Multispecies Fisheries Assessment for NAFO

European Maritime and Fisheries Fund (EMFF)

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Multispecies Assessment for NAFO

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2.   EXECUTIVE SUMMARY

Since the creation of the Working Group for Ecosystem Studies and Assessment (WGESA) in NAFO, there have been substantial advances towards the implementation of the roadmap for an Ecosystem Approach to Fisheries (EAF), as for example the calculations of Ecosystem and Fisheries Production Potential (EPP and FPP respectively) and the estimates of natural mortality using a multispecies model. The purpose of this specific contract SC05 is shedding light on the foundations and operationality of the the multispecies approach in the NAFO area, contributing to the development of the technices, with the aim of improving the estate of the fish resources and the sustainability of the exploitation. In order to achieve these goals, the project was subdivided in 6 subtasks.

In the task 1 ("Setting the context"), two main goals were addressed. The first goal was reviewing the strategies developed for the implementation of the multispecies approach worldwide (European Seas, Alaska region and the Conservation of Antarctic Marine Living Resources region (CCAMLR)) and the approaches addressed and the results and conclusions achieved in international projects like MYFISH in the EU or REDUS in Norway. The results of this review showed that in all the management areas studied (European seas, Alaska region and CCAMLR) in first place the institutional objectives and regulations that support the necessary data collection and scientific research. All these areas have developed multispecies models that include the most relevant stocks. The most direct and common application of those multispecies methods has been the estimation of natural mortaility (or total prey consumption) to be use in single species stock assessment or advice (for example in the assessment of north sea cod, Baltic herring, Barents sea capelin, Antarctic krill, etc) . A more advanced approach (developed only in some areas like the North Sea or the Barents Sea) is the estimation of multispecies based biological reference points. However, as shown in the project MYFISH, it is unlikely that stocks with strong technical (mixed fisheries) and biological interactions can all be fished at the F_{MSY} level. It is then necessary the development of alternatives concepts, like the Pretty Good Multiespecies Yield (PGMY) that allow some flexibility when defining reference points in order to allow respecting economic, social and ecological constrains. All the studied areas promoted activities and project structures that promoted the inclusion of stakeholders in the process of selecting management strategies. The second goal of task 1 was the revision of the NAFO Ecosystem Approach to Fisheries (EAF) roadmap and the suitability of the Flemish Cap as a case study for the development of the multispecies approach in NAFO. The NAFO EAF roadmap was developed in 2010, around a 3 tiers structure (ecosystem, multispecies and single species tiers) and requires identifying the ecological subunits, implementing a spectrum of different multispecies and full ecosystem models, and finally evaluate the management options using existing management tools for specifying ecosystem exploitation rates. The suitability of the Flemish Cap as a case study for the implementation of the multispecies approach in NAFO was based in the independent dynamic of Flemish Cap demersal stocks like cod, redfish and shrimp from the same species in the Grand Banks and Newfoundland shelf due to the high degree of isolation. The relative simplicity of the trophic web, with a low number of interactions but of strong entity, strong knowledge about the functioning of the ecosystem, and the existence of a multispecies model (GadCap) developed for cod, redfish and shrimp were also considered very important reasons to consider the Flemish Cap as the best candidate fishing ground in NAFO for developing a multispecies approach.

In Task 2 ("updating and improving GadCap"), the multispecies model GadCap, developed in Gadget, which covers the period 1988–2012, was updated and several components were improved. All the necessary data sources (EU survey indices, length distribution, diet

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composition, total catches and length distribution from trawl, gillnet and longline fleets, etc) were updated until year 2016 and reviewed to ensure comparability with the single species stock assessment. The model structure was reviewed and improved, including a new fleet (cod longline fleet), and improving the maturity and growth models for all the three stocks, and trophic interactions (specially the prey-predator length relationships). The results highlight the interdependent dynamic of cod, redfish and shrimp stocks and reveals strong interactions among recruitment, fishing, and predation (including cannibalism). These drivers have shown marked changes in their relative importance by species, age, and length over time, producing a transition from a traditional redfish- and cod-dominated system in the early 1990s to an intermediate shrimp and other fish species state by the late 1990s and in turn back to something close to the initial state by the late 2000s. The multispecies model developed in this paper shows that disregarding the species interactions would lead to serious underestimates of natural mortality and overestimations of the exploitable biomass and highlights the need to move beyond single-species management in this highly coupled ecosystem. The diagnostics showed that the model simulated very closely the observed values, and hence supported the use of the improved model for further applications in Tasks 3 and 4.

In Task 3 ("Practical implementation of the multispecies approach") the updated and improved multispecies model GadCap was used for practical purposes in fisheries advice. The first approach was using the estimates of natural mortality at age as input in the Flemish Cap cod stock assessment model during the benchmark process that took place as part of the SC03 project *"Support to a robust model assessment, benchmark and development of a management strategy evaluation for cod in NAFO Division 3M".* The results of this subtask 3.1 allow concluding that there exist a strong variability in the predation mortality on cod, both at age and over time, which support the need of considering alternative estimates of natural mortality for a proper assessment of the Flemish Cap cod. A more advanced implementation of the multispecies approach was developed in Tasks 3.2 and 3.3. In Task 3.2 potential candidate HCRs were designed with single species criteria, but also under multispecies criteria by selecting all those combinations of F (for cod, redfish and shrimp) that resulted in cod, redfish and shrimp above Blim in the long term (all the three stocks at the same time or alternatively) when running long term deterministic simulations using GadCap. In Task 3.3, by the first time in NAFO, an MSE framework with a multispecies model (GadCap) as operating model was developed. This multispecies MSE framework was used to assess the performance of the selected candidate combinations of HCRs for the three stocks at the same time when the uncertainty in the recruitment process and the assessment error is accounted for. The results of this Task 3 allow concluding that combinations of HCRs designed under a single species approach were not precautionary for cod and shrimp in a framework where species interactions are directly modelled and simulated. In addition, the risk analysis of HCRs combinations defined with multispecies criteria indicated that it is not possible maintaining the 3 stocks above B_{lim} at the same time. The reasons are the strong trophic interactions between the three stocks. Trying to maintain shrimp above Blim requires excessive fishing pressure on cod and redfish in order to reduce predation mortality, and this involves high risk of collapse on cod. On the contrary, maintaining cod above Blim involves high predation and high risk of collapse on shrimp and redfish. As a solution, disregarding one stock may allow finding precautionary multispecies reference points for the other stocks. Disregarding cod would result on fishing redfish within precautionary levels. Disregarding redfish would allow fishing cod without collapsing the stock. However, this was not possible for shrimp. It is probable that the uncertainty in the recruitment process, taken randomly in this study have been determinant on this. Precautionary HCRs for two stocks at once were only found when shrimp SSB in relation to B_{lim} was disregarded. The estimated yield in the long term indicates that this strategies are in the line of the yields obtained for both stocks since the reopening of the cod fishery in

2010. The results showed that the two stages HCRs for cod reduces predation and increases probability of cod and redfish being above B_{lim}.

In the Task 4 ("Economic analysis of trade-offs"), the existing bioeconomic models were studied in first place, and the needs for the development of an integrated bioeconomic analysis in the NAFO 3M are were studied. The results of this subtask allow concluding that none of the existing models fit to the goal of this project of a full integrated bioeconomic analysis of multispecies HCRs for the Flemish Cap. However, it was found during the review, that currently an integrated framework that includes GADGET and FLBEIA is being developed at the IMR in Bergen (Norway). This combination of an ecological and economic models defining the operating model in an MSE framework is the appropriate option for NAFO bioeconomic advice. The second part of Task 4 a bioeconomic analysis of selected multispecies HCRs was performed with the intention of assessing the trade offs in the economic indicators, the time time frame (short versus long term), variance in catches and revenues and fleets effort. Despite the limitations in the economic modelling approach it can be concluded that while one HCR can be the most appropiate (in terms of economic performance) for one fleet (or country) it may not be the best option for other EU fleets. In this study, a best option at the same time for all EU fleets fishing in Flemish Cap was not found. The same conclusion is obtained when long term vs short term economic indicators are considered or even when indicator's variability is considered. However, it was clear that when the state of the shrimp stock in relation to SSB was disregarded (not penalized if shrimp SSB went below B_{lim}) the 2 stage HCR produced clearly better results than the 1 stage HCR in all the dimensions studied (fleet, time and variabibility).

As part of Task 5 ("Outreach activities"), the project SC05 and the results of the previous tasks were presented to the NAFO scientific community by attending the meetings of the WGESA in 2017 and 2018, and presentations via webex during the NAFO SC June meeting on 2018. In addition, a two days workshop was celebrated in Vigo, on January 2018, where all the relevant stakeholders (fishing industry, managers and scientists) were invited. During this workshop, the foundations of the multispecies approach, the methodologies and data requirements, as well as work, difficulties and results obtained in this project SC05 were presented and discussed with the stakeholders during the plenary sessions of this workshop.

In Task 6 ("Potential future research") the future research lines of work were suggested in order to support the development of the multispecies approach in the NAFO area. First a summary of advances achieved in this project and knowledge on the multispecies approach gained from other parts of the world. Next, building on gaps and synergies identified in previous sections, recommendations on next steps are provided to operationalise the multispecies approach in the context of the NAFO roadmap for an EAF.

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3. SOMMAIRE EXECUTIF

Depuis la création du Groupe de Travail pour l'étude et l'Évaluation des Écosystèmes (WGESA) de l'OPANO, des progrès substantiels ont été réalisés dans la mise en œuvre de la feuille de route pour une approche écosystémique des pêches (AEP), comme par exemple le calcul du Potentiel de Production des Écosystèmes et des Pêches (EPP et FPP respectivement) et les estimations de la mortalité naturelle en utilisant un modèle multiespèces. L'objectif de ce Contrat Spécifique SC05 est de mettre en lumière les fondements et le caractère opérationnel de l'approche multi-espèces dans la zone OPANO, en contribuant au développement des techniques, dans le but d'améliorer le patrimoine des ressources halieutiques et la durabilité de l'exploitation. pour atteindre ces objectifs, le projet a été subdivisé en 6 sous-tâches.

Dans la Tâche 1 (" Établir le contexte "), deux objectifs principaux ont été abordés. Le premier objectif était de passer en revue les stratégies élaborées pour la mise en œuvre de l'approche multispécifique à l'échelle mondiale (mers européennes, région de l'Alaska et Conservation de la Faune et de la Flore Marines de l'Antarctique (CCAMLR)), les approches adoptées et les résultats et conclusions des projets internationaux comme MYFISH en UE ou REDUS en Norvège. Les résultats de cette étude ont montré que dans toutes les zones de gestion étudiées (mers européennes, région de l'Alaska et CCAMLR), les objectifs institutionnels et les réglementations qui soutiennent la collecte de données et la recherche scientifique nécessaires sont en première place. Toutes ces régions ont développé des modèles multi-espèces qui incluent les stocks les plus pertinents. L'application la plus directe et la plus courante de ces méthodes multispécifiques a été l'estimation de la mortalité naturelle (ou consommation totale de proies) à utiliser pour l'évaluation ou la consultation de stocks d'une seule espèce (par exemple, pour l'évaluation de la morue de la mer du Nord, du hareng de la Baltique, du capelan de Barents, du krill antarctique, etc). Une approche plus avancée (développée seulement dans certaines régions comme la mer du Nord ou la mer de Barents) est l'estimation de points de référence biologiques basés sur plusieurs espèces. Toutefois, comme le montre le projet MYFISH, il est peu probable que les stocks ayant de fortes interactions techniques (pêcheries mixtes) et biologiques puissent tous être pêchés au niveau de la Fmsy. Il est alors nécessaire de développer des concepts alternatifs, comme le Pretty Good Multiespecies Yield (PGMY) qui permettent une certaine flexibilité dans la définition des points de référence afin de permettre de respecter les contraintes économiques, sociales et écologiques. Toutes les zones étudiées ont promu des activités et des structures de projet qui ont favorisé l'inclusion des parties prenantes dans le processus de sélection des stratégies de gestion. Le deuxième objectif de la Tâche 1 était la Révision de la feuille de route de l'Approche Écosystémique des Pêches (AEP) de l'OPANO et la pertinence de Flemish Cap comme cas d'étude pour l'élaboration de l'approche multispécifique de l'OPANO. La feuille de route de l'AEP de l'OPANO a été élaborée en 2010, autour d'une structure à trois niveaux (écosystème, multi-espèces et niveaux d'espèces uniques) et nécessite l'identification des sous-unités écologiques, la mise en œuvre d'un éventail de différents modèles multi-espèces et d'écosystèmes complets, et enfin l'évaluation des options de gestion en utilisant les outils existants pour spécifier les taux d'exploitation des écosystèmes. La pertinence de Flemish Cap comme cas d'étude pour la mise en œuvre de l'approche multispécifique de l'OPANO était fondée sur la dynamique indépendante des stocks démersaux du Flemish Cap comme la morue, le sébaste et la crevette de la même espèce sur les Grands Bancs et sur le plateau de Terre-neuve en raison du degré élevé d'isolement. La relative simplicité du réseau trophique, avec un faible nombre d'interactions mais une entité forte, une bonne connaissance du fonctionnement de l'écosystème et l'existence d'un modèle multi-espèces (GadCap) développé pour la morue, le sébaste et la crevette ont également été considérées comme des raisons très importantes pour

considérer le Flemish Cap comme la meilleure zone de pêche candidate de l'OPANO pour développer une approche multispécifique.

Dans la Tâche 2 ("Mettre à jour et améliorer GadCap"), le modèle multi-espèces GadCap, développé dans Gadget, qui couvre la période 1988-2012, a été mis à jour et plusieurs composants ont été améliorés. Toutes les sources de données nécessaires (indices d'enquête de l'UE, distribution de la longueur, composition du régime alimentaire, captures totales et distribution de la longueur des flottes de chaluts, de filets maillants et de palangriers, etc.) ont été mises à jour jusqu'en 2016 et revues pour assurer leur comparabilité avec l'évaluation du stock de chaque espèce. la structure du modèle a été revue et améliorée, y compris une nouvelle flottille (flottille palangrière de morue) et l'amélioration des modèles de maturité et de croissance pour les trois stocks, ainsi que les interactions trophiques (en particulier les relations proies-prédateurs de longueur). Les résultats mettent en évidence la dynamique interdépendante des stocks de morue, de sébaste et de crevette et révèlent de fortes interactions entre le recrutement, la pêche et la prédation (notamment le cannibalisme). Ces facteurs ont connu des changements marqués dans leur importance relative selon l'espèce, l'âge et la durée au fil du temps, ce qui a entraîné une transition d'un système traditionnel dominé par le sébaste et la morue au début des années 1990 puis à un état proche de l'état initial à la fin des années 2000. Le modèle multi-espèces développé dans cet article montre qu'ignorer les interactions entre les espèces conduirait à de sérieuses sous-estimations de la mortalité naturelle et à des surestimations de la biomasse exploitable et souligne la nécessité d'aller au-delà de la gestion par espèce unique dans cet écosystème fortement couplé. Les diagnostics ont montré que le modèle simulait de très près les valeurs observées et qu'il favorisait donc l'utilisation du modèle amélioré pour d'autres applications dans les Tâches 3 et 4.

