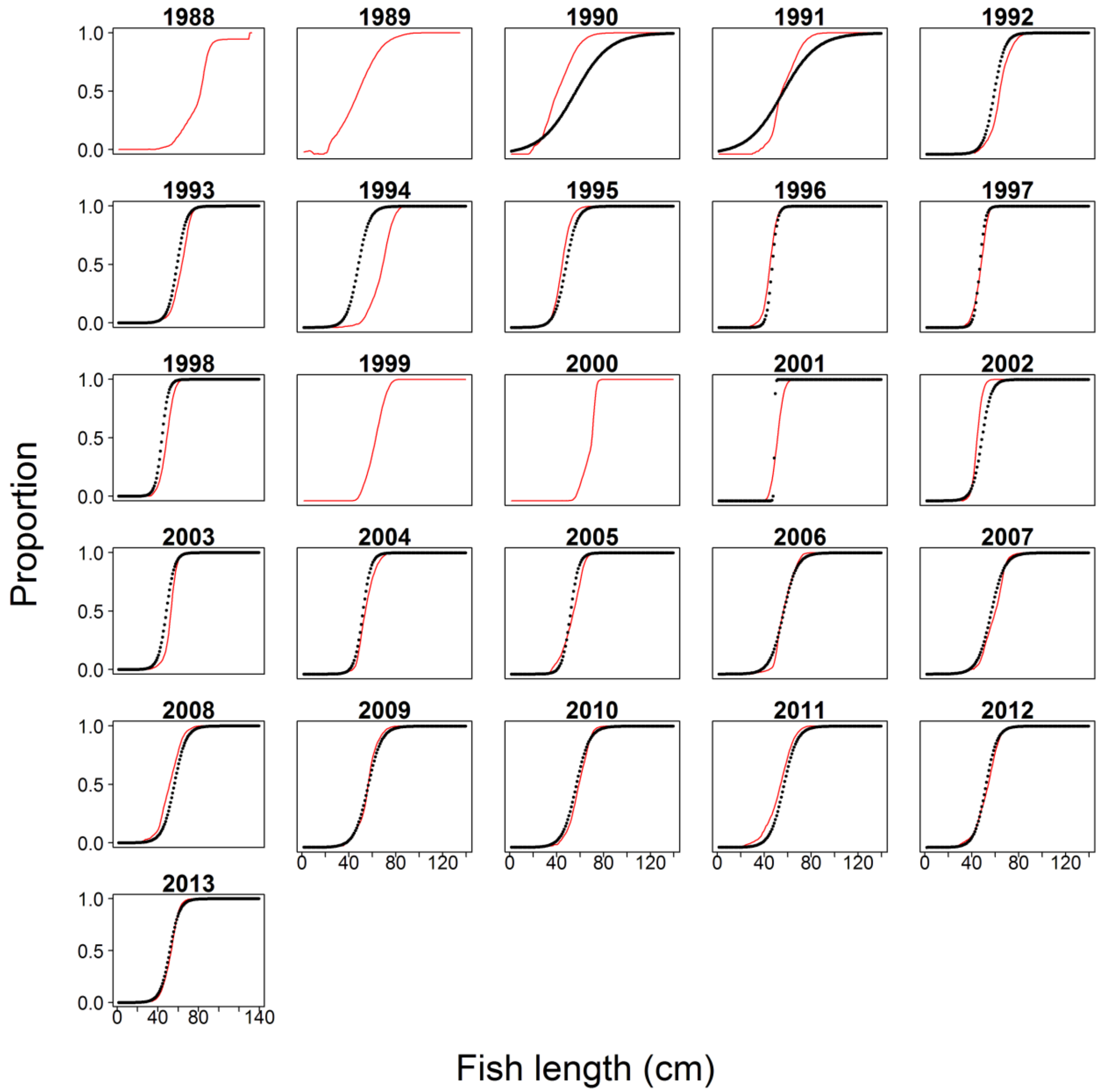

Fig. 13. Cod maturity ogives as probability, relative to 1, of being mature as a function of fish length. Estimated probabilities by the fit model in red color lines; Observed proportions in black color points.

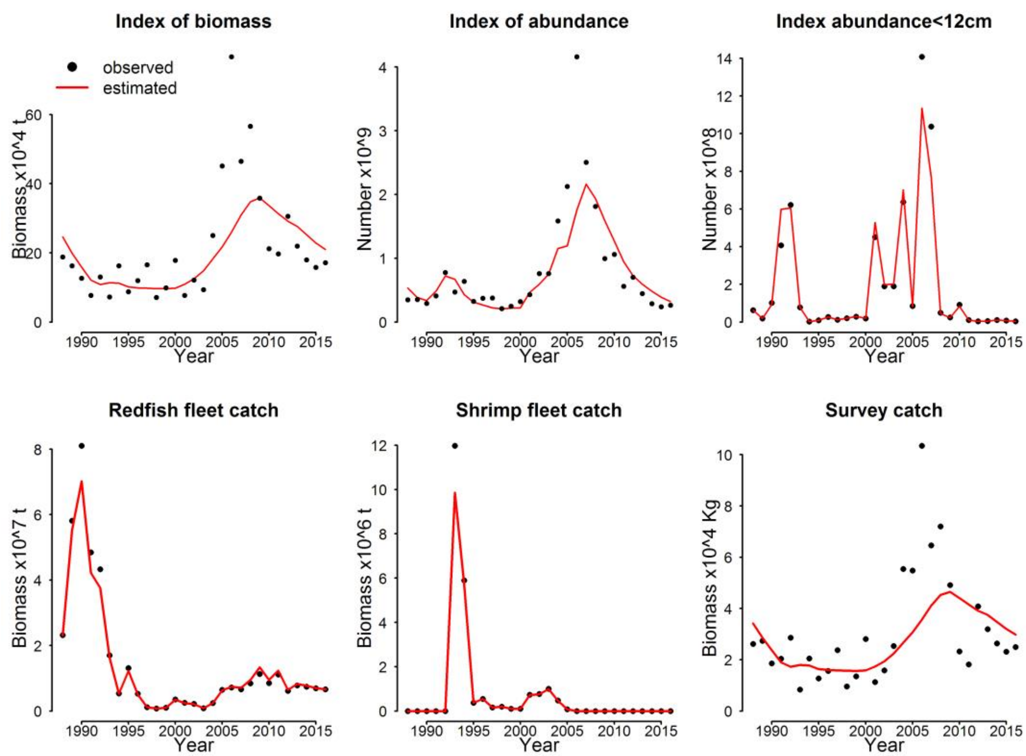

Fig.14. Redfish survey indexes of biomass, abundance and abundance of individuals smaller than 12 cm (from left to right in the first row). Total redfish catches in tones by the international redfish trawl, shrimp trawl (as by-catch) fleets.