Dans la Tâche 3 ("Mise en œuvre pratique de l'approche plurispécifique"), le modèle plurispécifique actualisé et amélioré GadCap a été utilisé à des fins pratiques dans les avis sur la pêche. La première approche consistait à utiliser les estimations de la mortalité naturelle selon l'âge comme données d'entrée dans le modèle d'évaluation des stocks de morue du Flemish Cap au cours du processus de référence qui a eu lieu dans le cadre du projet SC03 "Support to a robust model assessment, benchmark and development of a management strategy evaluation for cod in NAFO Division 3M". Les résultats de cette sous-tâche 3.1 permettent de conclure qu'il existe une forte variabilité dans la mortalité par prédation de la morue, tant à l'âge qu'au fil du temps, ce qui confirme la nécessité d'envisager d'autres estimations de la mortalité naturelle pour une évaluation appropriée de la morue du Flemish Cap. Une mise en œuvre plus avancée de l'approche multispécifique a été développée dans les Tâches 3.2 et 3.3. Dans le cadre de la Tâche 3.2, les HRC candidats potentiels ont été conçus en fonction de critères propres à une seule espèce, mais aussi de critères multispécifiques en sélectionnant toutes les combinaisons de F (pour la morue, le sébaste et les crevettes) qui ont abouti à long terme à des biomasses de morue, de sébaste et de crevette supérieures à Blim (les trois stocks en même temps ou alternativement) lors de simulations déterministes à long terme utilisant GadCap. Dans la Tâche 3.3, pour la première fois à l'OPANO, on a élaboré un cadre de travail MSE sur les TPE avec un modèle multi-espèces (GadCap) comme modèle opérationnel. Ce cadre MSE multi-espèces a été utilisé pour évaluer la performance des combinaisons candidates sélectionnées de HCR pour les trois stocks en même temps, lorsque l'incertitude du processus de recrutement et l'erreur d'évaluation sont prises en compte. Les résultats de cette Tâche 3 permettent de conclure que les combinaisons de HCR conçues dans le cadre d'une approche par espèce unique n'étaient pas prudentes pour la morue et la crevette dans un cadre où les interactions entre espèces sont directement modélisées et simulées. En outre, l'analyse de risque des combinaisons de HCR définies avec des critères multi-espèces a indiqué qu'il n'est pas possible de maintenir les 3

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stocks au-dessus de Blim en même temps. Les raisons en sont les fortes interactions trophiques entre les trois stocks. Essayer de maintenir les crevettes au-dessus de Blim exige une pression de pêche excessive sur la morue et le sébaste afin de réduire la mortalité par prédation, ce qui implique un risque élevé d'effondrement sur la morue. Au contraire, le maintien de la morue au dessus de Blim entraîne une prédation élevée et un risque élevé d'effondrement des stocks de crevettes et de sébastes. Comme solution, le fait de ne pas tenir compte d'un stock peut permettre de trouver des points de référence multispécifiques de précaution pour les autres stocks. Si l'on ne tient pas compte de la morue, la pêche du sébaste serait pratiquée à des niveaux de précaution. Ne pas tenir compte du sébaste permettrait de pêcher la morue sans effondrer le stock. Cependant, cela n'a pas été possible pour les crevettes. Il est probable que l'incertitude du processus de recrutement, pris au hasard dans cette étude, a été déterminante à cet égard. Des HCR de précaution pour deux stocks à la fois n'ont été trouvés que lorsque la SSB de la crevette par rapport à Blim n'a pas été prise en compte. Le rendement estimé à long terme indique que ces stratégies sont dans la ligne des rendements obtenus pour les deux stocks depuis la réouverture de la pêche à la morue en 2010. Les résultats ont montré que les HCR en deux étapes pour la morue réduisent la prédation et augmentent la probabilité que la morue et le sébaste soient au-dessus de Blim.

Dans la Tâche 4 ("Analyse économique des compromis"), les modèles bioéconomiques existants ont été étudiés en premier lieu, et les besoins pour le développement d'une analyse bioéconomique intégrée dans l'OPANO 3M ont été étudiés. Les résultats de cette sous-tâche permettent de conclure qu'aucun des modèles existants ne correspond à l'objectif de ce projet d'analyse bioéconomique intégrée complète des HCR multi-espèces pour le Flemish Cap. Toutefois, il a été constaté au cours de l'examen qu'un cadre intégré incluant GADGET et FLBEIA est actuellement en cours d'élaboration à l'IMR de Bergen (Norvège). Cette combinaison d'un modèle écologique et d'un modèle économique définissant le modèle d'exploitation dans un cadre de MSE est l'option appropriée pour les conseils bioéconomiques de l'OPANO. La deuxième partie de la Tâche 4 consistait en une analyse bioéconomique d'une sélection de HCR multi-espèces dans le but d'évaluer les compromis entre les indicateurs économiques, le calendrier (à court terme et à long terme), la variance des prises et des revenus et l'effort des flottilles. Malgré les limites de l'approche de modélisation économique, on peut conclure que si un HCR peut être le plus approprié (en termes de performance économique) pour une flotte (ou un pays), il peut ne pas être la meilleure option pour les autres flottes de l'UE. Dans cette étude, la meilleure option n'a pas été trouvée pour toutes les flottes de l'UE pêchant dans le Flemish Cap au même moment. La même conclusion s'applique aux indicateurs économiques à long terme par rapport à ceux à court terme ou même à la variabilité de l'indicateur. Cependant, il était clair que lorsque l'état du stock de crevettes par rapport à la SSB n'était pas pris en compte (pas pénalisé si la SSB de la crevette était inférieure à Blim), le HCR en 2 étapes produisait des résultats nettement meilleurs que le HCR en 1 étape dans toutes les dimensions étudiées (flotte, temps et variabiité).

Dans le cadre de la Tâche 5 ("Activités de sensibilisation"), le projet SC05 et les résultats des tâches précédentes ont été présentés à la communauté scientifique de l'OPANO en participant aux réunions du Groupe de travail WGESA en 2017 et 2018, et aux présentations via webex lors de la réunion de juin 2018. En outre, un atelier de deux jours a été organisé à Vigo, en janvier 2018, où tous les acteurs concernés (secteur de la pêche, gestionnaires et scientifiques) ont été invités. Au cours de cet atelier, les fondements de l'approche multi-espèces, les méthodologies et les besoins en données, ainsi que les travaux, les difficultés et les résultats obtenus dans le cadre du projet SC05 ont été présentés et discutés avec les parties prenantes lors des sessions plénières de cet atelier.

Dans la Tâche 6 ("Recherche future potentielle"), les axes de recherche futurs ont été suggérés afin de soutenir le développement de l'approche multi-espèces dans la zone OPANO. Tout d'abord, un résumé des progrès réalisés dans le cadre de ce projet et des connaissances sur l'approche multi-espèces acquises dans d'autres parties du monde. Ensuite, en s'appuyant sur les lacunes et les synergies identifiées dans les sections précédentes, des recommandations sur les prochaines étapes sont fournies pour rendre opérationnelle l'approche multispécifique dans le contexte de la feuille de route de l'OPANO pour un AEP.

4.   RESUMEN EJECUTIVO

Desde la creación del Grupo de Trabajo para Estudios y Evaluación de Ecosistemas (WGESA) en NAFO, ha habido avances sustanciales hacia la implementación de la hoja de ruta para un Enfoque de Ecosistemas para la Pesca (EEP), como por ejemplo los cálculos del Potencial de Producción de Ecosistemas y Pesquerías. (EPP y FPP, respectivamente) y las estimaciones de mortalidad natural utilizando un modelo multiespecífico. El propósito de este contrato específico SC05 es arrojar luz sobre los fundamentos y la operatividad del enfoque multiespecífico en el área NAFO, contribuyendo al desarrollo de las técnicas, con el objetivo de mejorar el patrimonio de los recursos pesqueros y la sostenibilidad de la explotación. Para lograr estos objetivos, el proyecto se subdividió en 6 subtareas.

En la Tarea 1 ("Contexto científico"), se abordaron dos objetivos principales. El primer objetivo fue revisar las estrategias desarrolladas para la implementación del enfoque multiespecífico en todo el mundo (mares europeos, la región de Alaska y la Organización para la Conservación de los recursos vivos marinos antárticos (CCAMLR)), y los enfoques abordados y los resultados y conclusiones alcanzados en proyectos internacionales como MYFISH en la UE o REDUS en Noruega. Los resultados de esta revisión mostraron que en todas las áreas de manejo estudiadas (mares europeos, región de Alaska y CCAMLR), en primer lugar se desarrollaron los objetivos institucionales y las regulaciones que respaldan la recopilación de datos necesarios y la investigación científica. Todas estas áreas han desarrollado modelos multiespecíficos que incluyen las interacciones ecológicas más importantes. La aplicación más directa y común de estos métodos multiespecíficos ha sido la estimación de la mortailidad natural (o el consumo total de presas) para su uso en la evaluación o asesoramiento monoespecífico (por ejemplo, en la evaluación de bacalao del mar del Norte, el arenque del Báltico, el capelán del mar de Barents, o el Krill antártico). Un enfoque más avanzado (desarrollado solo en algunas áreas como el Mar del Norte o el Mar de Barents) es la estimación de puntos de referencia biológicos basados en modelos multiespecíficos. Sin embargo, como se muestra en el proyecto MYFISH, es poco probable que las poblaciones con interacciones técnicas notables (pesquerías mixtas) e interacciones biológicas notables se puedan capturar todas a nivel de FMSY. Por esto, es necesario el desarrollo de conceptos alternativos, como Pretty Good Multispecies Yield (PGMY), que permite cierta flexibilidad al definir puntos de referencia para cumplir con las restricciones económicas, sociales y ecológicas. En todas las áreas estudiadas, los proyectos de investigación se estructuraron con el objetivo de incluir todos los sectores interesados en la gestión del recurso durante el proceso de selección de las estrategias de gestión que son potencialmente interesantes y viables. El segundo objetivo de la Tarea 1 fue la revisión de la hoja de ruta para el enfoque de ecosistema de la NAFO (EAF) y la idoneidad del Flemish Cap como caso de estudio para el desarrollo del enfoque multiespecífico en NAFO. La hoja de ruta NAFO EAF se desarrolló en 2010, en torno a una estructura de 3 niveles (nivel de ecosistema, multiespecífico y monoespecífico) que requiere la identificación de las subunidades ecológicas que forman el área NAFO, la implementación de un espectro de modelos de ecosistemas y multiespecíficos, y finalmente una evaluación de las estrategias de gestión utilizando las herramientas de existentes para especificar las tasas de explotación de ecosistemas. La idoneidad de Flemish Cap como caso de estudio para la implementación del enfoque multiespecífico en NAFO se debe por un lado al alto grado de aislamiento de las poblaciones demersales que habitan las áreas más someras del Flemish Cap, como el bacalao, la gallineta y el camarón, produciendo una dinámica independiente respecto a las poblaciones de los Grandes Bancos. También se consideró muy importante la relativa simplicidad de la red trófica, con un bajo número de interacciones tróficas pero de gran intensidad, un conocimiento sólido sobre el

funcionamiento del ecosistema y la existencia de un modelo multiespecífico (GadCap) desarrollado para bacalao, gallineta y camarón.

En la Tarea 2 se actualizó el modelo multiespecífico GadCap, desarrollado en Gadget, que abarcaba el período 1988-2012, y se mejoraron varios de sus componentes. Todas las fuentes de datos necesarias (índices de campaña, distribución tallas, composición de la dieta, capturas totales y distribución de la talla de las capturas comerciales para todas las flotas, etc.) se actualizaron hasta el año 2016 y se revisaron para garantizar la comparabilidad con los resultados de los modelos de evaluación monoespecíficos. La estructura del modelo se revisó y mejoró, incluida una nueva flota (flota de palangre de bacalao), la mejora de los modelos de madurez y crecimiento para las tres poblaciones, y las interacciones tróficas (especialmente las relaciones de longitud presa-depredador). Los resultados resaltan la dinámica interdependiente de las poblaciones de bacalao, gallineta nórdica y camarón y revelan fuertes interacciones entre el reclutamiento, la pesca y la depredación (incluido el canibalismo). Estos drivers han mostrado cambios marcados en su importancia relativa por especie, edad y longitud a lo largo del tiempo, produciendo una transición de un sistema tradicional dominado por gallineta y bacalao a principios de la década de 1990 a otro sistema intermedio formado por camarón y otras especies de peces a finales de los 90, y finalmente alrededor del año 2010 la vuelta al estado inicial. El modelo multiespecífico desarrollado en este proyecto muestra que desconsiderar las interacciones entre las especies llevaría a importantes infraestimaciones de la mortalidad natural y a una sobre-estimación de la biomasa explotable, y destaca la necesidad de avanzar más allá de una gestión monoespecífica en sistemas con dinámicas altamente acopladas. Los diagnósticos mostraron que el modelo simula muy bien los valores observados, y así soportan el uso de este modelo mejorado para que sea utilizado en las Tareas 3 y 4.

En la Tarea 3 ("Implementación práctica del enfoque multiespecífico"), el modelo GadCap actualizado y mejorado se utilizó con fines prácticos en el asesoramiento de pesquerías. El primer enfoque fue utilizar las estimaciones de mortalidad natural por edad estimadas en GadCap como entrada en el modelo de evaluación monoespecífico del bacalao de Flemish Cap durante el benchmark que se tuvo lugar como parte del proyecto SC03 "Support to a robust model assessment, benchmark and development of a management strategy evaluation for cod in NAFO Division 3M". Los resultados de esta subtarea 3.1 permiten concluir que existe una gran variabilidad en la mortalidad por depredación en el bacalao, tanto por edad como a lo largo del tiempo, lo que respalda la necesidad de considerar estimaciones alternativas de mortalidad natural para una evaluación adecuada del bacalao del Flemish Cap. Una implementación más avanzada del enfoque multiespecífico se desarrolló en las Tareas 3.2 y 3.3. En la Tarea 3.2, las potenciales candidatas para HCR se diseñaron con criterios monoespecíficos y multiespecíficos, seleccionando todas aquellas combinaciones de F (para bacalao, gallineta y camarón) que llevaron al bacalao, gallineta y camarón por encima de Blim a largo plazo (los tres stocks al mismo tiempo o alternativamente) cuando se corrieron simulaciones deterministas utilizando GadCap. En la Tarea 3.3, por primera vez en NAFO, se desarrolló un marco para hacer MSE con un modelo multiespecifico (GadCap) como modelo operativo. Este marco MSE multiespecífico se usó para evaluar el funcionamiento de las combinaciones de HCR para los tres stocks al mismo tiempo cuando se tiene en cuenta la incertidumbre en el proceso de reclutamiento y el error de evaluación. Los resultados de esta Tarea 3 permiten concluir que las combinaciones de HCR diseñadas bajo un enfoque monoespecífico no fueron precautorias para el bacalao y el camarón en un marco donde las interacciones de las especies se modelan y simulan directamente. Además, el análisis de riesgo de las combinaciones de HCR definidas con criterios multiespecíficos indicó que no es posible mantener los 3 stocks por encima de Blim al mismo tiempo. Las razones son las fuertes interacciones tróficas entre las tres poblaciones. Tratar de

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mantener el camarón por encima de Blim requiere una presión de pesca excesiva sobre el bacalao y la gallineta para reducir la mortalidad por depredación, y esto implica un alto riesgo de colapso en el bacalao. Por el contrario, mantener el bacalao por encima de Blim implica una gran depredación y un alto riesgo de colapso en el camarón y gallineta. Así, el hecho de no tener en cuenta un stock puede permitir encontrar puntos de referencia multiespecíficos precautorios para los otros stocks. Hacer caso omiso del estado del bacalao resultaría en la pesca de gallineta en niveles precautorios. Despreciar el estado de la gallineta permitiría la pesca de bacalao sin colapsar el stock. Sin embargo, esto no fue posible para el camarón. Es probable que la incertidumbre en el proceso de reclutamiento, estimada al azar en este estudio, haya sido determinante en este resultado. HCRs precautorias para dos poblaciones a la vez solo se encontraron cuando no se atendió al SSB de camarón en relación con Blim. El rendimiento estimado a largo plazo indica que estas estrategias están en la línea de los rendimientos obtenidos para ambas poblaciones desde la reapertura de la pesquería de bacalao en 2010. Los resultados mostraron que las HCR de dos etapas para el bacalao reducen la depredación y aumentan la probabilidad de que el bacalao y la gallineta estén por encima de Blim.

En la Tarea 4 ("Análisis económico de los trade-offs"), se estudiaron en primer lugar los modelos bioeconómicos existentes y se estudiaron las necesidades para el desarrollo de un análisis bioeconómico integrado en el área 3M de NAFO. Los resultados de esta subtarea permiten concluir que ninguno de los modelos existentes se ajusta al objetivo de este proyecto de un análisis bioeconómico completo e integrado de las HCR multiespecíficas. Sin embargo, durante la revisión se descubrió que actualmente se está desarrollando un marco integrado que incluye GADGET y FLBEIA en la IMR en Bergen (Noruega). Esta combinación de modelos ecológicos y económicos que definen el modelo operativo en un marco de MSE es la opción adecuada para el asesoramiento bioeconómico de NAFO. La segunda parte de la Tarea 4, un análisis bioeconómico de HCR multiespecíficas seleccionadas, se realizó con la intención de evaluar los trade-offs en los indicadores económicos, el marco temporal (corto versus largo plazo), la variación en las capturas y los ingresos y el esfuerzo de las flotas. A pesar de las limitaciones en el enfoque de modelos económicos, se puede concluir que si bien una HCR puede ser la más apropiada (en términos de rendimiento económico) para una flota (o país) puede no ser la mejor opción para otras flotas de la UE. En este estudio, no se encontró una opción que sea la mejor al mismo tiempo para todas las flotas de la UE que pescan en Flemish Cap. La misma conclusión se obtiene cuando se consideran los indicadores económicos a largo plazo y a corto plazo, o incluso cuando se considera la variabilidad del indicador. Sin embargo, quedó claro que cuando se ignoró el estado del stock de camarón en relación con el SSB (no se penalizó si el SSB del camarón estaba por debajo de Blim), el HCR de 2 etapas produjo resultados claramente mejores que el HCR de 1 etapa en todas las dimensiones estudiadas (flota, tiempo y variabilidad).