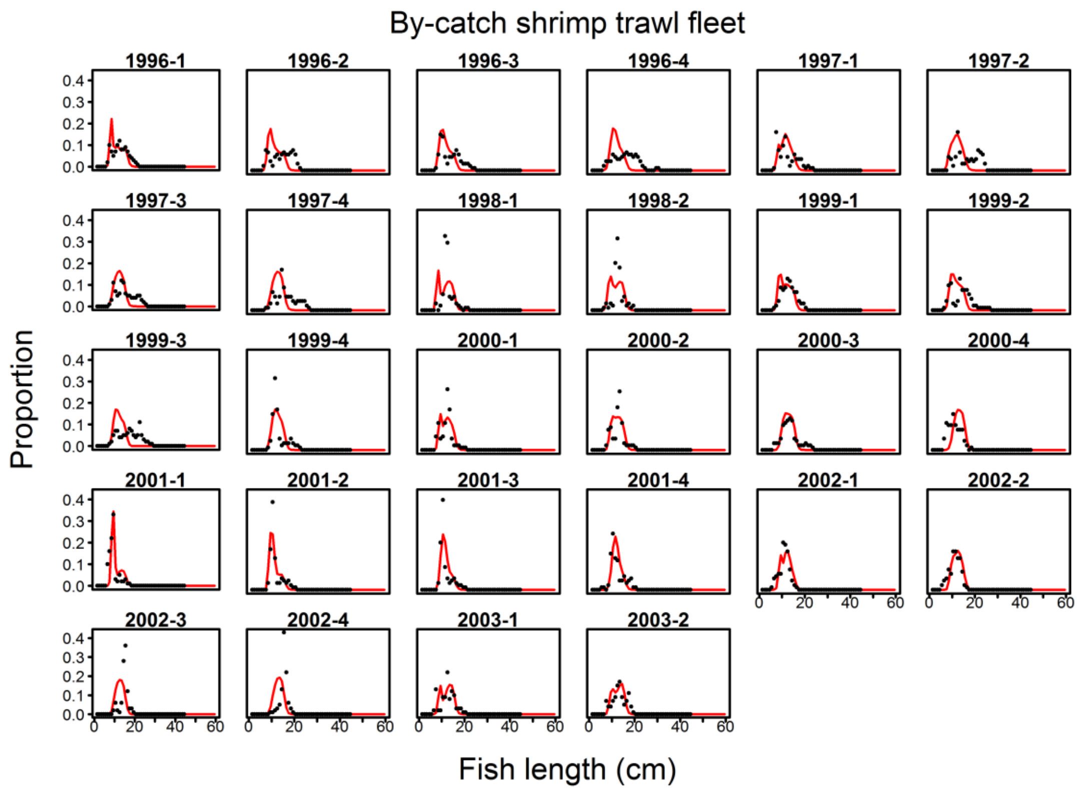

Fig.15. Size distribution (in proportion relative to 1) of redfish by-catches in the shrimp trawl fleet. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 is winter of 1988). Red lines are the estimated values versus black points which represent the observed data.

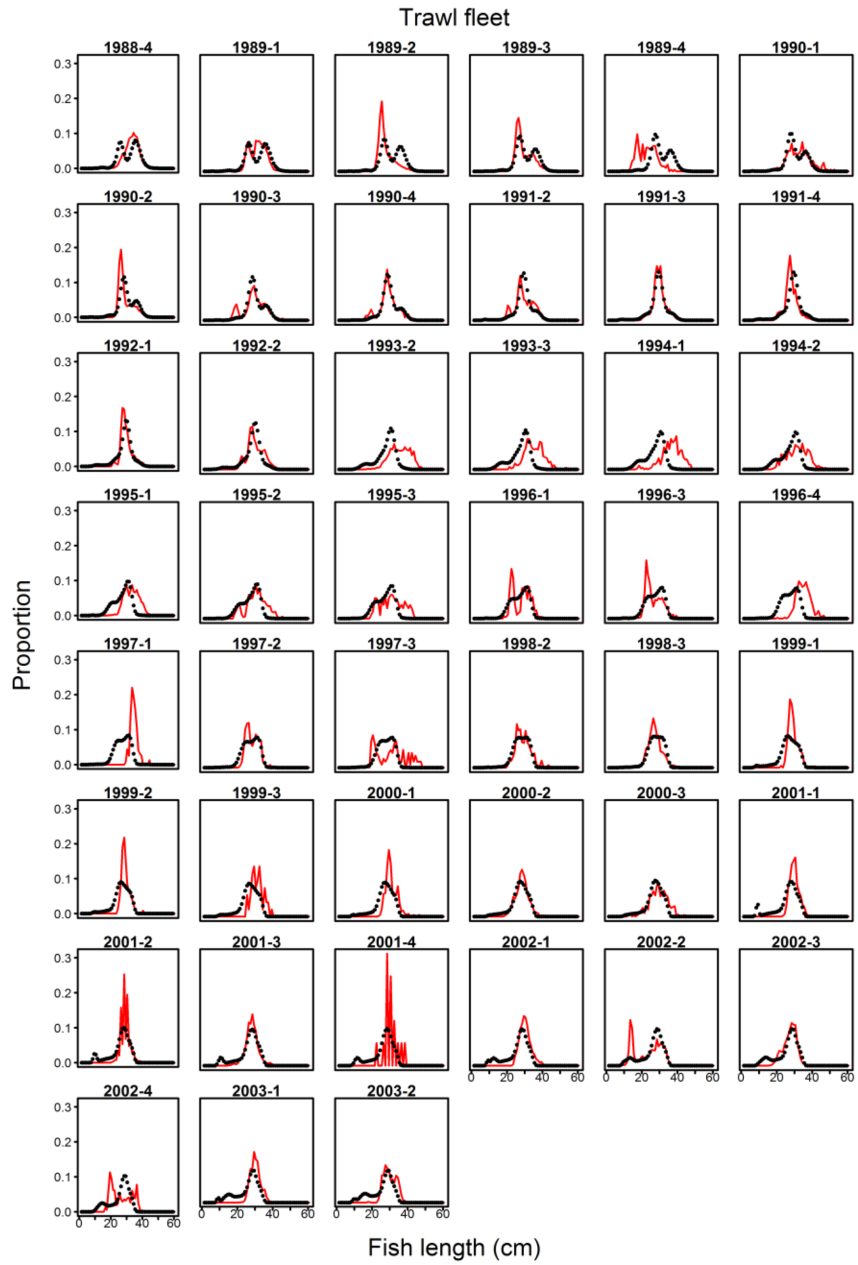

Fig. 16. Size distribution (in proportion relative to 1) of redfish catches in the redfish trawl fleet over the years 1988-2003. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 is winter of 1988). Red lines are the estimated values versus black points which represent the observed data.

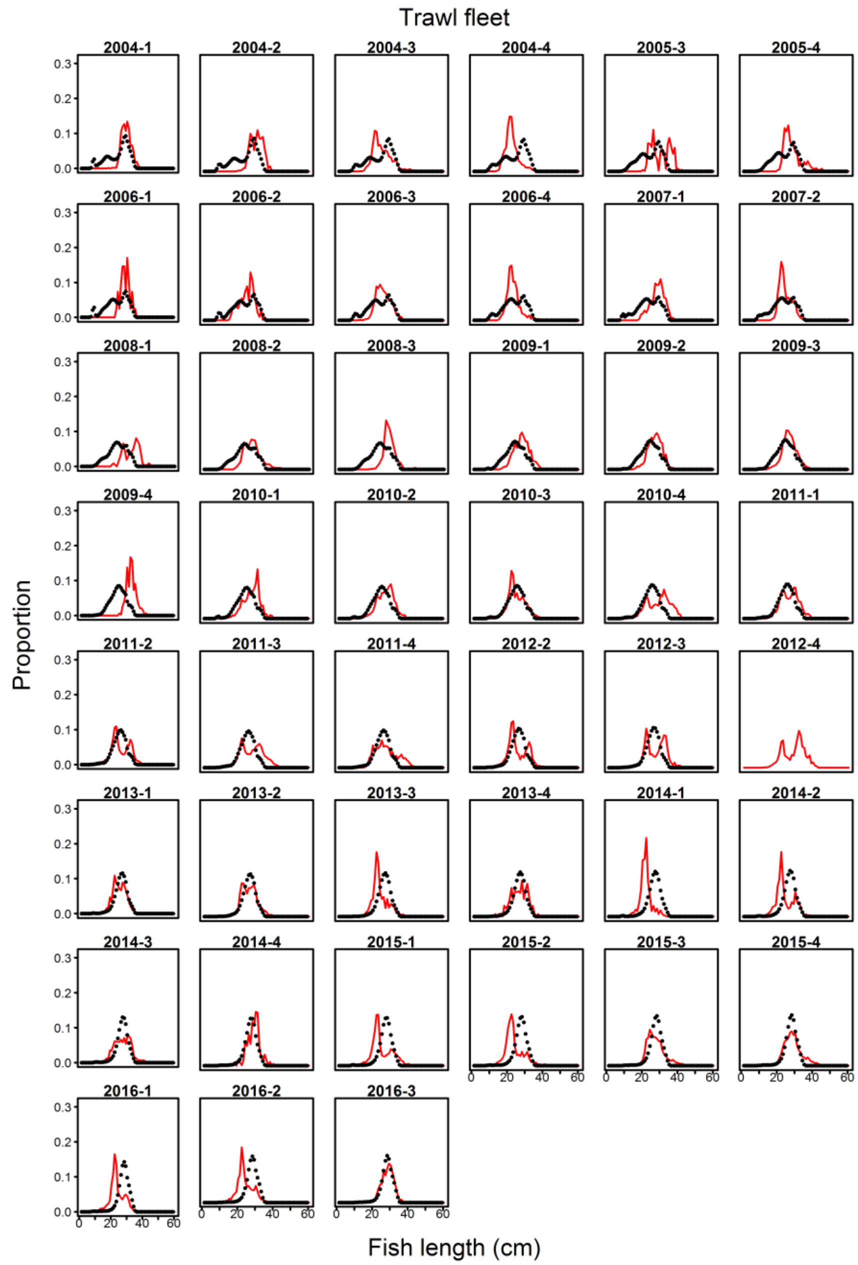

Fig.17. Size distribution (in proportion relative to 1) of redfish catches in the redfish trawl fleet over the years 2003-2016. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 is winter of 1988). Red lines are the estimated values versus black points which represent the observed data.