Como parte de la Tarea 5 ("Actividades de divulgación"), el proyecto SC05 y los resultados de las tareas anteriores se presentaron a la comunidad científica de NAFO asistiendo a las reuniones de WGESA en 2017 y 2018, y las presentaciones vía webex durante la reunión de NAFO SC en junio reunión en 2018. Además, se celebró un taller de dos días en Vigo, en enero de 2018, donde se invitó a todas las partes interesadas (industria pesquera, administradores y científicos). Durante este taller, los fundamentos del enfoque multiespecífico, las metodologías y las necesidades de datos, así como el trabajo, las dificultades y los resultados obtenidos en este proyecto SC05 se presentaron y discutieron con las partes interesadas durante las sesiones plenarias de este taller.

En la Tarea 6 ("Investigación potencial futura"), se sugirieron las líneas de trabajo de investigación futuras para apoyar el desarrollo del enfoque multiespecífico en el área de la NAFO. Primero, un resumen de los avances logrados en este proyecto y el conocimiento sobre el

enfoque multiespecífico obtenido de otras partes del mundo. A continuación, sobre la base de las brechas y sinergias identificadas en las secciones anteriores, se proporcionan recomendaciones sobre los próximos pasos para poner en práctica el enfoque multiespecífico en el contexto de la hoja de ruta de NAFO para un EAF.

5. INTRODUCTION

5.1. GENERAL INTRODUCTION TO THE SPECIFIC CONTRACT

EASME has commissioned the AZTI led Consortium (AZTI, AGROCAMPUS, CEFAS, IEO, IPMA, WMR, IRD, MRAG) for the Framework Contract EASME/EMFF/2016/008 for the "*Provision of scientific advice for fisheries beyond EU waters*"[1]. The present report refers to the Specific Contract (SC) Nº 5 EASME/EMFF/2015/1.3.2.3/05/SI2.760000 under this framework.

The purpose of this specific contract is to provide a comprehensive overview and analysis on how:

- Multispecies assessment would fit into the scientific and decision making processes within NAFO.
- The study should provide clear indication on new management systems developed from multispecies assessment principles. The new management system should be pragmatic with a reasonable balance between complexity and practicality and taking into account a long-term view of the state of stocks.
- The ultimate goal is to obtain a multispecies management tool to achieve higher long-term stability assuring fishery resources sustainability.

To this end the following tasks were proposed and are being developed:

Task 1: a general overview of the different approaches and most cutting-edge techniques developed by the main fisheries research institutions and management agencies worldwide to bring the multispecies approach into practice. The study will also provide a thorough description of the biological, ecological, fishery and scientific features that makes the Flemish Cap an ideal case study for the exploration of the multispecies approach to fisheries in the NAFO area.

Task 2: An updated version of the multispecies model GadCap (Flemish Cap cod, redfish and shrimp multispecies Gadget model, Pérez-Rodríguez et al (2016)) 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.

Task 3: Explore the provision of scientific advice for a multispecies approach in the Flemish Cap from different fronts: Use of alternative values of natural mortality in single species models stock assessment model in the Flemish Cap; First configuration of an MSE framework with GadCap as operating model to estimate multispecies reference points and assessing HCRs could be assessed from the precautionary and MSY perspectives.

Task 4: A first analysis of the socio/economic implications of moving from single to multispecies assessment and management, and the available techniques and models needed to assess the trade-offs resulting of the decisions taken from a multispecies approach to management.

Task 5: Discussion and interaction between scientists and other stakeholders through the organization of a workshop to present the results of the study to main stakeholders and

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[1] See Appendix I for list of acronyms used in the report.

administrations in the EU. In parallel, the results of Tasks 3 and 4 will be presented to the NAFO-WGESA and Scientific Council and the ways to integrate them within the Roadmap for the development of an ecosystem approach to fisheries management (EAF) will be explored.

Task 6: indicate the future necessary steps and research activities to progress in the implementation of the multispecies assessment in the Flemish Cap, and extensively in the area NAFO.

5.2. GEOGRAPHIC, ECOLOGICAL AND TAXONOMICAL SCOPE OF THE STUDY

The geographical scope of this study will vary from a worldwide perspective to accomplish the literature review work in Task 1 to the Flemish Cap in the NAFO area when the multispecies assessment tools are developed in Tasks 2 to 4. The ecological scope will be focused mainly in the realm of the commercial species (cod, redfish and shrimp). However other abiotic (namely temperature) and biotic components of the ecosystem like different pelagic invertebrate taxa, non-commercial fish species will be also considered. From the institutional perspective, this study will be developed in tight connection and in agreement with the roadmap for the EAF of NAFO (NAFO, 2010).

5.3. OBJECTIVE AND STRUCTURE OF THE REPORT

The objective of this Report is to inform about the main results and outcomes achieved in the development of the project SC05, specifying in detail the work under the specific Tasks 1 to 3 (subtask 1.1). Note that the other project tasks, namely Task 3 (Subtasks 3.2, Management Strategy Evaluation) Task 4 (economic analysis), Task 5 (workshop) and Task 6 (gaps and future research) will only start after this report and as such, advancements are not reported here.

6. OBJECTIVES, METHODS AND MAIN RESULTS BY TASK

6.1. TASK 1 – SETTING THE CONTEXT

6.1.1. Summary

In this task a literature review was conducted in first place with the intention of compiling the advancements in the development and application of the multispecies approach in different areas in the world. Three major areas based in their importance in relation to fisheries have been selected: The European Seas (North Sea, Baltic Sea and Barents Sea), the West Coast of the USA (focus in the Alaska region) as well as the Conservation of Antarctic Marine Living Resources region (CCAMLR) have been selected as the areas to be studied. In addition, the approaches addressed and the results and conclusions achieved in international projects like MYFISH in the EU or REDUS in Norway, have been analyzed. From this review it is concluded that the main advancements in applying the multispecies approach for scientific advice are related with:

- Use multispecies methods to estimate natural mortality to be used in single species stock assessment

- Estimate of multispecies based biological reference points and assessment of HCRs
  - ○ First estimations in the Baltic Sea using the SMS model for cod, herring and sprat.

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- - - The results showed that there are multiple FMSY for each stock.
      - Due to differences in catchability and productivity, it is most likely imposible managing at F_{MSY} levels all the stocks that interact technically (mixed fisheries) and biologically.
  - Multispecies Pretty Good Yield (MPGY):
    - As an alternative to the impossibility of managing all the stocks at the F_{MSY} level, during the MYFISH project the MPGY concept was developed: range of Fs where the productivity is not lower than 95% of the MSY.
  - Use of MSE frameworks with multispecies or ecosystem models as operating models: alternative way to determine reference points and define HCRs.
  - Allow estimating the economic, social and ecological trade-offs due to the application of different HCR considering uncertainty along the whole management cycle.

- Inclusion of stakeholders in the process of selecting management strategies
  - Stakeholders involved in the process are gathered, the objectives and underlying hypotheses for management could be identified, debated and agreed. The approach facilitated identification of conflicts between user group's objectives and potentially enhances the fishery management compliance.

Next, in this task the NAFO roadmap for an EAF was described in detail. The NAFO EAF roadmap was designed in 2010 by members of the NAFO-WGESA, as a spatially specific framework, where the productivity and variability of the ecosystem had to be assessed at different levels. Concretely three different tiers were defined: ecosystem, multispecies and single species tiers. In order to apply an EAF, it is necessary:

- Identify and define the ecological subunits on the shelf based on an analysis of physiographic, oceanographic and ecological variables
- Implementation of a spectrum of different multispecies and full ecosystem models which can be used to assess ecosystem state and function, particularly of higher order variables such as primary productivity and total biomass
- Evaluation of the management options using existing management tools for specifying ecosystem exploitation rates.

Finally the conditions that makes the Flemish Cap suitable to start developing the multispecies approach in the Flemish Cap were reviewed. It was found:

- High indepence level in the dynamic of the demersal stocks like cod, redfish and shrimp due to the high degree of isolation at both the egg-larvae and juvenile-adult stages produced by the anticyclonic gyre and the deep water Flemish Pass channel
- Relative simplicity of the trophic web, with a low number of interactions but of strong entity.
- Relative low number of stocks accumulating most of catches and biomass in the ecosystem (cod, redfish and shrimp being on average the 85% of total annual biomass)
- Abundant scientific and commercial data of relative good quality

- Deep knowledge about the functioning of the ecosystem, with a multispecies model developed in 2016.
- It is defined as an Ecosystem Production Unit (first stage of the NAFO EAF roadmap).

It was concluded that these findings support the Flemish as an ideal candidate to start developing the multispecies approach to fisheries management in NAFO.

6.1.2. Objectives

This Task aims to:

- Review the multispecies approach in different management organizations with special attention to the efforts made and the approaches followed to operationalize the multispecies approach.
- Analyze the conditions in NAFO for the application of the multispecies approach.

To accomplish this, Task 1 is divided in the following sub-tasks:

- Subtask 1.1.- Multispecies approach in other management organizations
- Subtask 1.2.- Revision of the case study: Flemish Cap and NAFO

6.1.3. Methodology

Overall, this task deals with reviewing the main achievements and specific approaches followed in different national or international management areas in relation to the multispecies approach to fisheries management, both in terms of ecological and socio-economic aspects. A Second goal of this task is setting the ecological, fisheries and historical context for the multispecies approach in NAFO and the Flemish Cap.

Sub-task 1.1 – Multispecies approach in other management organizations

For the development of this subtask different management areas around the world were the multispecies approach is being implemented have been reviewed. These areas were selected because they represented different approaches to address the multispecies approach, or they had different levels of development and implementation. Special attention has been put into the efforts made and the approaches followed to operationalize the multispecies approach by means of the determination of multispecies based reference points and their use to define Harvest Control Rules (HCRs) with some degree of consideration of multispecies interactions as well as socio-economic related issues.

The European Seas (North Sea, Baltic Sea and Barents Sea), the West Coast of the USA (focus in the Alaska region) as well as the Conservation of Antarctic Marine Living Resources region (CCAMLR) have been selected as the areas to be studied. In addition, the approaches addressed and the results and conclusions achieved in international projects like MYFISH in the EU or REDUS in Norway, have been analyzed.

This literature review has been very focused on the ecological aspect of the multispecies approach to fisheries management (i.e. the methods to incorporate species interactions in the advice process). However, approaches followed to involve stakeholders into this advice process have also been mentioned due to their relevance for a successful implementation of any management plan. The economic elements becomes a main issue at this stage. Although this will

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be briefly introduced here, subtask 4.1 within Task 4 (section 3.4 of this report) is the section where a deep review of methods to assess the economic trade-offs will be presented.

Accordingly, the review of each area has been structured to cover the next four elements:

    a. Framework for multispecies management
    b. Developments of research in multispecies and ecosystem modelling
    c. Use of multispecies model for stock assessment and fisheries management advice
    d. How multispecies considerations are captured in Fisheries management and quota setting

Sub-task 1.2 – Revision of the case study: Flemish Cap and NAFO

In this task, a literature review has beed carried out to describe the main elements of the EAF of NAFO, and the way the development of the multispecies approach would fit within this framework. In addition, a review of the most relevant NAFO Scientific Council Reserarch and Scientific Council Summary documents[2] (SCR and SCS respectively) has been conducted to describe the ecological and fisheries features, the scientific knowledge as well as the advancements in NAFO approach that support the Flemish Cap within NAFO as a candidate case study to move forward in the development of a multispecies approach to fisheries assessment and management.

6.1.4. Results

Sub-task 1.1 – Multispecies approach in other management organizations

Annex II presents an extended version of the review carried out for each of the selected management areas. Next, a summary of this review is presented, which includes the main advances in research and application of the multidisciplinary approach in Europe, North America and Antarctica.

Summary of multispecies approach in other management areas worldwide

The three regions addressed in this literature review represent an example of the widespread recognition that the assumption of a constant natural mortality over time for all ages is in most of cases an excesive simplification that leads to overestimates of stock productivity, and therefore to higher risks of over-exploitation

The three regions have produced the normative and institutional support that makes possible the development of the necessary research for the development of a multispecies and ecosystem approach. In addition, the necessary management structures have been developed, and stakeholders directly interested in the stocks have been considered. In these three regions, similar lines of applied research have been developed, and in some cases with similar strategies for the implementation of the multispecies approach. However, there are still different degrees of development in science, with some areas being more focused in pragmatic application of multispecies approach than a real intention of understanding the ecological processes as a whole.

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[2] https://www.nafo.int/Library/Science/SC-Documents

This section constitutes a brief summary of the different approaches compiled in this review work, from less to greater complexity and integration of ecological information in the management process. The resulting summarized list of approaches can be considered as a guidance for potential approaches to apply the multispecies approach in the NAFO area.

Use multispecies methods to estimate natural mortality

As described in the sections above, multispecies models are directly used to provide the estimates of natural mortality to be used in single species models in many fishing grounds. However, in some other of the studied regions, despite the availability of multispecies models, a more pragmatic approach has been taken when incorporating ecological information in the provision of catch advice. This pragmatic solution is supposed to overcome the problems of the uncertainty derived from increased complexity of multispecies models, that may lead to accumulation of uncertainties as well as an increased difficulty to interpreting results. In these cases, consumption models are used to provide estimates of natural mortality that are implemented in single species stock assessment methods.

CCAMLR applies an ad-hoc approach as a first step to define quotas for krill which involves setting a minimum krill biomass that needs to be maintained to ensure that there is sufficient food for predators (e.g. seals, sea birds, whales). The requirement is to maintain krill biomass at 75% of its unexploited size which is considerable higher than the 40 or 50% biomass target that is often used in fisheries assessments. In addition to that, CCAMLR scientists use estimates of predator consumption to further examine the effects of krill catches on the food web. They use those estimates in multi-species models that test different scenarios about the spatial distribution of exploitation. This is a second step that has helped CCAMLR allocate the original krill quota into subareas to reduce the risks of localised adverse impacts of fishing.

In the Barents Sea the assessment and provision of catch advice is based on the results provided by to assemble methods: 1) CapTool to estimate the catch quota corresponding to the harvest control rule using stochastic prognostic simulation. 2) Bifrost, a multispecies model for the Barents Sea with main emphasis on the cod-capelin dynamics that provides information about maturation and predation by cod. Captool is used hence for implementing results from Bifrost in the short-term (half-year) prognosis used for determining the quota.

The SMS multispecies model is the method to estimate total natural mortality (M1+M2) in the North Sea and Baltic Sea. These mortality values are used for the assessment and catch advice of a number of species such as cod, haddock, whiting and some others. SMS provides a matrix of natural mortality by age and year that is used as values of natural mortality within the single species assessment model during the optimization process. In addition, values of natural mortality for the last 3 years of the assessment are used to set natural mortality by age for the short-term projections. These projections constitute the basis for the catch advice together with the estimated reference points.

In the Alaska region, multispecies modelling has primarily served as an additional component that supports single species stock assessment. This approach has been used for walleye Pollock in the Gulf of Alaska and its stock assessment report goes one step further by including results from both the main single-species stock assessment and a multispecies model. The later showcased the effects of different components of the ecosystem on natural mortality of walleye Pollock to provide a perspective on the contribution of fishing to the mortality of this species.

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The implementation of age/year varying estimates of natural mortality is the inmediate improvement from multispecies methods in relation to the constant natural mortality often used in single-species traditional assessments. This, in addition to more reliable stock assessments and increased understanding of the SSB-Recruitment relationship, supposes an improvement in the short-term projections. Consideration of predation in short term forecast allows for more realistic productivity estimates and better prediction of the state of the stock. However, the reference points that together with the stock status in the short term projections are used to provide the catch advice are still estimated disregarding the trophic interactions and the exploitation of other stocks. Considering multispecies interactions when defining reference points is the next level in the implementation of the multispecies approach.

Estimate of biological reference points and assessment of HCRs with MSE

As showed in previous sections, in the Baltic Sea the SMS model was used to estimate multispecies based reference points. The first conclusion of that exercise is that reference point values are not unique. Unlike the single species approach, where M is assumed constant over time, in multispecies methods, the M for a given stock changes depending on what occurs with the stocks with which it interacts. In addition, higher or lower prey availability has the potential to affect on predator growth and survivorship. This implies that the MSY and the F_{MSY} can potentially be different depending on the combination of fishing scenarios for the different species considered. In summary there are multiple F_{MSY} possible for each stock.