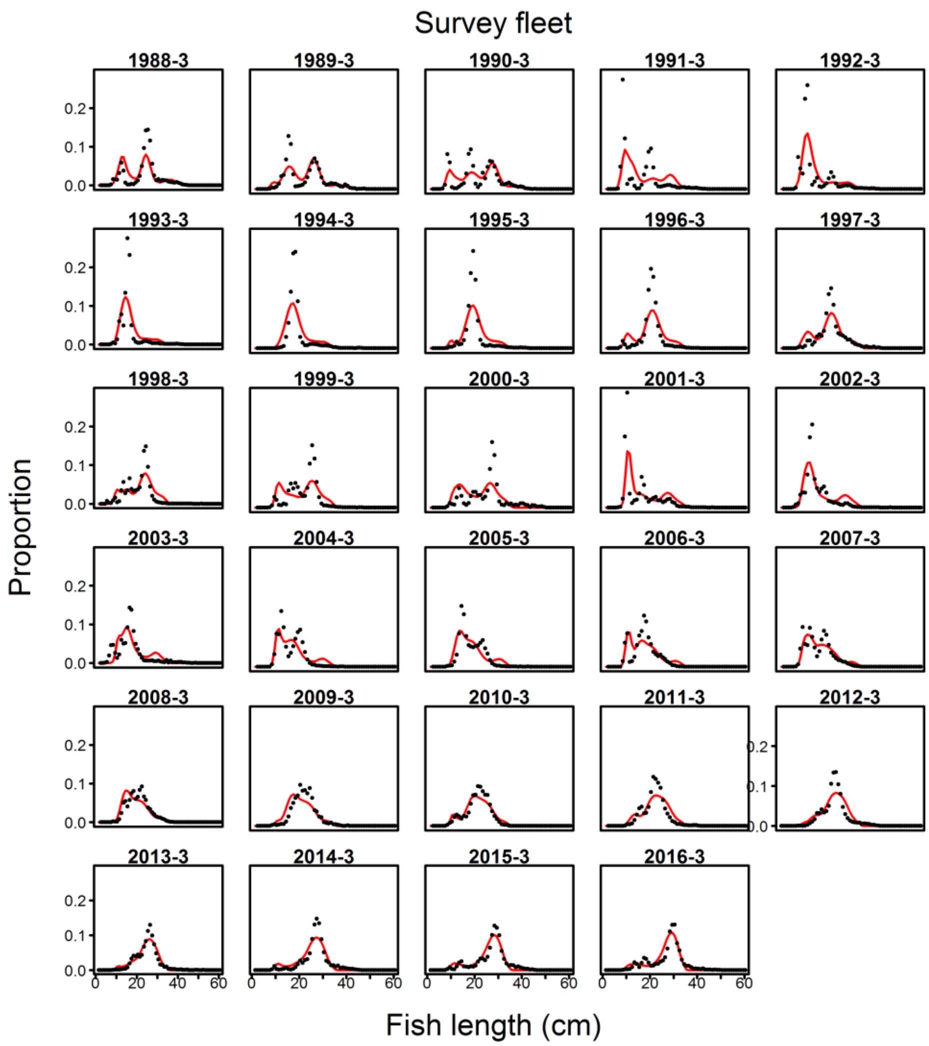

Fig. 18. Size distribution (in proportion relative to 1) of redfish in the survey fleet. The label in each subpanel represents the year (Years: 1988 to 2016). For this fleet the season is always 3, when the survey takes place. Red lines are the estimated values versus black points which represent the observed data.

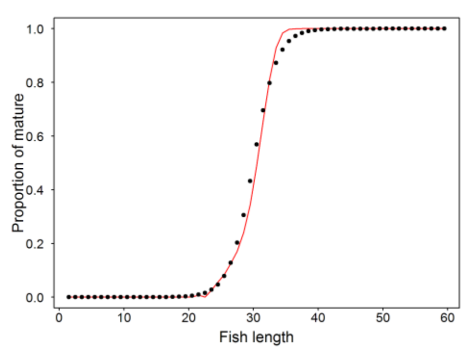

Fig.19. Estimated (red line) and observed (black points) proportion by length of mature female individuals in the redfish stock.

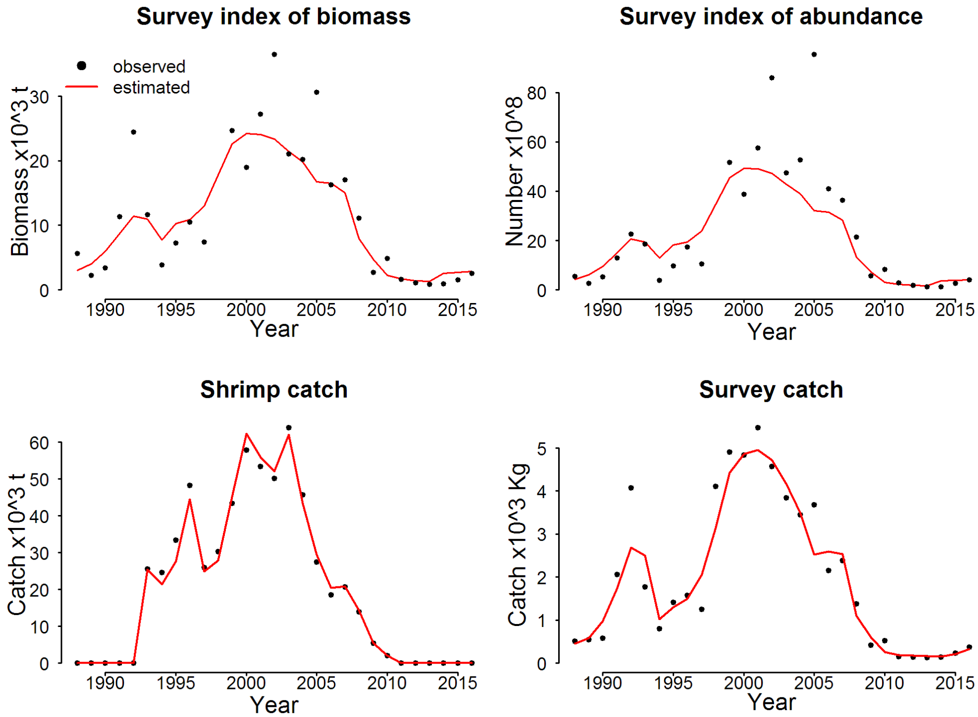

Fig. 20. Shrimp survey indexes (swept area method) of biomass (upper-left panel) and abundance (upper-right), and catch in tones by the international trawl fleet (bottom-left), and in kg for the EU survey fleet (bottom right).