Despite being a good first approach, the exercise done in the Baltic Sea was unable to provide F values within the MSY framework for all species at once. Species have different productivities, and this makes their F_{MSY} different. In addition many of these species are also caught by the same fishery (i.e. technical interactions), but usually with different catchability. Therefore, different productivity and catchability in species that interact biologically and technically brings very likely to an impossibility of managing all them at the F_{MSY} level.

This inability to manage all stocks at the F_{MSY} level has been addressed in the MYFISH project through the so-called "Pretty Good Multispecies Yield" PGMY, which can be extended to include also economic and social aspects. The PGMY approach allows some flexibility around the FMSY in the final selection of F target. The range of Fs is selected so that the productivity is not lower than 95% of the MSY, and stocks are maintained safe in relation to the precautionary reference points. The more restrictions that are introduced (ecological, economic, social), the more difficult it becomes finding a value of F that meets the requirements indicated above. This approach represents the most advanced and suitable approach to estimate F values considering at the same time biological and technical aspects of the multispecies approach within the MSY approach. This PGMY approach has been applied in the North Sea as a case study in the MYFISH project.

An alternative way to determine the reference points and define HCRs is the use of MSE frameworks with multispecies or ecosystem models as operating models. In these MSE frameworks large number of sources of uncertainty can be tested, both in the observations and in the processes. This frameworks allow estimating the economic, social and ecological trade-offs due to the application of a single or multispecies based HCR considering different sources of uncertainty. Within this approach to estimate reference points, the PGMY can also be used, defining the possible range of F values that can be tested for each stock. These MSE frameworks also allow assessing the effectiveness of different HCRs, which may have or not been defined with multi or single species foundations. This approach has been addressed in different regions

like Alaska (Punt et al. 2016b 924), the Barents Sea (see REDUS project section), or CCAMLR (Plaganyi and Butterworth[3]).

Assessment of the impact of environmental changes:

As described above, the multispecies approach and the tools developed for this approach can be used to estimate natural mortality, alternative reference points and alternative HCRs. But MICEs can also be used to run simulations and evaluate management strategies under very different environmental conditions, like those related to climate change or more specific environmental changes at regional scales. This approach has been taken up in the Alaska region, the Barents Sea or CCAMLR to provide a better understanding of sustainability of fishing once the potential effects of climate change are also factored into the analysis (e.g. CEATTLE model in CCAMLR).

Inclusion of stakeholders:

This review work has indicated that the uncertainty in the predictions of complex multispecies/ecosystem models coupled with limited exposure of managers and others to such models can act as a barrier for their use. To overcome this fundamental limitation the inclusion of Stakeholders in all stages of the process was found as the only solution. During the development of MYFISH project it was demonstrated that by having an inclusive process from the beginning, where all the stakeholders involved in the process are gathered, the objectives and underlying hypotheses for management could be identified, debated and agreed. The approach facilitated identification of conflicts between user group's objectives and potentially enhances the fishery management compliance. In addition to this, preparation of figures and DST was very synthetic but informative, reflecting the effects and trade-offs of implementing different MSY options on ecosystem, economic and social constraints with a particular focus on the risk of exceeding acceptable levels for constraints, will facilitate the transmission of complex results to all stakeholders, and will ease the decision-taking process. Finally, the credibility of multispecies methods, both within the scientific community and the stakeholders was increased in the Alaska region by holding multi-day review panels and involving international experts to challenge the model and the data used. Such activities have also provided insights into the credibility and quality control standards that they deem appropriate for such models and could be of help in designing other multispecies models.

Considerations on data and methodology requirements:

The literature review carried out for each of the three regions indicates that moving from single species to multispecies assessment requires new biological and ecological information. These data are specially related with the diet composition, but also with predator-prey size relation. It is important developing research projects that contribute to obtain estimates of consumption as a function of size and water temperature. Considering also technical in addition to the biological interactions requires knowledge about the species composition in the total catches (landings and discards), size/age distributions, as well as information about the species that was target on each fishing set.

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[3] https://open.uct.ac.za/bitstream/item/21235/Plag%C3%A1nyi_A_spatial_multi_species_2007.pdf?sequence=1

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Implementation in NAFO

Many of these varied strategies for a multispecies approach could already be implemented in NAFO. There are already some ecopath with ecosim models (EwE) in the NAFO area that could be used to inform about posible trends in species dynamics as consequence of climate and environmental changes, and how this would affect at the fisheries and socio-economic level (Bundy 2001, Bundy 2005). This models could also be used to inform about natural mortality and species interactions. However, for this task, more MICE models like GadCap model (Pérez-Rodríguez et al. 2016), that were updated and improved as part of this EU project SC05, more specifically developed for multispecies assessment, can be used to provide estimates of natural mortality to be used for single species stock assessment of cod, redfish and shrimp in the Flemish Cap. Likewise, GadCap and other multispecies model could be used to provide the M values needed to perform short term forecast and catch advice.

The approaches explored in MYFISH or REDUS to define reference points and HCRs that account for ecological and technical multiespecies interactions have not been developed in NAFO. However the necesary tools to start exploring this alternatives were developed as part of this SC05 project, subtask 3.2 and 3.3, multispecies MSE. Hence, the approaches developed as part of MYFISH and/or REDUS could be explored already for NAFO.

The inclusion of stakeholders, as described and justified in previous sections, is completely necesary for a proper development and implementation of a multispecies approach. These are steps that haven´t been done in NAFO yet, however, as part of this project SC05 (Task 5) there will be a first interaction with stakeholders to share perspectives, knowledge and preferences. The use of DST is highly recommended to communicate the effects and trade-offs of implementing different MSY options on ecosystem, economic and social constraints with a particular focus on the risk of exceeding acceptable levels for constraints. The whole cycle of interactions with stakeholders developed in the project MYFISH cannot be implemented as part of SC05. This will require of a longer project, with more work and feedback.

Sub-task 1.2 – Revision of the case study: Flemish Cap and NAFO

1.- Roadmap for developing an EAF for NAFO

a) Introduction

The ecosystem approach is an extension of the conventional principles for sustainable development to cover the ecosystem as a whole. When applied to fisheries, the Ecosystem Approaches (EAF) is intended to ensure that the planning, development, and management of fisheries will meet social and economic needs, without jeopardizing the options for future generations to benefit from the full range of goods and services provided by marine ecosystems (FAO 2003). Achieving this purpose requires addressing components of ecosystems within a geographic area in a more holistic manner than is used in classical target resource oriented management approaches. It requires identifying [geographically] exploited ecosystems together with explicit recognition of the many, and often competing, human interests in fisheries and marine ecosystems (FAO 2003). Therefore, following FAO (2003) "…an ecosystem approach to fisheries (EAF) strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties of biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries".

As the recognition for the need of ecosystem approaches grow, political commitments to ecosystem-based fisheries management are increasing worldwide and NAFO is no exception. In line with the spirit of the EAF definitions, the proposed amendment to the NAFO convention indicates in its preamble that "effective conservation and management of these fishery resources should be based on the best available scientific advice and the precautionary approach" while it commits to "apply an EAF in the Northwest Atlantic that includes safeguarding the marine environment, conserving its marine biodiversity, minimizing the risk of long term or irreversible adverse effects of fishing activities, and taking account of the relationship between all components of the ecosystem".

b) Integrated Ecosystem assessments

The general implementation of EAF requires ecosystem assessments that are essentially the counterparts of stock assessments currently used in support of conventional single-species management. For this purpose, Integrated Ecosystem Assessments (IEA) have been defined as: "a synthesis and quantitative analysis of information on relevant physical, chemical, ecological, and human processes in relation to specified ecosystem management objectives" (Levin et al. 2009). As a whole, IEAs should not be viewed as a replacement of single-sector and/or single-species management; instead, they should be consider as a necessary supplement that highlights potential conflicts among human activities, as well as potential inconsistencies between human goals and ecosystem states and/or processes.

The steps involved in the development of an IEA are depicted in **Error! Reference source not found.**, which begins by scoping and identifying the goals and ecosystem objectives covering a wide range of marine ecosystem components (Heslenfeld and Enserink 2008). To achieve such objectives, the mechanistic relationships between the state of these components or attributes and one or more manageable anthropogenic activities needs to be understood (Jennings 2005). Therefore, for scientists in charge of the provision of advice in support of EAF, determining the theoretical, mechanistic links between state and so-called pressure indicators often poses the greatest challenge (Greenstreet 2008). To implement an EAF successfully, therefore, it is not only necessary to have a suite of indicators that accurately portray the "state" of various ecosystem components, but it is also critical to have indicators that describe changes in the level of different manageable human activities (Daan 2005).
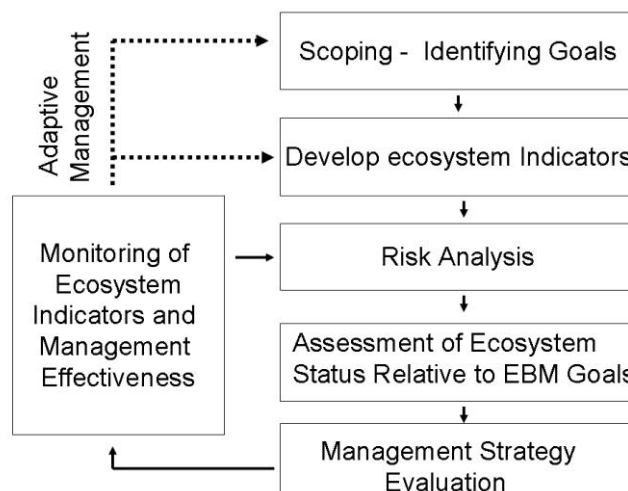

Figure 6.1-1. (from Levin et al. (2009)). The Five-Step Process of Integrated Ecosystem Assessment.

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c) Practical Implementation of an EAF

In considering the development of EAF strategies for the Northeast United States, the following pragmatic approach is under development:

1. Identification and definition of ecological subunits on the shelf based on an analysis of physiographic, oceanographic and ecological variables
2. Implementation of a spectrum of different multispecies and full ecosystem models which can be used to assess ecosystem state and function, particularly of higher order variables such as primary productivity and total biomass
3. Evaluation of the management options using existing management tools for specifying ecosystem exploitation rates.

Given the general similarities and relatedness between marine ecosystems in the Northeast United States with the other ecosystems within the NAFO convention area, the experience already gained in the US towards developing an EAF scheme as depicted by Figure 6.1-2 provided a useful and meaningful starting point towards developing an EAF for NAFO.
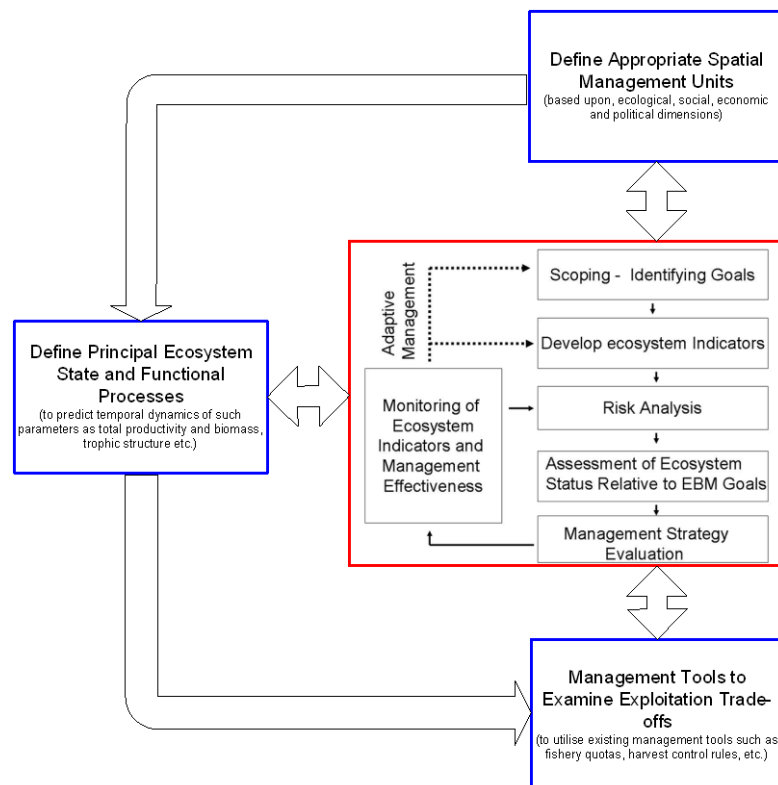
Figure 6.1-2.- The relationship between the 3 practical steps in moving towards the implementation of an EAF (blue boxes) and the steps required to deliver effective holistic integrated ecosystem assessments (IEA) shown in the red box.

Below there is a short description of the rationale and type of activities associated with the 3 practical steps of EAF (highlighted in blue in Figure 6.1-2). Together these form the basis for developing a plan for the possible implementation of an EAF in NAFO.

Defining Spatial Management Units: The specification of spatial management units is a critical pre-requisite to the development of ecosystem approaches to management. Therefore, defining

meaningful ecosystem management units within the NAFO area is considered the first step in the process towards EAF.

Defining Ecosystem State and Function Processes: A wide range of analytical methods should be employed (including a range of model types) to define and understand the principal dynamic properties of the spatially defined ecosystem (DFO 2008, Plagányi 2007). The choice of appropriate models depends on the specific objectives of the analysis and factors such as the interplay between model complexity and parameter uncertainty (DFO 2008, Fulton 2003, Koen-Alonso 2009, Plagányi 2007).

Utilising Management Tools: Although the conceptual framework encapsulated in EAF is broader than classical single-species management, the goal is to keep it simple and work with current management and assessment tools as much as possible. The move towards EAF should be evolutionary rather than revolutionary. The evolutionary aspect of this process is critical for EAF success. Both people as well as institutions need to adapt to the new EAF perspective.

However, it is important to note that an EAF will use the same basic tools as conventional management like effort limitation and control, conservation engineering, use of protected areas, and output controls (TACs). Some new aspects brought about by EAF will include the need for developing suitable types of output to inform managers and stakeholders about likely trade-offs among fisheries, as well as expected changes in the status of specific ecosystem components given anticipated variations in fishing and climate pressures. One important requirement at this level will be the identification and definition of explicit management objectives.

c) The NAFO Roadmap to EAF

When the amendments to the NAFO convention called for the application of an ecosystem approach, it was unclear what that implied for NAFO in practical terms. NAFO began the implementation of an EAF in the years following the publication of the FAO Guidelines on Deep Sea Fisheries. In addition to the traditional stock assessment of commercial fish species, NAFO also required advice regarding vulnerable species and habitats. In response, the Scientific Council established a new Working Group on the Ecosystem Approach to Fisheries Management (WGEAFM; In 2013 the working group changed its name to the Working Group on Ecosystem Science and Assessment (WGESA)), which began with a meeting in 2008 to identify and delineate marine benthic habitats subject to significant adverse impacts and in need of protection. However, since its early foundation, this working group was tasked with the development of a framework that could deliver an EAF for NAFO, as well as supporting the NAFO Scientific Council work on ecosystem issues. To accomplish these tasks the work within the WGESA has been developed under two complementary contexts:

- work intended to advance the Roadmap, which typically involves medium to long-term research, and
- work intended to address specific requests from Scientific Council (SC) and/or Fisheries Commission (FC), which typically involves short to medium-terms analysis, aligned to roadmap priorities.

WGESA revised and up-dated its long-term ToRs in 2016 to be implemented at its 2017 meeting and thereafter:

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Theme 1: Spatial considerations

ToR 1. Update on identification and mapping of sensitive species and habitats in the NAFO area. In support of the Roadmap develop research and summarize new findings on the spatial structure and organisation of marine ecosystems with an emphasis on connectivity, exchanges and flows among ecosystem units in the NAFO Convention Area.

Theme 2: Status, functioning and dynamics of marine ecosystems

ToR 2. Develop research and summarize new findings on the status, functioning and productivity of ecosystems (including modelling multi-species interactions) in the NAFO Convention Area.

Theme 3: Practical application EAFM

ToR 3. Develop research and summarize new findings on long-term monitoring of status and functioning of ecosystem units (including ecosystem summary sheets) and the application of ecosystem knowledge for the assessment of impacts and management of human activities in the NAFO Convention Area.

Theme 4: Specific requests

ToRs 4+. As generic ToRs, these are place-holders intended to be used when addressing expected additional requests from Scientific Council or Fisheries Commission that don't fit in to the standing ToRs above.

WGEAFM presented the first version of the "Roadmap for developing an Ecosystem Approach to Fisheries (EAF) for NAFO" in 2010 (NAFO 2010a, b). The proposed framework was endorsed by SC, and subsequent efforts towards EAF development were focused along the path outlined in the Roadmap. Between 2012 and 2013 the Roadmap took a qualitative step forward. The progress made so far was formally presented to FC, describing the Roadmap as an operational work-flow process that could be implemented in practice at the full organization scale. By 2014, the Roadmap had evolved from an original framework developed by WGEAFM/WGESA within the context of SC, to a plan recognized by NAFO as a whole to guide the efforts of the entire organization towards implementing EAF.

The current representation of the Roadmap (Figure 6.1-3) provides an operational perspective of how the EAF is being conceived in a work-flow process that suits NAFO structure and practices. This schematic incorporates the hierarchical approach to define exploitation rates, and integrates the impacts on benthic communities (e.g. Vulnerable Marine Ecosystems –VMEs-) associated with the different fisheries that take place within the ecosystem.
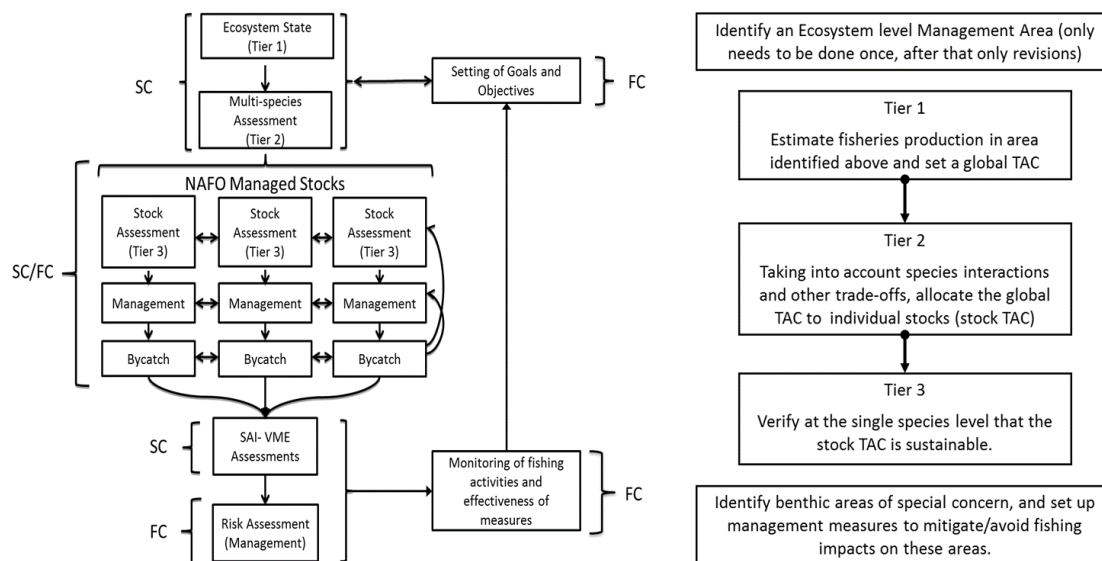
Figure 6.1-3.- Schematic representation of NAFO roadmap for implementing an EAF (left) with a synoptic overview of the key steps required for using it (right). Tier 1 corresponds to the place-based management step – the effective integration of Tiers 1 and 2, with Tier 3 (single species stock assessments) remains a challenge for most fisheries management organisations. FC=Fisheries Commission; SC=Scientific Council; SAI= Significant Adverse Impacts; VME= Vulnerable Marine Ecosystem.

Core premises of the Roadmap are: a) the approach has to be objective-driven; b) it should consider long-term ecosystem sustainability; c) it has to be a place-based framework,; and d) trade-offs have to be explicitly addressed (NAFO, 2015).

Within a functional ecosystem unit, addressing long-term ecosystem sustainability can be conceptualized as two complementary and interrelated pieces:

- Defining harvest levels for all exploited stocks which are compatible with each other, and when taken together, do not compromise overall ecosystem structure and function.
- Assessment of the impacts of fishing on non-target components (not just by-catch of other fish species, but also including benthic communities and habitats).

Identifying harvest levels that do not compromise ecosystem functionality requires wide range of analytical methods (including a range of model types) to define and understand the principal dynamic properties of the spatially defined ecosystem (Plagányi 2007). The choice of appropriate models depends on the specific objectives of the analysis, and accordingly multi-model approaches is often recommended (Fogarty and McCarthy 2014). In agreement with this, the NAFO Roadmap aims at establishing sustainable exploitation levels through a three-tiered hierarchical approach where at each level one or more models/analyses could be employed:

The **first tier** defines fishery production potential at the ecosystem level, taking into account environmental conditions and ecosystem state (overall ecosystem sustainability).

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The **second tier** utilizes multispecies assessments to allocate fisheries production among commercial species, taking into account species interactions and the trade-off among fisheries (multispecies sustainability) (e.g. ICES (2016c)).

The **third tier** involves single-species stock assessment, where the exploitation rates derived from Tiers 1 and 2 are further examined to ensure single-species sustainability.

The first tier is focused on an ecosystem state assessment, and includes the estimation of fishery production potential at the functional ecosystem unit level, taking into account environmental conditions and ecosystem state. This allows a first order consideration for the potential influence of large scale climate/ecological forcing on fishery production, as well as explicitly considering the basic limitation imposed by primary production on fisheries production (Fogarty and McCarthy 2014, Rosenberg and al. 2014). In practical terms, this stage is aimed at defining a productivity-based Total Catch Ceiling (TCC) at the ecosystem level that should not be exceeded.

The second tier utilizes multispecies models to allocate fisheries production among a set of target stocks, taking into account species interactions and considerations pertaining the stability and dynamic resilience of the exploited community. This allows consideration of trade-off among specific fisheries, identification of exploitation rates which are consistent with multispecies sustainability (Gaichas et al. 2012, Rindorf et al. 2017b). In practical terms, the multispecies analyses at this tier are aimed at evaluating plausible exploitation scenarios (e.g. portfolios of TACs) based on a range of management objectives, and which do not exceed the estimated TCCs, to ensure that, if applied, species interactions would not compromise long-term sustainability (e.g. harvesting forage species also require considering their role in building production of higher trophic levels).

The third tier involves single-species stock assessment, where the exploitation rates derived from Tiers 1 and 2 can be further examined to ensure single-species sustainability. Tier 3 analyses are intended to prevent that the possible lack of biological detail in tier 1 and 2 models generates unintended impacts on specific species, while it provides yet another set of models with different structural details and assumptions. At this level, existing PA frameworks and harvest control rules will continue to be useful, but as the other tiers developed, these may need to be revised/updated, depending on the assumptions and considerations used when they were originally constructed. This tier also recognizes that not all managed stocks would necessarily have strong trophic linkages, and in those cases, exploitation level would still count against total ecosystem catch limits, but it would have to be defined directly from the single-species assessment.

Taken together, exploitation levels are defined by sequentially examining sustainability at the ecosystem, multispecies, and stock levels, where each step can constrain exploitation rates. In this way, the resulting harvest rates would be consistent with current knowledge indicating that it is not possible to simultaneously extract the single-species Maximum Sustainable Yield (MSY) from all stocks within an ecosystem (Rindorf et al. 2017b), where the multispecies MSY is typically less than the sum of all corresponding single-species MSYs.

In summary, the Roadmap requires for each geographically defined functional ecosystem unit, the development of a series of interconnected assessments aimed at different spatial scales and levels of ecological organization which can be schematically described as ecosystem state, multispecies, stock, and habitat impacts assessments (Figure 6.1-2). These assessments require the implementation of different models aimed at defining total ecosystem catch levels, exploring

ecological trade-offs among exploited species, defining the status of each exploited stock, and evaluating the cumulative impacts of fishing on benthic habitats. However, these assessments should not be simply equated to specific models; other analyses also provide valuable information to put model results in context, and some of these elements, like environmental regime shifts, trends in community structure, diet studies, estimations of food consumption, among other ecosystem indicators, are also integral components of the assessments. During implementation stages, when there is a need to start considering ecosystem interactions but not all necessary models are in place, these elements can support implementation of transitional management measures. Once the EAF is fully functional, these types of analyses would have the important role of detecting changes that may be beyond the ability of the implemented models to capture. Regardless of their quality and complexity, no battery of models can fully represent every possible ecosystem behavior; data-driven pattern and trend analyses would be the tools to detect those ecosystem changes. This would be particularly important as the impacts of climate change on ecosystem dynamics play themselves out.

e) NAFO Roadmap progress

The development of the NAFO EAF roadmap requires advances in several lines of work on each of the tiers and components (Figure 6.1-5), like the ecosystem status, the provision of multispecies advice that takes into consideration the effects of trophic interactions, and assessment of the likelihood of significant adverse impacts on VMEs. These elements can provide the context around which current assessment and management practices can be framed and evaluated

To date, significant progress in several areas of the Roadmap has been made. The identification and delineation of areas with significant concentrations of VMEs has been thoroughly documented and information is being continuously added to the knowledge base, procedures to improve the delineation process are being developed and refined, and a comprehensive assessment of the potential interaction between VME and fishing activities is being developed (Kenchington et al. 2014, NAFO 2011, 2012, 2014, 2015, 2016a).

In addition, Ecosystem Production Units (EPUs) within NAFO Regulatory Area (NRA) have been defined (Figure 6.1-4). The process of identifying ecosystem units was based on a suite of physiographic, oceanographic and biotic variables, which were integrated using a combination of principal components and cluster analyses (Fogarty and Keith 2005, Pepin et al. 2010, Pepin et al. 2014, Pérez-Rodríguez et al. 2010, Zwanenburg et al. 2010). These studies allowed identifying three nested spatial scales deemed useful for the development of ecosystem summaries and ecosystem-level management plans: bioregion, Ecosystem Production Units (EPU), and ecoregion (NAFO 2014, 2015, Pepin et al. 2014).

The intermediate scale, the EPU, was identified as the best suited for integrated ecosystem management plans, and SC is focusing on three of these EPUs, Flemish Cap, Grand Bank, and Newfoundland Shelf, to further develop the science tools and advice required for pilot EAF exercises. These EPUs were chosen because they contain most of the stocks under direct NAFO management.

There has also been considerable progress on development of tiered modeling approaches to investigate ecosystem production potential (EPP – Tier 1) (Koen-Alonso et al. 2013, NAFO 2016b) for each of the three Ecosystem Production Units (EPUs) identified in the NAFO area, i.e. the Flemish Cap (3M), the Grand Banks (3LNO), and the Newfoundland Shelf (2J3K) (Figure 6.1-4). These EPP models have been used to derive Total Catch Ceilings (TCCs) for

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these ecosystem units (NAFO 2016a). EPP models provide a good representation of energy flow through key functional ecosystem components and the research conducted to date provides a comprehensive assessment of reliance of predictions on food web complexity/structure. EPP estimates of Total Catch Ceilings (TCC) should represent an essential foundational element that delimits overall production potential of higher trophic levels among all EPUs given that currently there have been no alternate approaches have been put forth to set ecosystem level reference points.
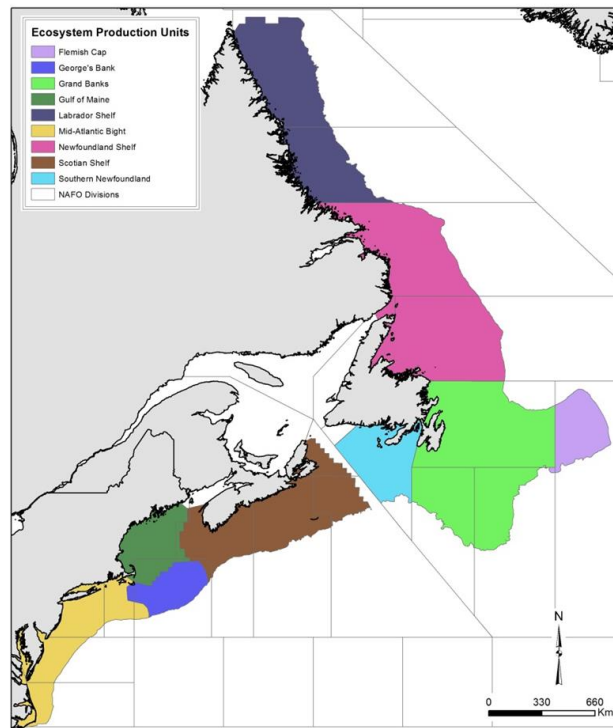
Figure 6.1-4. Ecosystem Production Units (EPUs) identified across the shelf ecosystems in the NAFO Convention Area. These EPUs have been proposed as candidate Ecosystem-level Management Areas, and pilot exercises on the Roadmap implementation are been conducted by SC on the Flemish Cap (3M), the Grand Bank (3LNO), and the Newfoundland Shelf (2J3K) EPUs.

The process for deriving the TCCs is schematically depicted in Figure 6.1-6. The areas of the EPUs were updated to fully match current delineations, and the penalty factors used for the Newfoundland Shelf (2J3K) and the Grand Bank (3LNO) were updated given the declines observed in total biomass in these EPUs (NAFO 2016a). Following with the practice started in 2016, TCC values are given by individual fishable nodes in the EPP model and the "Standard Demersal Components" (SDC) aggregate which combines benthivore and piscivore nodes and includes all traditional groundfish and shellfish commercial species in these EPUs.
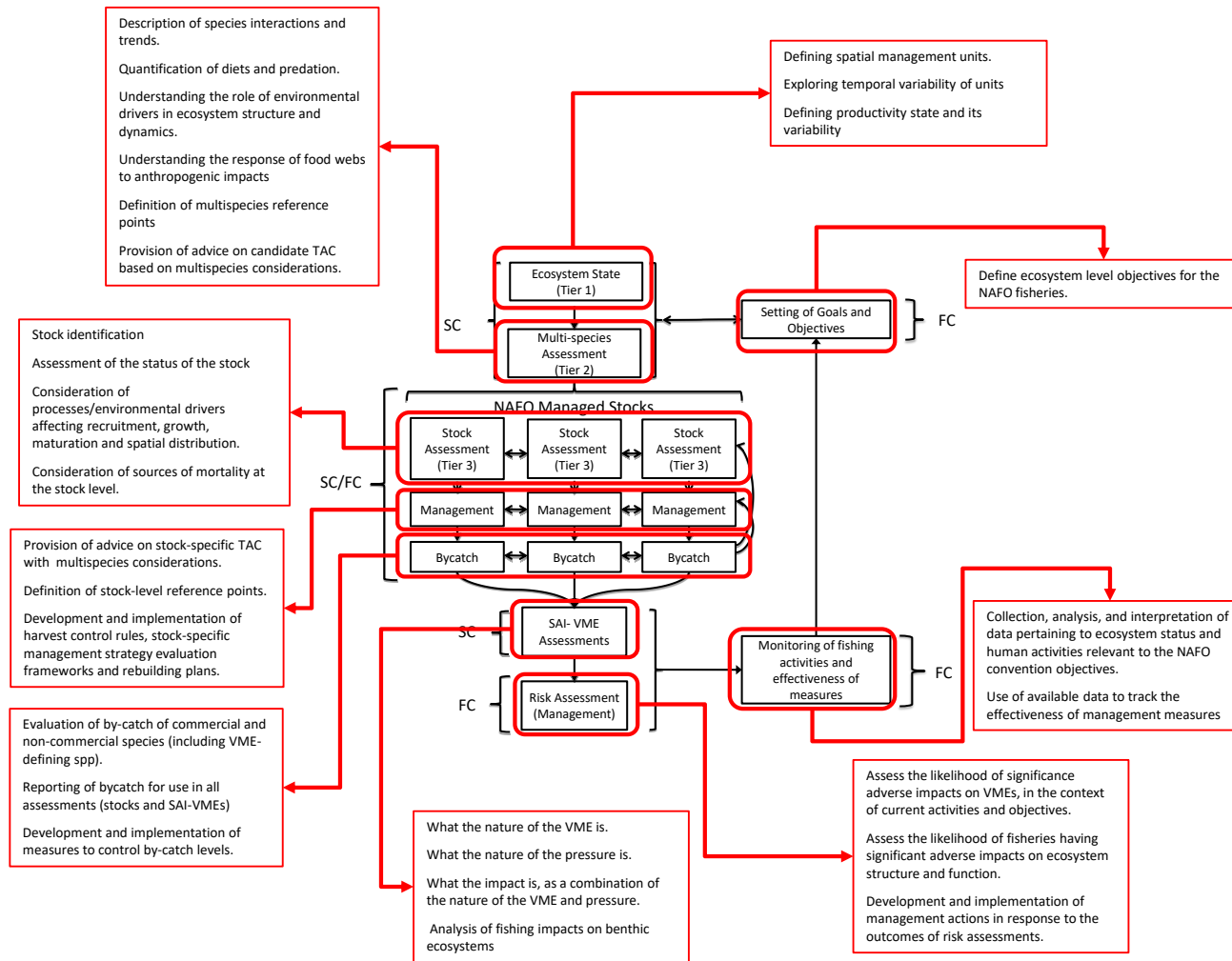
Figure 6.1-5. Summary description of the NAFO Roadmap components, including the main elements that needs to be developed and solved on each section of the roadmap (from NAFO SCS Doc. 15/19. Serial No. N6549).