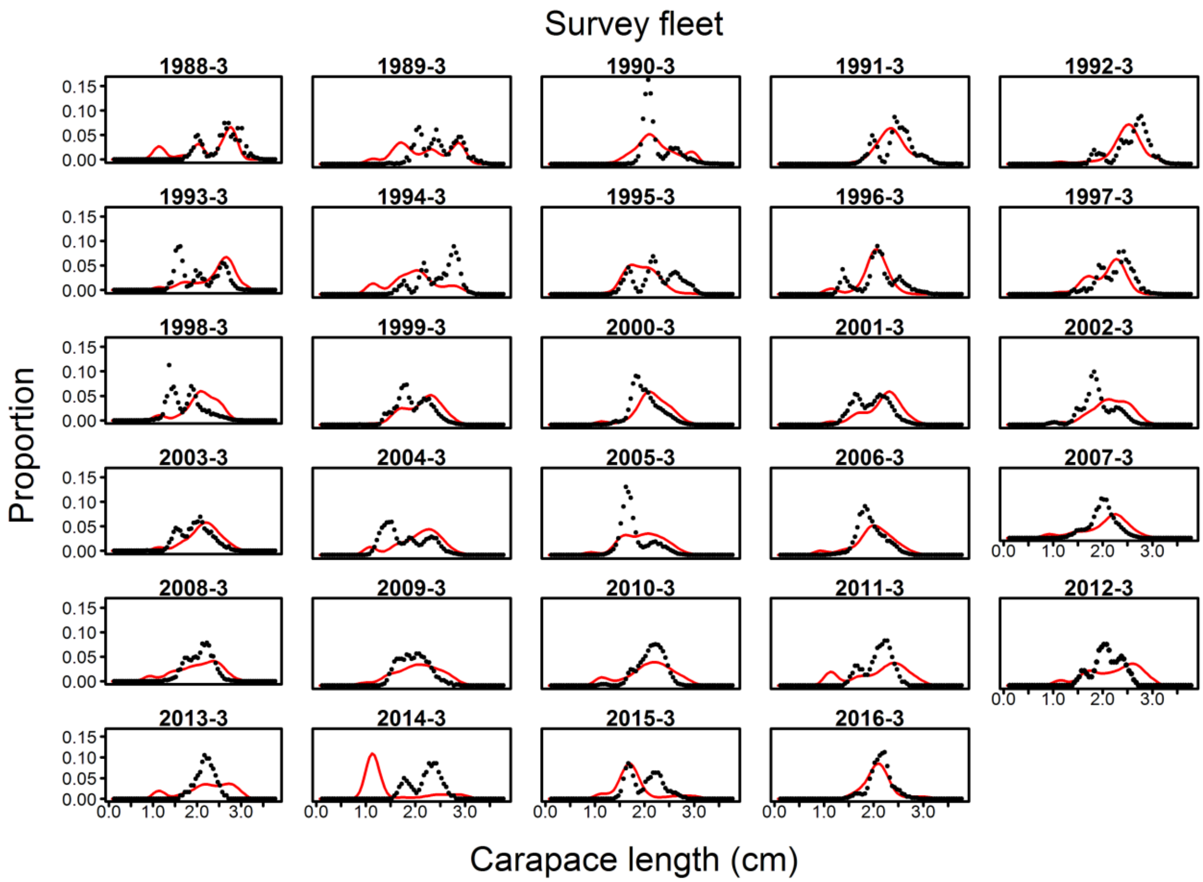

Fig. 21. Distribution by carapace length (in proportion relative to 1) of shrimp in the survey fleet. The label in each subpanel represents the year (Years: 1988 to 2016). For this fleet the season is always 3, when the survey takes place. Red lines are the estimated values versus black points which represent the observed data.

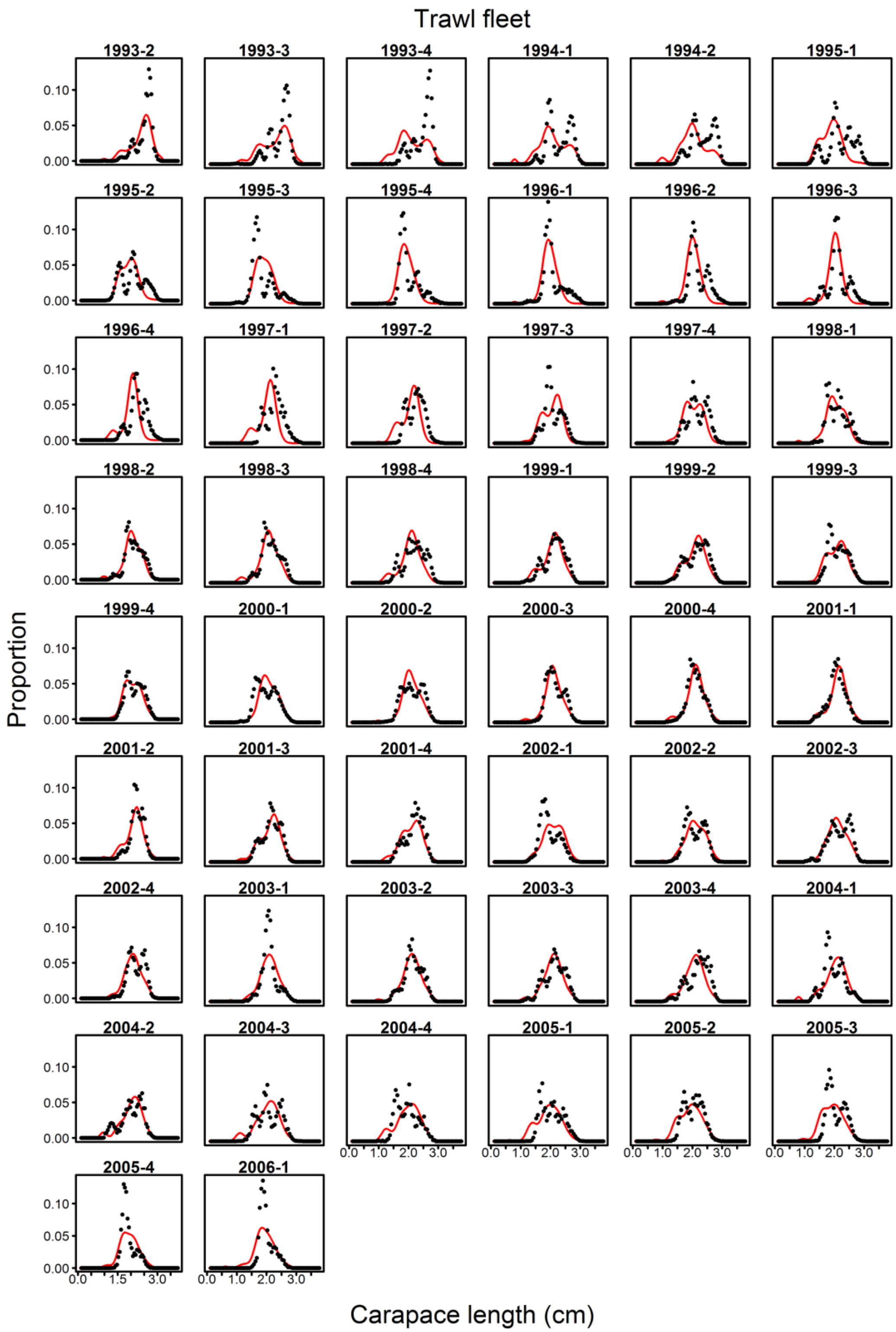

Fig. 22. Distribution by carapace length (in proportion relative to 1) of shrimp catches by the trawl fleets. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 is winter of 1988). Red lines are the estimated values versus black points which represent the observed data.

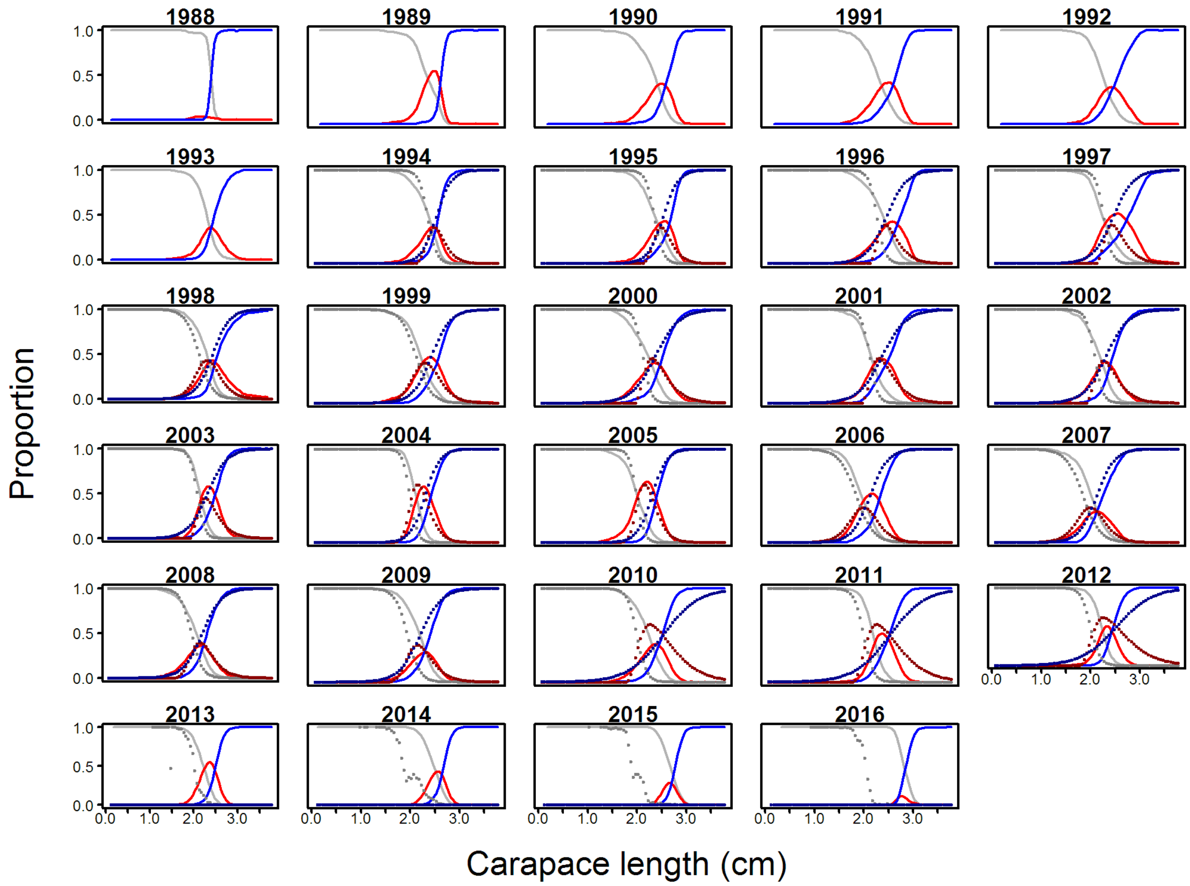

Fig.23. Shrimp sex change and maturity ogives as probability, relative to 1, of being male (grey color), female primiparous (red color) and female multiparous (blue color) with carapace length (in cm). Estimated probabilities by the fit model are represented by continuous lines while the observed proportions are represented by points.

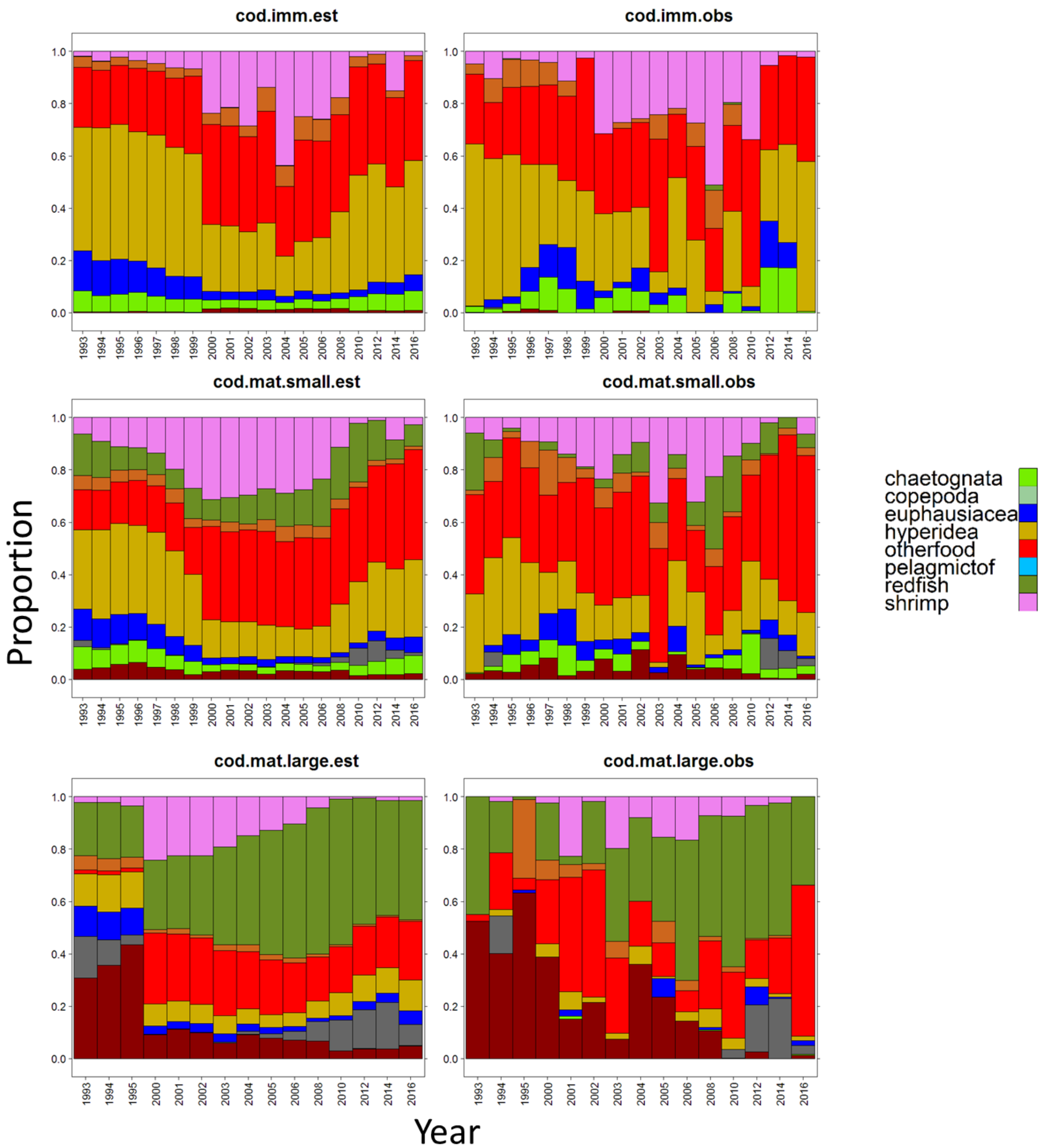

Fig. 24. Model estimated diet (left column) and observed diet during the EU survey (right column) for immature cod (cod.imm), small mature cod (<85cm; cod.mat.small) and large mature cod (>85cm; cod.mat.large), represented as the average proportion (relative to 1) of each prey in the stomach content from 1993 to 2016.