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In order to compare nominal catches with TCC values, it is necessary to recognize that production for individual target species is associated to different EPP nodes due to diet changes linked to different life history stages. Analyses done by WGESA in 2016 for the Flemish Cap EPU indicated that assigning 100% of Greenland halibut to the piscivore node seemed reasonable, but fractionation for cod and redfish was required. Although work on these aspects is ongoing, an initial fractionation for cod and redfish for EPUs in the NL bioregion was implemented in 2017. Overall, fractionation factors have been derived from information on diet composition (2J3K, 3LNO and 3M), and the size distribution of commercial catches (3M only).
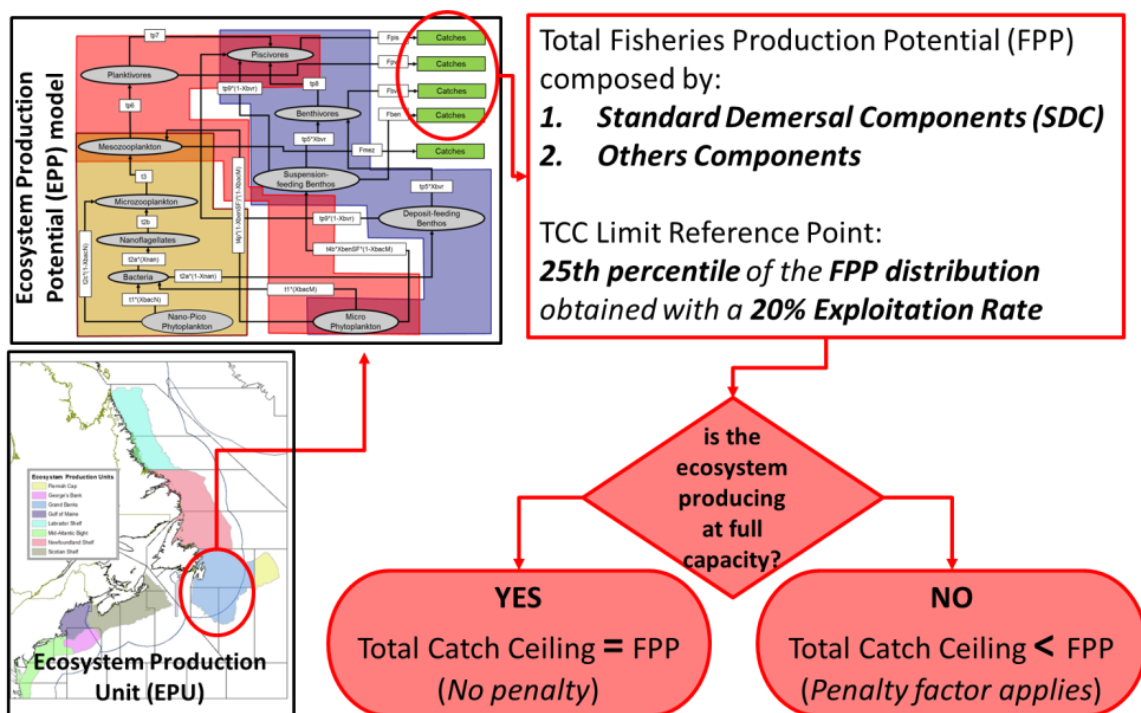
Figure 6.1-6.- Schematic depiction of the process to derive TCC LRPs from the FPP estimated using the EPP model, including the discrimination between SDC and Other FPP.

There has also been considerable progress in development of environmental and multispecies models in the NAFO area. A Gadget multispecies model for Flemish Cap cod, redfish and shrimp (GadCap) was developed with the financial support of the EU Marie Curie program (Pérez-Rodríguez et al. 2016). The model showed the interdependent dynamic of these stocks, and revealed strong interactions between recruitment, fishing and predation (including cannibalism).

However, there has yet to be a case study in which the output from a multispecies model has been applied in the provision of advice for a specific stock or stocks in the NAFO area. This specific contract SC05 will serve as the starting point to bring into practice the multispecies approach in NAFO, and integrating the output of multispecies models into the NAFO framework for the EAF.

2.- Ecological, fisheries and scientific conditions that support the Flemish Cap as a candidate case study to move forward in the development of a multispecies approach within NAFO

Traditional approaches to fisheries management frequently consider species exploited in the same ecosystem as if they were completely independent populations (i.e. a single species approach), setting the Total Allowable Catches (TACs) without any consideration of species interactions. However, it has been widely demonstrated that predation is in many cases more important than fishing mortality, and that natural mortality could be much higher than it is assumed by single species models (e.g. Bax (1998), Jennings et al. (2001), Wooton (1998)). Accordingly, disregarding trophic interactions could lead to overestimations of yield per recruit (Pinnegar et al. 2008), which would imply exploitations of resources beyond the real surplus production. It has been widely recognized that the development of a more holistic approach is required, taking into account the relationship of fishing resources with their environment, and with special attention to the trophic interactions and other sources of mortality (Garcia et al. 2003).

Since the early 1980s, multispecies and ecosystem models have been developed more intensively with diverse assumptions and scopes (Pinnegar et al. 2008). One of this models is Gadget (Globally applicable Area Disaggregated General Ecosystem Toolbox), a powerful and flexible framework that models marine ecosystems within a fisheries and eco-biological context (Begley and Howell 2004a). It has been classified as a dynamic multispecies or minimum realistic model suitable for practical advice in fisheries management (Plagányi 2007). The model has potential applications both as an operating model in Management Strategy Evaluations (MSE), and as a stock assessment modeling tool. As a multispecies model, Gadget has been applied in the Barents Sea, Icelandic Sea and the Celtic Sea (Lindstøm et al. 2009, Taylor and Stefansson 2004, Trenkel et al. 2004), and further models are under development in the Baltic and the Bay of Biscay.

Historically, the management of fishing resources within NAFO has been based on a single-species approach. However since the generalized collapse of cod stocks in the Northwest Atlantic, NAFO has been promoting the development of a precautionary and more comprehensive approach for fisheries management. After years of non-recovery of cod stocks, as described in previous sections, in 2008 the Working group for the Ecosystem Approach to Fisheries Management (WGEAFM) was created with the mission of advising the NAFO Scientific Council about the functioning of the NAFO ecosystems, and more specifically on issues such as Vulnerable Marine Ecosystems (VME), fisheries production potential, ecological production units and with special interest the interactions between species (NAFO 2010a, b). As part of the NAFO roadmap for an EAF, the assessment of species interactions has to be conducted and the results integrated within a framework where higher level of ecological information is also considered.

In the Flemish Cap, despite the influence of the North Atlantic Current, the Labrador Current dominates the water mass properties (Colbourne and Foote 2000). The cap is separated from the Newfoundland shelf by the Flemish Pass, a channel characterized by depths greater than 1100 m. This channel hinders migratory movements for juvenile and adult stages of shallow demersal species like Atlantic cod (*Gadus morhua*, Linnaeus, 1758) (Konstantinov 1970, Templeman and Fleming 1963). In addition a quasi-permanent anti-cyclonic gyre dominates the oceanography over the Cap (Colbourne and Foote 2000), resulting in the retention of eggs and larvae within the Flemish Cap. Accordingly, the Flemish Cap is a largely separate ecosystem from the Grand Banks, as shown by the genetic differences found in cod (Bentzen

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et al. 1996, Carr and Marshall 2008) and shrimp *Pandalus borealis* (Jordel et al. 2014), and reinforced lately by the different dynamics observed in the 3NO and 3M cod stocks after the 1990s collapses (González-Troncoso 2015, González-Troncoso et al. 2015).

As a typical boreal ecosystem, in the Flemish Cap most of the biomass and production is concentrated in a few species, connected by strong trophic interactions (Pérez-Rodríguez 2012). Zooplankton is mostly dominated by copepods, hiperiids and chaetognaths, which constitute the basis of the diet for a pelagic fish community that in the Flemish Cap is characterized by the lack of key traditional boreal fish species like sandlance (*Ammodytes* sp.) or capelin (*Mallotus villosus*). Instead, the pelagic fish community is mostly formed by deep water species like myctophiids, and especially by the demersal-pelagic redfish species (*Sebastes marinus, Sebastes fasciatus* and *Sebastes mentella*). The piscivorous guild prey on pelagic fishes and is mostly represented by large cod, although wolffishes *Anarhichas* sp and Greenland halibut *Reinhardtius hippoglossoides* are also of high importance when the cod stock is reduced (Pérez-Rodríguez et al. 2011). As a result of the absence of sandlance and capelin, a particular feature in the Flemish Cap is the high relevance of zooplankton in the diet of medium size individuals of piscivorous species (Gomes 1993, Pérez-Rodríguez 2012). The Northern shrimp is a key component in the trophic web in the Flemish Cap (Parsons 2005), being preyed on by most demersal fish species and especially by cod and redfish (Pérez-Rodríguez et al. 2011, Román et al. 2004). Preliminary consumption estimates studies in the Flemish Cap suggested that the dynamics of redfish and shrimp stocks may be strongly influenced by cod predation (González-Iglesias and Casas 2012a, NAFO 2012, Pérez-Rodríguez et al. 2011), while cannibalism might control the degree of recruitments success in cod (NAFO 2013).

The Flemish Cap has been a traditional fishing ground for cod and redfish especially since mid 20th century. Similar to all the northwest Atlantic cod stocks, after a period of extreme high fishing pressure, the Flemish Cap cod experienced a sharp decline that ended up with the collapse of the stock by mid 1990s (Vázquez and Cerviño 2002). In parallel, redfish catches also showed a steep decline by mid 1990s, after a period of very high values. The declines of cod and redfish were followed by the increase of shrimp, Greenland halibut, wolffishes and other demersal stocks (Pérez-Rodríguez 2012). New fisheries targeting shrimp and Greenland halibut started by the mid 1990s and kept total landings from the area at similar levels to before the collapse of cod. The recovery of both redfish and cod stocks since 2000-2005 were followed by the decline and collapse of shrimp by 2010 (Casas-Sánchez 2012), when the cod fishery was reopened. The fisheries for cod and redfish have been traditionally made by pelagic and bottom trawlers, although gillnetters and longliners were of importance before mid 1990s, and longliners again since the reopening of cod fishery in 2010. Interaction between fisheries has been highlighted for redfish, since discards of juveniles were high in the bottom trawl shrimp fishery, especially before the introduction of a sorting grid in 1995 (Ávila de Melo et al. 2013). However, mix fisheries may also be an important issue for cod and redfish fisheries, where by-catch of redfish and cod respectively could be an important element to consider.

Based on the relative simplicity of the food web in the Flemish Cap with strong trophic connections between the most important commercial species (i.e. cod, redfish and shrimp), the relatively high isolation of the demersal community in relation to the nearby Grand Banks and the high availability of data from the commercial fishery and the European Union bottom trawl survey, the Flemish Cap constitutes an ideal case study for the development of the multispecies and EAF in NAFO. For this reason, between 2014 and 2016, the EU Marie

Curie Program funded the project GadCap (https://gadcap.wordpress.com/the-eu-marie-curie-program/), with the aim of developing a Gadget multispecies model considering cod, redfish and shrimp. This model highlighted the interdependent dynamic of these three stocks, and revealed strong interactions between recruitment, fishing and predation (including cannibalism in cod and redfish). These drivers showed marked changes in their relative importance by species, age, and length over time, producing a transition from a traditional redfish-cod dominated system in the early 1990s, to an intermediate shrimp-other fish species state by late 1990s, and in turn back to something close to the initial state by late 2000s. GadCap showed that disregarding the interactions between cod, redfish and shrimp in the Flemish Cap would lead to serious underestimates of natural mortality, overestimations of the exploitable biomass, and highlighted the need to move beyond single-species management in this highly coupled ecosystem.

Due to all the above mentioned ecological, fisheries, scientific and management reasons, the Flemish Cap is an ideal case study to continue progressing in the multispecies approach to fisheries management in the NAFO area (NAFO roadmap tier 2), but also on its integration within the whole NAFO framework for an EAF. To achieve that goal, an updated version of the multispecies model GadCap needs to be produced, by including new data sources and extending the time period covered. In addition, 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 would need to be improved. Once this updated version of GadCap is available, the actual work for the implementation of a multispecies approach in the Flemish Cap, as case study within the NAFO area, can be started. As a first step, from GadCap, natural mortality at age (residual+ predation, M1+M2) can be estimated and used as alternative values of natural mortality in single species stock assessment models currently used in the Flemish Cap. As a second step, a first configuration of an MSE framework with GadCap as operating model can be develop (i.e. a multispecies MSE). This MSE framework 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. As a third step, a first analysis of the implications of moving from single to multispecies assessment and management from the socio-economic perspective could be addressed.

6.1.5. Difficulties

In the development of s*ubtasks 1.1 and 1.2* no major difficulties were found.

6.2. TASK 2 - UPDATE AND IMPROVEMENT OF GADCAP MULTISPECIES MODEL

6.2.1. Summary

In this chapter the multispecies model GadCap (Pérez-Rodríguez et al, 2016), developed in Gadget, which covers the main commercial stocks over the period 1988–2012: cod (*Gadus morhua*), redfish (*Sebastes* spp.), and northern shrimp (*Pandalus borealis*) was updated and several components were introduced by the first time or improved. Once the model was assembled, all the necessary diagnostics were performed, as well as sensitivity analysis to ensure that the model was ready to be used for further steps in Task 3.

All the necessary data sources: the EU annual summer survey (survey indices of biomass, length distribution, maturity state, diet composition, water temperature,…), the commercial

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fleets (total catches and length distribution from trawl, gillnet and longline fleets) and other sources of information like the Continuous Plankton Recorder (CPR), were updated until year 2016 and reviewed to ensure comparability with the assessment performed from a single species approach. The model structure was reviewed and improved, including a new fleet (longline fleet) for cod, and improving the maturity and growth models for all the three stocks. The trophic interactions (specially the prey-predator length relationships) were also reviewed and improved. The diagnostics indicated that the model estimates simulated very closely the observed values.

The biomass and abundance population estimated over the period 1988-2016 by the improved GadCap multispecies model showed very similar values to those estimated in the single species assessment for cod. For redfish there were more important differences, which are due probably to two different reasons: 1) in this study all the three redfish species (*Sebastes mentella*, *S.fasciatus* and *S. marinus*) are included within the redfish stock, while in the single species assessment S.marinus is excluded; 2) predation mortality increases the estimates of population biomass. For shrimp this is the first time that a stock assessment has been developed and estimates of population biomass are provided.

The results highlight the interdependent dynamic of cod, redfish and shrimp stocks and reveals strong interactions among recruitment, fishing, and predation (including cannibalism). These drivers have shown marked changes in their relative importance by species, age, and length over time, producing a transition from a traditional redfish- and cod-dominated system in the early 1990s to an intermediate shrimp and other fish species state by the late 1990s and in turn back to something close to the initial state by the late 2000s. The multispecies model developed in this paper shows that disregarding the species interactions would lead to serious underestimates of natural mortality and overestimations of the exploitable biomass and highlights the need to move beyond single-species management in this highly coupled ecosystem.

6.2.2. *Objectives*

This Task aims to updating the database, improving the multispecies model GadCap and preparing it to be used in the subsequent Tasks 3 and 4. Flemish Cap cod, redfish and shrimp multispecies Gadget model, Pérez-Rodríguez et al (2016) was updated, 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 were improved. This work was developed in three different subtasks:

- Subtask 2.1.- Updating model input databases
- Subtask 2.2.- Improvement of GadCap model
- Subtask 2.3.- Model assemblage

6.2.3. *Methodology*

During the EU Marie Curie project GadCap[12] a gadget multispecies model for the Flemish Cap cod, redfish and shrimp was developed (Pérez-Rodríguez et al. 2016). Gadget was used

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to model the interdependent dynamic of the Flemish Cap cod, redfish and shrimp populations over the period 1988-2012, the effect of fishing and other environmental factors.