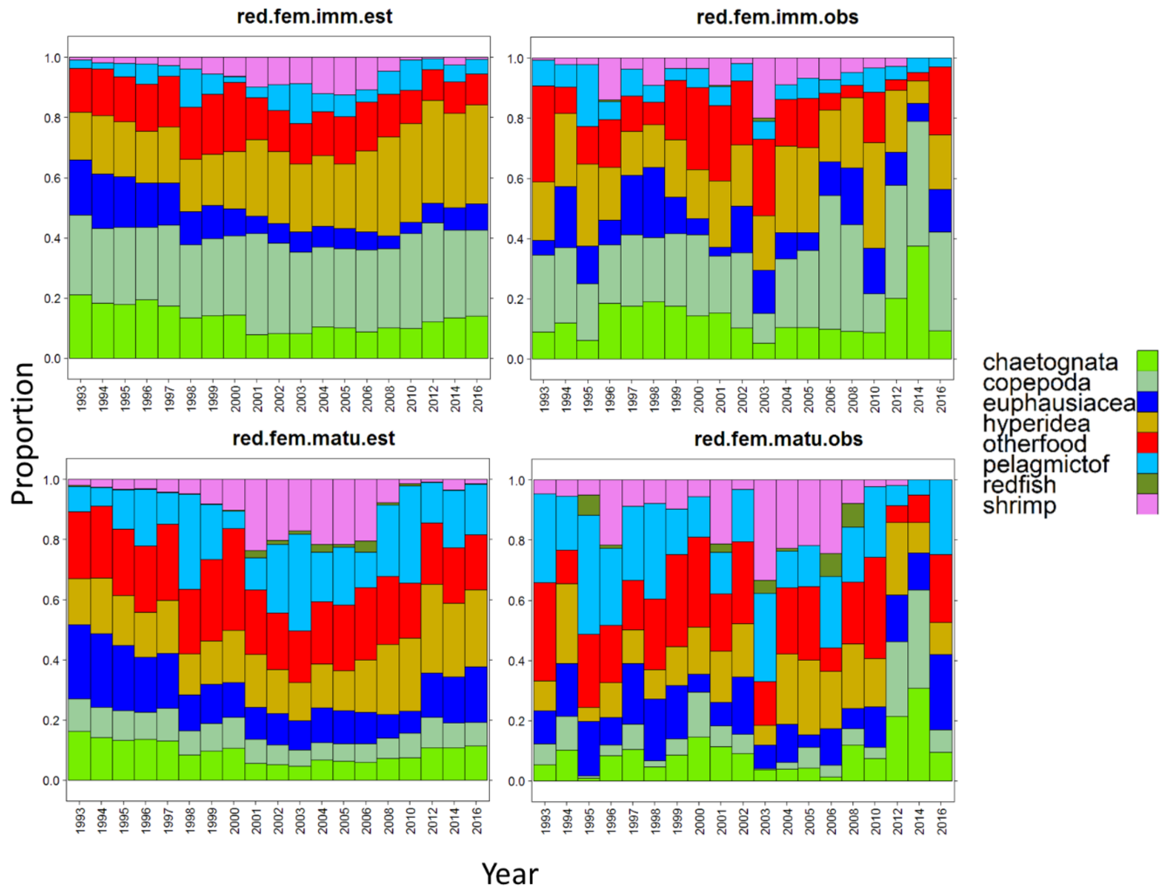

Fig. 25. Model estimated diet (left column) and observed diet during the EU survey (right column) for immature redfish (red.imm) and mature redfish (red.matu), represented as the average proportion (relative to 1) of each prey in the stomach content from 1993 to 2016.

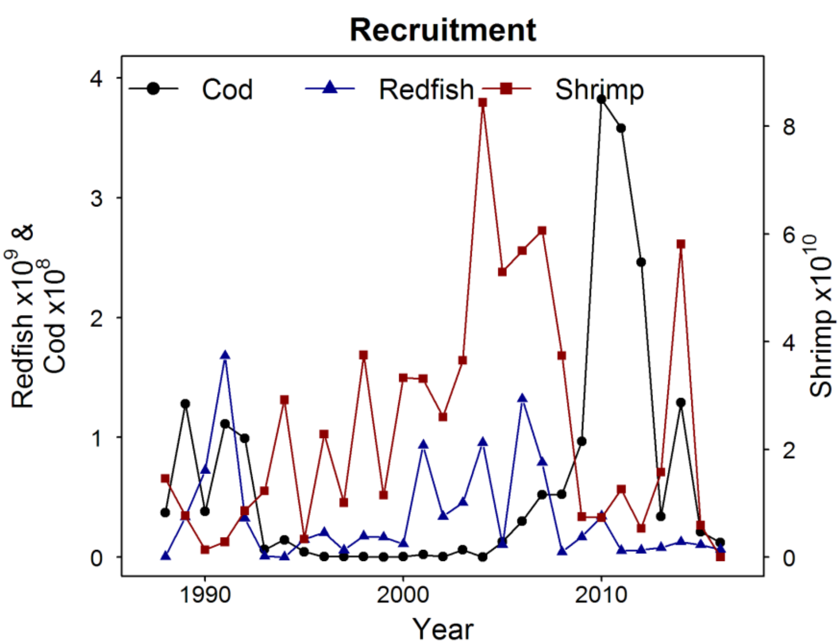

Fig. 26. Annual recruitment at age 1 as estimated by the GADGET model for each of the three stocks.

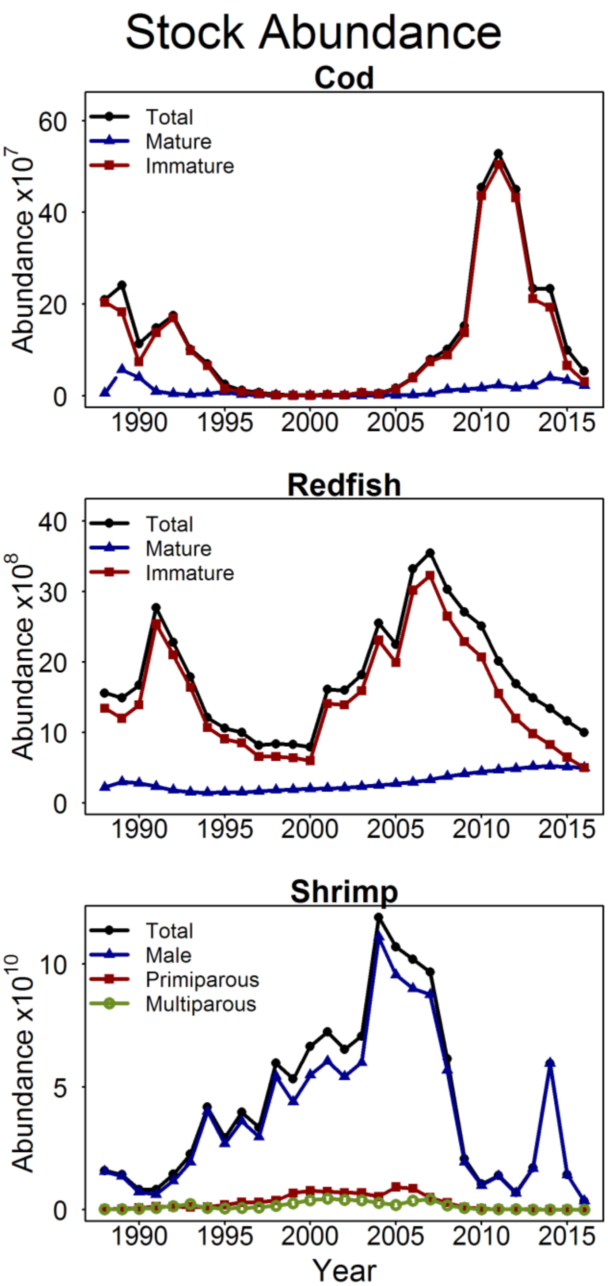

Fig. 27. Annual estimates of stock abundance, total and by maturity stage, for each of the three modeled stock (top: cod, middle: redfish, bottom: shrimp).

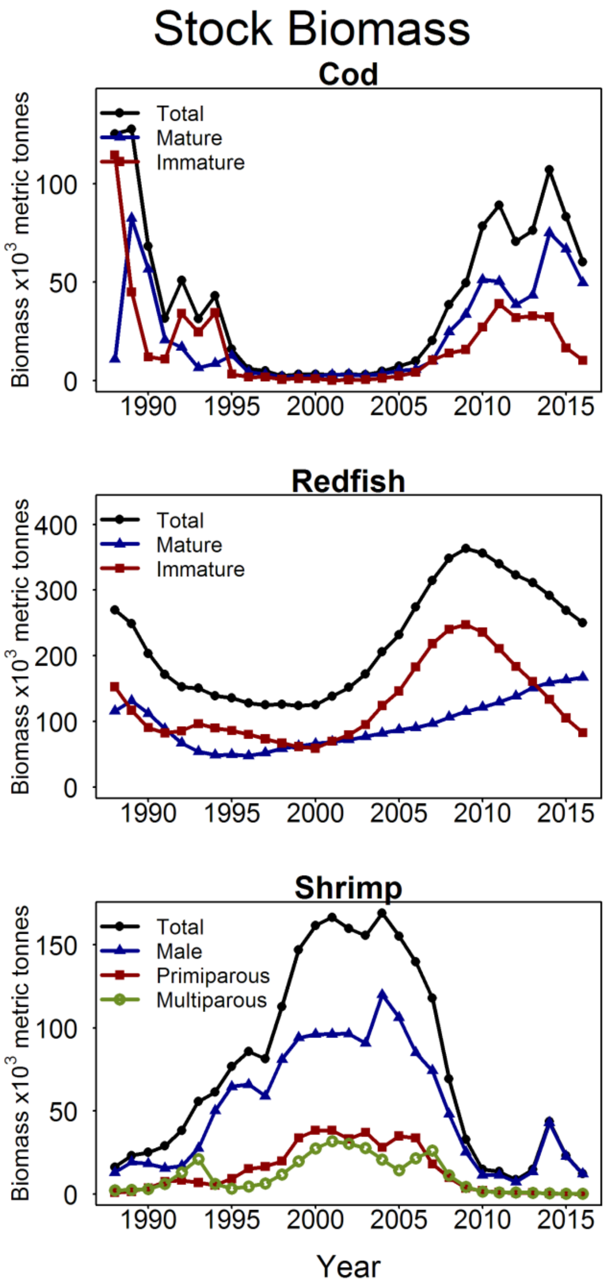

Fig.28. Annual estimates of stock biomass, total and by maturity stage, for each of the three modeled stocks (top: cod, middle: redfish, bottom: shrimp).

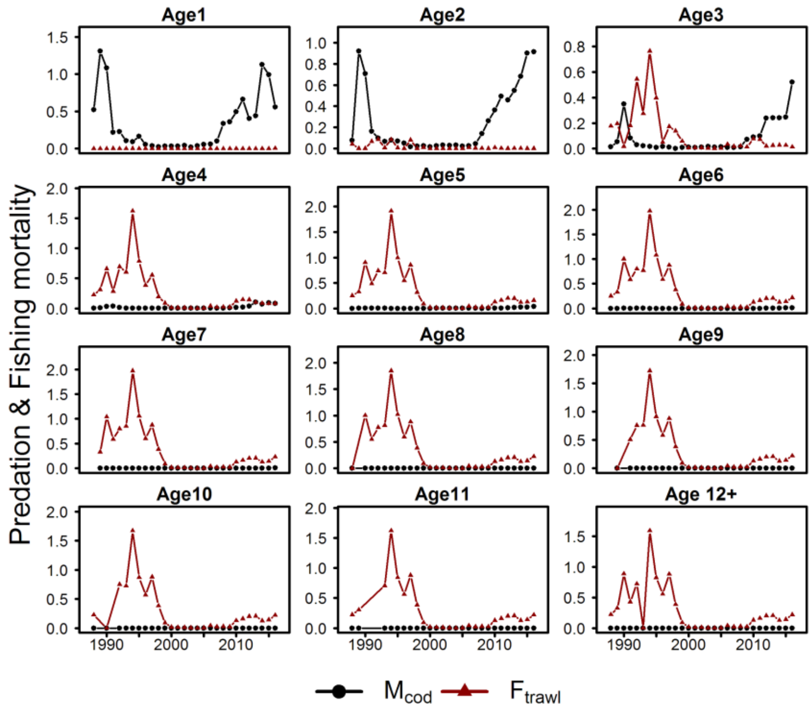

Fig. 29. Predation mortality by cod (M_pred by cod) and fishing mortality by age in the modeled cod stock. The "Age 12+" pannel shows the mortality rates for individuals of age 12 and older.

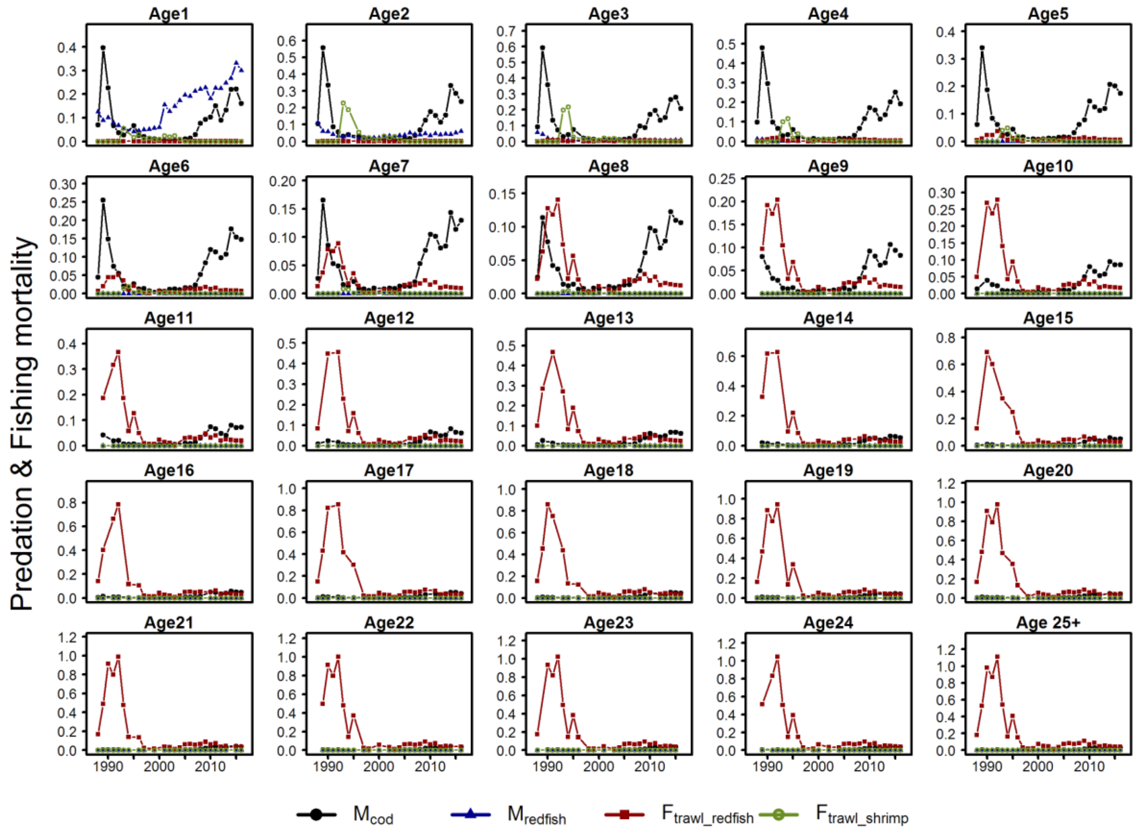

Fig. 30. Predation mortality by age in the modeled redfish stock, by cod (M_pred by cod), by redfish (M_pred by redfish) and fishing mortality by the redfish trawl fleet (F_red_trawl) and the shrimp trawl fishery (F_shrimp_trawl). The "Age 25+" pannel shows the mortality rates for individuals of age 25 and older.