Gadget is a flexible tool that allows the user to include a number of features of the ecosystem into the model: one or more species, each of which may be split into multiple components; multiple areas with migration between areas; predation between and within species; growth; maturation; reproduction and recruitment; multiple commercial and survey fleets taking catches from the populations (Begley 2005, Begley and Howell 2004a). It is a process-based model and for each modeled population Gadget allows modeling different biological and ecological processes, setting the parameters for sub-models of predation, growth, maturation, length-weight relationship or change of sex.

The Gadget framework consists of three different and interdependent steps:

1. A parametric model to perform simulations of the modeled system.
2. Statistical functions to compare the simulation model with original data.
3. Search algorithms to optimize the model parameters.

An initial population (in the form of abundance at age) needs to be defined, as well as the annual recruitment (as an abundance value at the defined age of recruitment) as an estimated annual value or through a stock-recruitment model. The way that each fleet interacts with each fished population need to be also defined. Fleets are considered as predators without length or age structure, affecting the fished stocks based on a suitability function, which parameters need to be set. Once all these parameters are defined, Gadget runs a forward simulation and different datasets are produced. These simulated datasets (hereafter likelihood components) are compared with the original datasets obtained from surveys or commercial catches. A goodness of fit value, or likelihood score, is estimated using different statistical likelihood functions. Then, parameters defining the fishing, biological and ecological modeled processes are randomly changed, and the simulation and likelihood score estimation are repeated. Search algorithms are employed to find the set of parameters that produce the best fit to the original data.

In this work the GADGET version 2.2.00 was employed[1] to create an age-length structured multispecies model considering different fleets and sub-populations as well as their interactions. Cod and redfish were considered both as prey and predators; while shrimp was modeled as prey (Figure 6.2-1). In addition other zooplankton invertebrate groups, as well as demersal and pelagic fishes were included as exogenous input variables in the model. The approach followed was developing first three separate single-species models (cod, redfish and shrimp), and second a multispecies model that incorporates the interactions among these modeled and other external species.

In the GadCap model presented in Pérez-Rodríguez et al. (2016) most of the data employed were obtained from the International European Union (EU) bottom trawl surveys, conducted annually in June-July since 1988. The surveys followed the NAFO recommendations with a random stratified design (Vázquez et al. 2013). This design allowed estimating indexes of total abundance and biomass for the three stocks modeled in this work using the swept area method (Gunderson 1993). These indices of biomass were employed in the model fitting as

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[1] https://github.com/Hafro/gadget

Catch per Unit of Effort (CPUE) indices. The population size distributions were also obtained from the EU survey and used as input data in the model optimization. A detailed biological sampling (age, length, weight, sex, maturity state) was carried out during the survey to a subset of individuals. These data were used to estimate externally to the model optimization the length-weight relationships for all the three stocks, as well as to optimize internally the growth functions, the sex change (for shrimp) and maturity ogives.

In addition to the three modeled stocks (cod, shrimp and redfish), the survey database was used to estimate the index of biomass of the demersal fish community. Although the survey is not designed for pelagic fish species, it could be also used to estimate a proxy of the index of total biomass. Data from the Continuous Plankton Recorder (CPR) marine monitoring program of the Sir Alister Hardy Foundation for Ocean Science[1] were used to estimate a five years moving geometric average reflecting long term patterns in biomass of copepods, hyperiids, chaetognaths and euphausiids over the study period. The estimated average values of annual ecosystem potential production (Koen-Alonso et al. 2013) were employed to estimate, together with the CPR indexes for zooplankton prey groups and the EU survey indexes of demersal and pelagic fish biomass, the time series of total biomass for these groups. Once estimated externally, these biomass time series were fixed in the model during the optimization and served as alternative prey source to the predators cod and redfish.

Since 1993 (with the exception of uneven years since 2007) stomach content information for cod and redfish has been sampled annually during the Flemish Cap survey (Román et al. 2004). This information was used to calculate the contribution of each prey (in percentage) to the diet of cod and redfish. These databases were used as likelihood components in the optimization process. In addition, the lengths of sampled predator and prey individuals found in stomachs were used to calculate externally the parameters defining the prey-predator length relationship. The stomach content database, in conjunction with the estimates of biomass for all the preys considered in this model, were used to estimate the suitability function and prey preference for each pair of prey-predator.

Water temperature was measured during the EU survey from surface to the bottom using conductivity-temperature-depth instruments (CTDs). The raw data was processed with Seabird Data Processing version 7.25.0.319. The average annual bottom temperature was estimated as the mean value of all CTDs at maximum depth, and was used to model the total consumption by fish length.

Total catches by season as well as the size distribution of these catches by the commercial fleet for cod, redfish and shrimp fisheries were obtained from research reports and research documents published in the NAFO website http://www.nafo.int/publications/frames/publications.html as well as the information collected from database STATLANT21B (http://www.nafo.int/data/frames/data.html). Due to the lack of detailed information for several countries fishing in NAFO, most of the information on size distribution and allocation of catches over the year were gathered from the Spanish and Portuguese annual research reports. Since Spain and Portugal are two of the four main nations fishing cod and redfish in Flemish Cap, this seems a reasonable simplification. In the shrimp model, the information from the Icelandic fleet was taken as the

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[1] https://www.cprsurvey.org/

basis for size distributions. These databases were used as likelihood components in the model optimization.

The trophic interactions in the final version of the GadCap EU Marie Curie project (GadCap_304) between modelled and non modelled stocks are presented in Figure 6.2-1. Cod and redfish were considered both as prey and predators; while shrimp was modeled as prey. In addition other groups from the zooplankton, as well as demersal and pelagic fishes were included as exogenous input variables in the model (Figure 6.2-1).

Although the version number 304 of GadCap performed satisfactorily (Pérez-Rodríguez et al. 2016), its use for further assessment and management strategies exploration needed from some improvement in the model structure, as well as an update in the data used. In order to carry out this improvements the same databases available online were used (published Research Reports and NAFO online databases). However in SC05 the contribution of the stock coordinator and stock assessors directly involved in the assessment of these stocks has ensured a higher quality of the data used in the model optimization, by providing esential input data not publicly available. Once the data were updated and reviewed, different components of the model were improved following the best practices indicated in the literature (Begley and Howell 2004a, Elvarsson 2015, Howell and Bogstad 2010, Howell and Filin 2014, Taylor et al. 2007) and online information (Gadget userguide[1]). It was also essential the support and feedback obtained from experienced scientists working with stock assessment in Flemish Cap, multispecies models and/or gadget.
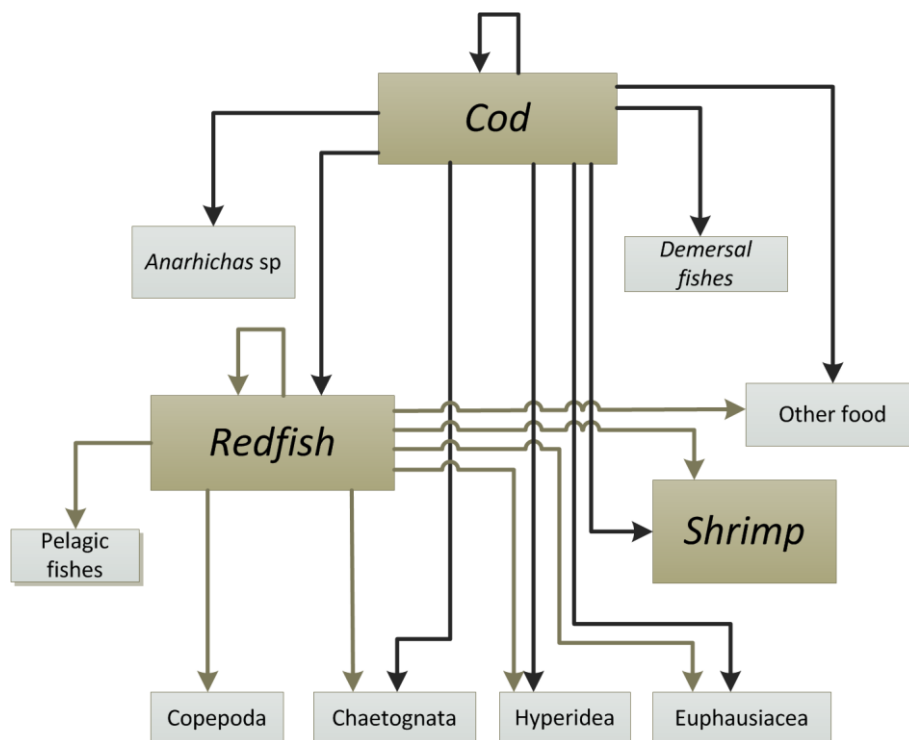

Figure 6.2-1.- Species interactions modeled in this study. Cod, redfish and shrimp are fully dynamically modeled, whereas species/prey groups in grey text boxes are incorporated as time series or constant values.

Subtask 2.1 Updating model input databases

Update and revision: In addition to updating commercial and survey input data, a thorough revision of the input data from 1988 to 2012 (period covered by GadCap so far) was also accomplished to ensure that the data used in GadCap is in agreement with the current data used in single species stock assessment models used for scientific advice.

- Commercial data: Total catch, size distribution, age/length keys and biological data like maturity or fecundity was checked for errors and re-estimated by season for each species and commercial fleet. As a starting point for a given fishing gear all countries have been considered as one only metier. NAFO online reports and data sources[1] as well as data and information from stock coordinators was used for this purpose.
- Survey data: Abundance and biomass indexes, total catch, size distribution, age/length keys, biological data (age, length, weight, sex and maturity state per individual) were checked for errors and prepared in the format needed by Gadget. Diet composition data for each sub-species in the model was updated and reviewed. Some of this data were obtained from the available survey database ARGO, some other data were directly provided by stock assessors.
- Oceanographic data: Mean water temperature in the Flemish Cap during the summer survey has been estimated from 2012 to 2017. This information was obtained from the data collected on each of the CTD (Conductivity Temperature Depth) casts conducted during the Flemish Cap survey, but also using information from the radial surverys conducted by the Department of Fisheries and Oceans (DFO) of Canada.

Subtask 2.2 Improvement of GadCap model

Some sections of the structure of GadCap (Pérez-Rodríguez et al. 2016) have been modified with the aim of improving the fit to the observed data and provide a better insight of consequences of different management strategies (Tasks 3 and 4). Next, a summarized list of the elements that have been improved or explored is presented:

- Growth model in cod, redfish and shrimp
- Maturation model in cod, redfish and shrimp.
- Consumption model (review for cod and redfish).
- Division of trawl fleet into trawl and longline fleets for cod fishery
- Weight-length relationship in cod.
- Separation of redfish into golden and beaked redfish stocks.
- Exploration of:
  o Functional response type III
  o Density-dependent and temperature-dependent growth in cod and shrimp.

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[1] https://www.nafo.int/

- Estimation of Natural mortality in cod using different alternative approaches.
- Introduction of an $M_{density}$ for long term forecast.

Subtask 2.3 Model assemblage

Once the databases, submodels and model structure were modified all elements were assembled to produce a new version of GadCap, and model parameters were re-optimized. The weight of the different likelihood components was determined using the iterative reweighting technique (Taylor et al. 2007). A sensitivity analysis was conducted to assess how close the loglikelihood score is to the minimum value, as well as to evaluate the sensitivity of the model to small changes in some parameters. All necessary diagnostics were done in order to assess the quality of the model fit.

It is important to highlight that, as it is usual in modelling exercises, there was a constant feedback between the three subtasks, which, in many cases were developed almost in parallel.

6.2.4. Results

Summary:

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. In this task, the multispecies model GadCap, considering the Flemish Cap cod, redfish and shrimp interdependent dynamics over the period 1988-2012 Pérez-Rodríguez et al (2016), has been improved and extended until 2016. This section describes the improvements in the model, 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.

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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Subtask 2.1 - Updating model input databases

As indicated above, the best model developed during the project GadCap (Gadcap model version 304, Pérez-Rodríguez et al. (2016)) 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 in Task 2 was extending the time coverage of the commercial and survey databases supporting all the different likelyhood components in the model version GadCap_304 until 2016. In addition, all these databases were reviewed to ensure, to the extent that it is possible, that the data employed in this study is comparable to the sources of information used in the aproved NAFO single species stock assessments for these stocks. In Table 6.2-1 the different databases that have been updated are compiled.

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 gillnet fleet fishing for cod were updated. The seasonal distribution and the length composition of this catches have been also reviewed and extended to 2016. For cod and redfish fisheries these data have been provided by the stock assessors and/or stock coordinators. For shrimp, due to the moratoria there is no trawl fishery since 2010 and hence, after confirmation with 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 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 fundamental source of data, taking the role of tunning 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 esencial 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, as part of this subtask 2.1, all data related with key processes for stock productivity like growth, maturation or trophic interactions (see next subtasks) 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 substocks of cod and redfish have also being reviewed and extended up to 2016. The biomass of alternative prey to those directly modeled in GadCap have also been updated. The Continuous Plankton Recorder[1] (CPR) database, collected by the Sir Alister Hardy Foundation for Ocean Science, provided indices of biomass for copepods, hiperiids,

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[1] https://www.cprsurvey.org/

chaetognaths and eufausiids in the Flemish Cap area over the period 1991-2015 (Figure 6.2-2). The biomass of other alternative prey like wolffishes, demersal fishes, mictofiids and pelagic fishes was obtained from the biomass survey indices obtained from the EU summer survey.
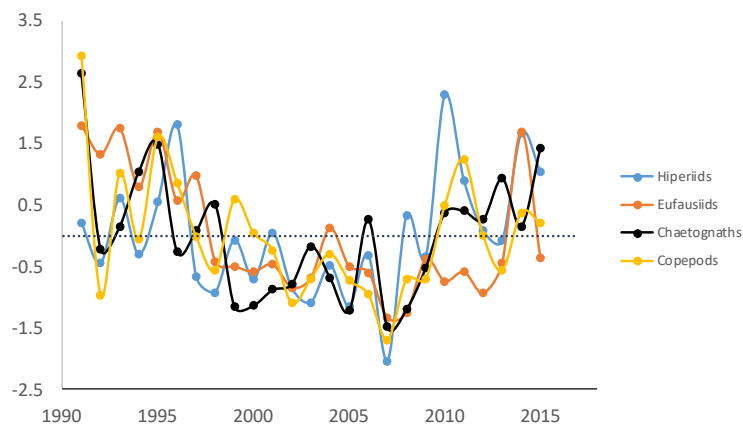
Figure 6.2-2.- Standardized abundance index of hyperiids, copepods, eufausiids and chaetognaths in the Flemish Cap area over the period 1991-2015. This index has been obtained from the Continous Pankton Recorder sampling program.

The EU survey is also a plaform 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[1] to produce a bottom water temperature database that allow estimating an annual average water temperature representative of the environmental conditions sorrounding the modeled stocks. This data were reviewed and updated to 2016 (Figure 6.2-3).

Figure 6.2-3.- Bottom water temperature in the Flemish Cap during the EU summer bottom trawl survey.

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Table 6.2-1.- List of databases that have been extended to the period 1988-2016 and reviewed. In addition, some data sources incorporated by the first time to GadCap are also indicated.

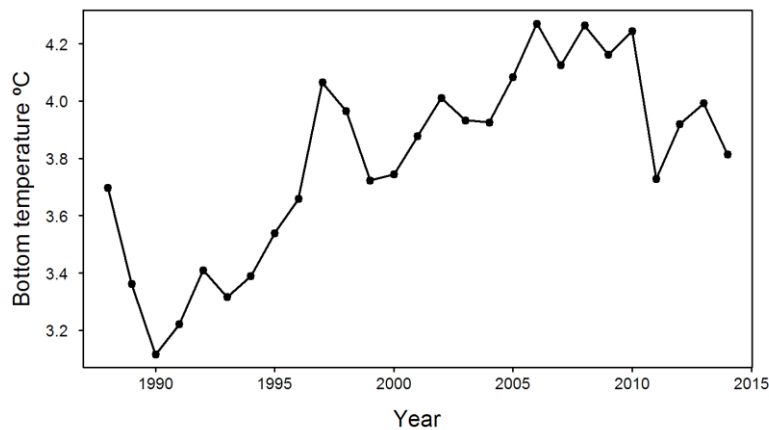| Element	Likelihood component	Action	Cod	Redfish	Shrimp
Trawl fishing	Length distribution of catches	Extension and review	X	X	Fishing ban
	Total catch in kg	Extension and review	X	X	Fishing ban
	Seasonal distribution of catches	Extension and review	X	X	Fishing ban
Longline fishing	Length distribution 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			

It is very important mentioning that due to problems with permissions, the use of data that directly or indirectly contain information about age and/or maturity stage for cod and redfish after year 2013 couldn´t be used for this SC05 project. For this reason, it had to be assumed that, for years 2014 to 2016, growth and maturation were the same than the observed/estimated for year 2013. This is not expected to have a very large impact in the assessment of these stocks at this moment. However, if the problem with full access permission to the biological data is not solved, this may be a more serious issue in the future years.