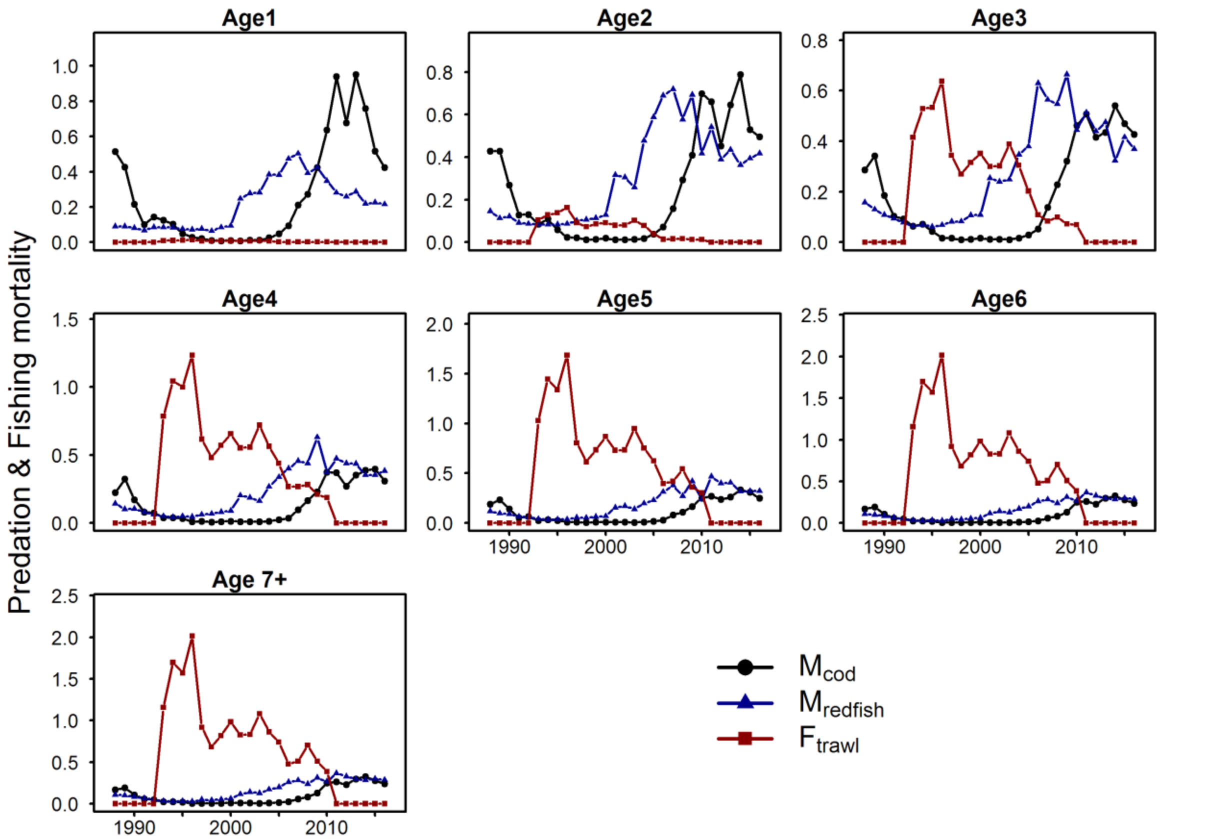

Fig. 31. Predation mortality by cod (M_pred by cod), by redfish (M_pred by redfish) and fishing mortality by the shrimp trawl fleet by age in the modeled shrimp stock.

TABLES

Table 1. List of databases that have been extended to the period 1988-2016 and reviewed. Data sources incorporated by the first time in the GadCap model are also indicated.

Element	Likelihood component	Action	Cod	Redfish	Shrimp
Trawl fishing	Length distribution of catches	Extension and review	X	X	Fishing ban
	Total catch in kg	Extension and review	X	X	Fishing ban
	Seasonal distribution of catches	Extension and review	X	X	Fishing ban
Longline fishing	Length distribution of catches	New inclusion	X		
	Total catch in kg	New inclusion	X		
	Seasonal distribution of catches	New inclusion	X		
EU Survey	Length distribution of catches	Extension and review	X	X	X
	Total catch in kg	Extension and review	X	X	X
	Survey index of biomass	Extension and review	X	X	X
	Survey index of abundance	Extension and review	X	X	X
	Survey index of recruitment abundance	Extension and review	X	X	
	Survey index of abundance by age	Extension and review	X		
Biological information	Age, length, weight, maturity, sex	Extension and review	X*	X*	X
	Stomach content	Extension and review	X	X	
Oceanography	Water temperature	Extension and review			

* This databases were updated only until 2013 due to limited access to the data since 2014.

Table 2. List of components that have been modified or explored for potential modification on GadCap.

Component	Element	Cod	Redfish	Shrimp
Trawl	Selectivity curve	X	X	X
	Annual scaling parameter	X	X	X
Gillnet	Selectivity curve	X		
	Annual scaling parameter	X		
Longline	Selectivity curve	X		
	Annual scaling parameter	X		
EU Survey	Selectivity curve	X	X	X
	Constant scaling parameter	X	X	X
Stock	Growth curves	X	X	
	Density dependent growth	X		X
	Maturation ogives	X	X	
	Sex change ogives			X
	Length-Weight relationship	X	X	
	Separation of redfish species		X	
	Residual Natural Mortality	X		
Trophic interactions	Prey-Predator suitability	X	X	
	Prey-Predator length selectivity curve	X	X	
	Functional relationship type III	X		

Table 3. Model structure, main ecological and biological features for cod stock.

	Immature	Mature_small	Mature_large
Period	1988-2016		
Time step	3 months		
Age range	1-12		
Length range (cm)	1cm-L_{50}^{*}	L_{50}^{*}-85cm	85cm-140cm
Length resolution	1 cm		
Fishing fleets	CT_I; CT_II;CG; CL ; EUs		
Residual mortality	$M_{ages1-12}$=0.35**		
Growth	Von Bertalanffy; annual estimate		
Maturation	Annual maturation ogive		
Maturation date	4th timestep		
Recruitment	Annual estimate		
Age at recruitment	1		

CT_I and CT_II: cod trawl fleet 1988-1998 and 1999-2016 respectively. CG: cod gillnet fleet. CL : cod longline fleet ; EUs: EU survey; L_{50}: Length at 50% probability of maturing.
** L_{50} refers to the maturity ogive defined by two parameters, L50 and α.*
*** Estimated using the catch curves, longevity method and loglikelihood profile. See subtask 2.2 section .*

Table 4. Model structure, main ecological and biological features for redfish stock.

	Male_immature	Male_mature	Female_immature	Female_mature
Period	1988-2016			
Time step	3 months			
Age range	1-25			
Length range (cm)	1cm- L_{50}^{*} male	L_{50}^{*} male-60cm	1cm-L_{50}^{*} fem	L_{50}^{*} fem-60cm
Length resolution (cm)	1 cm			
Fishing fleets	RT_I; RT_II; ST; EUs			
Residual mortality	Age1-10: 0.05*standardized EU survey biomass index of wolfish and Greenland halibut Age 11-16=0.05; Age 17-25: Efimov et al (1986)			
Growth	Von Bertalanffy; 4 periods			
Maturation	One maturation ogive 1988-2016		One maturation ogive 1988-2016	
Maturation date	4th timestep		4th timestep	
Recruitment	Annual estimate		Annual estimate	
Age at recruitment	1		1	

RT_I and RT_II: redfish trawl fleet 1988-1998 and 1999-2016 respectively; ST: Shrimp trawl fleet; EUs: EU survey; L_{50} male and L_{50} fem: Length at 50% probability of maturing for male and female sub-stock respectively.
** L_{50} refers here to the maturity ogive defined by two parameters, L50 and α, fitted separated for males and females.*

Table 5. Model structure, main ecological and biological features for shrimp stock.

	Male	Female_primiparous	Female_multiparous
Period	1988-2016		
Time step	3 months		
Age range	1-7		
Length range (cm)	0.05cm-L_{50sex}*	L_{50sex}*-L_{50mat}*	L_{50mat}*-3.8cm
Length resolution (cm)	0.05		
Fishing fleets	ST; EUs		
Residual mortality	Age1=0.2; Age2-7=0.1		
Growth	Von Bertalanffy; three periods		
Sex change	Bi-annual ogive		
Sex change date	4th timestep		
Maturation		Bi-annual ogive	
Maturation date		4th timestep	
Recruitment	Annual estimate		
Age at recruitment	1		

ST: Shrimp trawl fleet; EUs: EU survey; L50 sex: length at 50% probability change from male to female primiparous. L50 mat: length at 50% probability change from female primiparous to multiparous.
**L50sex and L50mat refers to the sex change (males to female primiparous) and maturity (female primiparous to multiparous change) ogives ogives, defined by parameters L50 and α.*