Sub-task 2.2 – Improvement of GadCap model

The updated and revised databases were incorporated into the multispecific model Gadcap presented by Pérez-Rodríguez et al. (2016). Some of these databases allowed just extending the time coverage of the model until 2016, while other in turn allowed modifying the structure of the Gadcap_304 model, incorporating new fleets, improving the adjustment of certain biological processes such as natural growth or mortality, or exploring new ecological aspects, as it was done with the type III functional response in the relationship of prey consumption/prey abundance (Table 6.2-2). 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 the annual modeling, with a single time step. In addition, alternatives to the current

optimization process have also been explored, such as the paramin tool[1] and the new algorithms of optimizations introduced by the Centre of Supercomputation of Galicia (CESGA).

Table 6.2-2.- 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		

a) <u>Improvements in the comercial and survey fleet components</u>

Like other parameters of the model, the inclusion of new data in the optimization process leads to readjustments of 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) are also reoptimized. This is an especially important aspect since fishing is one of the main factors that determine the dynamics of the modeled 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 importance 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 longline catches reported by Norway and Faroe Islands, as well as the size distributions obtained in the commercial fisheries sampling programs of these countries. Although the length selectivity may have changed over time, here an example for year 1988 is presented (the only year for which data for all the three fleets was available), where the differences in the length distribution of trawl, gillnet and longline cod catches can be noticed (Figure 6.2-4)
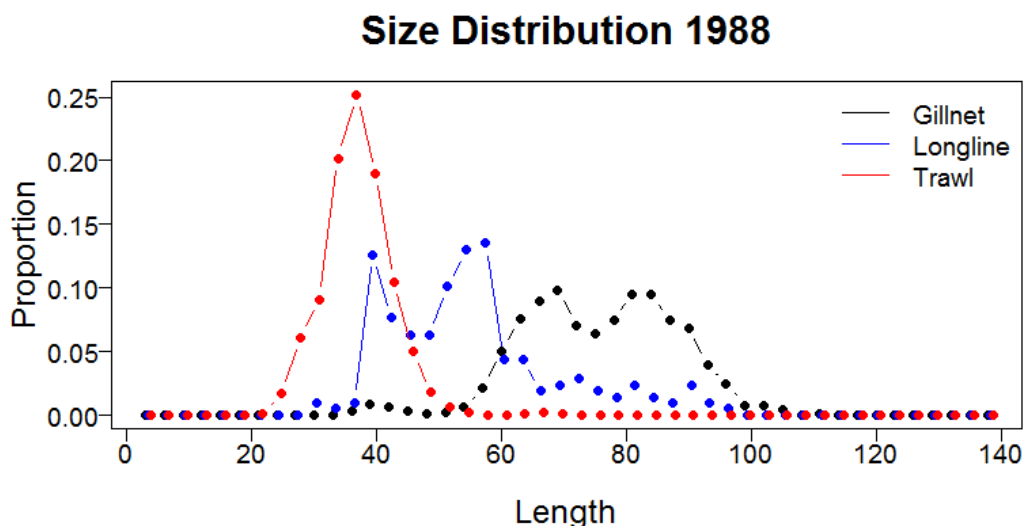
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[1] https://github.com/Hafro/paramin

Figure 6.2-4.- 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).*

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 database. The size distribution of shrimp survey catches have been reviewed and modified, using the best estimates provided by the stock assessor designated expert by the EU. 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 of allowing 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. 2016), 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. Although this is only a first tentative the annual configuration of the model has been explored, and redfish species have been separated by the first time in two stocks (beaked and golden redfish).

- 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 has been adjusted annually instead of bi-anually as it was the case in GadCap_304 model version (Pérez-Rodríguez et al. 2016). In addition, the length at age infinite (L_{inf}) has also been adjusted

annually, unlike GadCap_304, in which L_{inf} was assumed constant over time. Finally, a new likelihood component with the average weight by age has been included to improve the growth model fit. For redfish stock, instead of 3 periods a separate growth model has been fit for 4 periods: 1988-1992, 1993-1997, 1998-2012, 2013-2016.

In addition, the importance of density-dependent processes and oceanographic conditions in the observed changes in growth on cod and shrimp have been analyzed and modelled (see Task 3 section). New growth models have been fit, incorporating the effect of population size and the environmental conditions over the K and Linf von Bertalanffy growth parameters. Considering density-dependent effect on growth it is not relevant for stock assessment, however, it is expected to be of relevance when running long-term projections during the MSE exercise, when the reference points will be estimated and the uncertainty in biological/ecological processes will be considered (see the section of Subtask 3.2).

- Sexual maturation:

The importance of achieving an accurate modelling of the maturation process is related with three important elements:

- o When an individual matures the preference for the different prey in the model changes.
- o The relation SSB-recruitment is fit using the estimates of spawning biomass and recruits by year from the final model.
- o The importance of points 1 and 2 in the forward projections that will be employed to determine reference points and MSE.

In this new revised version of GadCap the adjustments to the observed maturity ogives have been improved. For cod stock, the maturation models have been readjusted in GadCap, going from a biannual adjustment to annual maturity ogives.

c) Modifications in the ecological processes

- Review of parameters defining the interaction prey-predator

The extension of the stomach content database until 2016 has allowed the revision of two essencial 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.

- Residual natural mortality

The residual natural mortality for redfish and shrimp has been maintained as it was defined in Pérez-Rodríguez et al. (2016) and it is presented in the next section. However, for cod stock, new values of natural residual mortality have been used. These values have been estimated

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using alternative methods. In the subtask 3.1 section, the work developed to estimate the residual natural mortality is presented.

d) Exploration of changes in the model structure:

- Separation of redfish species

The posibility of separating the redfish stock into golden (*Sebastes marinus*) and beaked redfish (*S.mentella* y *S.fasciatus*) has been explored. The process is still in a very early stage of development and the model presented in this report (see the next section for subtask 2.3) still consider all the three species together. Still, in this section the motivation to separate the species, and the approach followed in that process is presented.

The main reasons supporting the separation of the redfish species are:

- Fishery developed by different fleets (Ávila de Melo et al. 2017):
  - Golden redfish: mostly by-catch from cod fishery.
  - Beaked redfish: mostly directed fishery, although by-catch from cod and Greenland halibut fisheries is also important.
- Strong differences in the growth curve, specially the L_{inf} (Figure 6.2-5).
- The depth distribution is different by species (Figure 6.2-6). Based in the more similar depth distribution of cod and golden redfish (*S.marinus*) it may be expected than predation on this redfish species is higher.
- Length and age at maturation seems to be also different between species (Saborido-Rey, PhD. Thesis). In the early 1990's L50 was 26.5 cm in *S. fasciatus*, 30.1 cm in *S. mentella* and 34 cm in *S. marinus*.
- The diet composition also show some important differences between golden and beaked redfish (Figure 6.2-7), such as the higher proportion of chaetognaths and copepods in golden redfish versus a higher proportion of other food in beaked redfish. But the most important difference for GadCap is that cannibalism occurs only in golden redfish, especially in mature individuals.

In relation to differences by sex the average length at age is higher in females than males, especially after age 15 (Figure 6.2-8). While K seems to be similar, Linf is probably higher for females than males. Hence, all three redfish species should be splitted by sex.
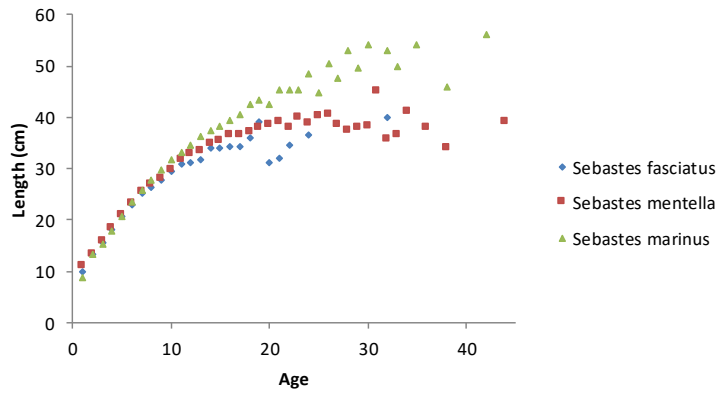
Figure 6.2-5.- Average size (in cm) at age for the three redfish species. Data from the EU surveys of period 1991 to 2013 have been used.
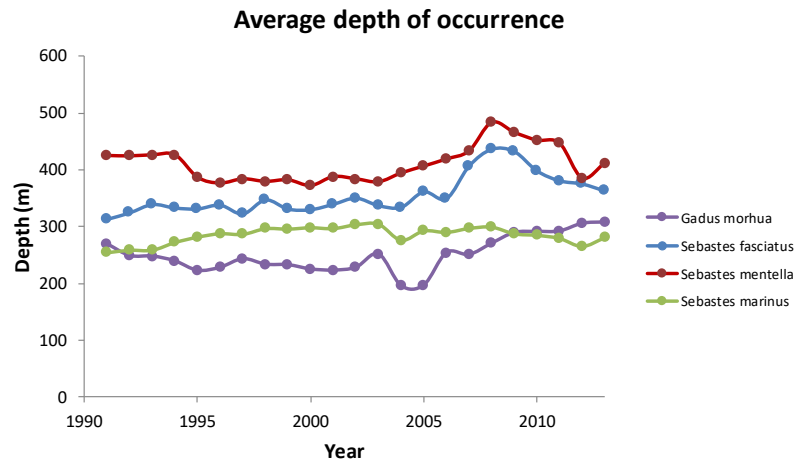
Figure 6.2-6.- Annual average depth of occurrence by species across the period 1991-2013

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Figure 6.2-7.- Diet composition (in proportions) for immature and mature golden and beaked redifsh over the time period 1993-2016. Proportions have been estimated for the prey species considered in GadCap.
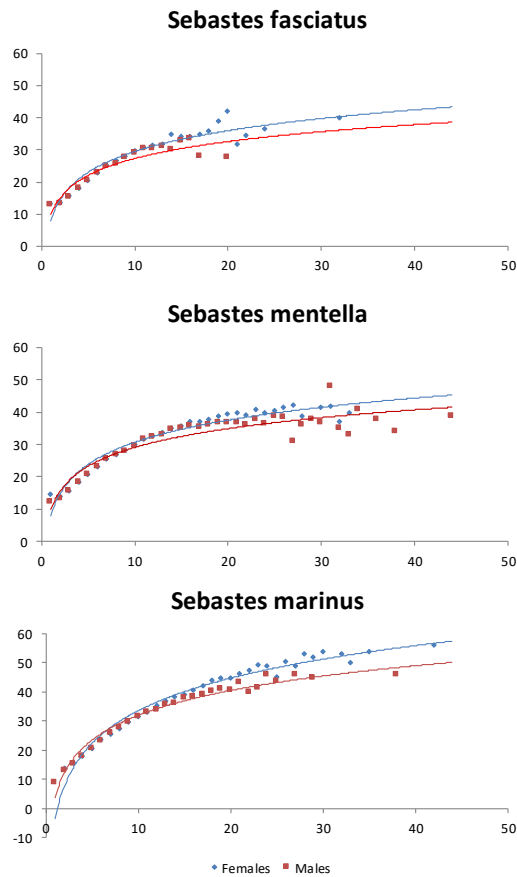
Figure 6.2-8.- Size (in cm) at age for males and females of three redfish species.

Maturation by sex considering all redfish species together and based in the data available for the period 1978-1985 (Canadian surveys), seems to occur at smaller size (L50: Males~24 cm; females~30 cm) and younger age (A50: Males~10 years; Females~16 years) in males than in females (Figure 6.2-9).
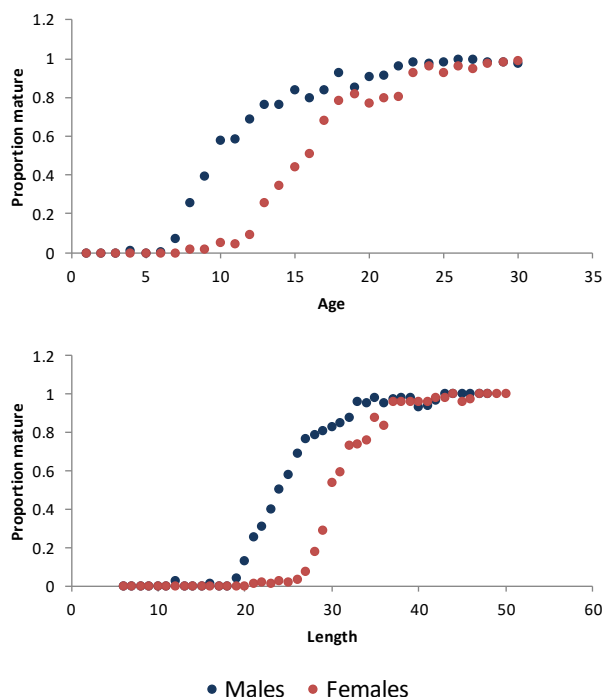
Figure 6.2-9.- Proportion of mature individuals by size (upper panel) and age (bottom panel) for all three redfish species together. Data from the Canadian surveys, 1978-1985.

For all these reasons a new configuration of the GadCap model was developed, with redfish species separated on golden and beaked redfish, which in turn are separated by sex. However, as indicated, this model is still in a preliminary stage and is not presented in this report. Different 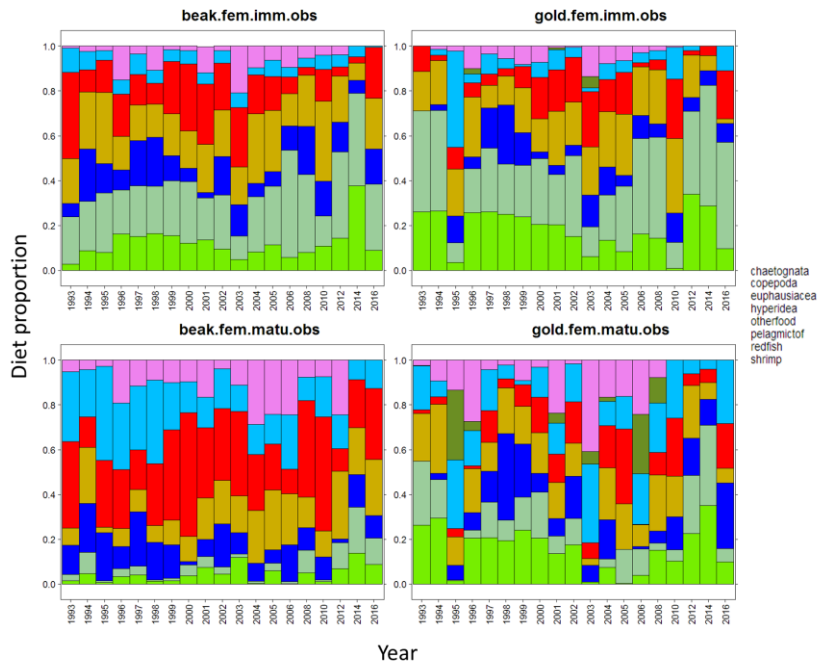elements need still to be improved before this model is used for scientific advice purposes. Among this issues, commercial catches of golden redfish from 1988 to 2005 has to be estimated as it has been done for the period 2006-2016 following the protocol described by Ávila de Melo et al. (2013).

- Annual structure

The model version called SC05_34 was taken as the basis to change the number of timesteps in the model, from four time steps (seasonal time steps) to one (annual time step). This means that all processes (predation, growth, fishing, etc) are calculated only once a year instead of four times (by season). The benefits of a model with annual timesteps are very important:

- Data used for the single species methods could be used for the multispecies model GadCap, and therefore would reduce considerably the work required to update the model.

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- The fact that the model has to do the calculations one time instead of four times per year makes the optimization and simulation process much faster.

However, exploring the possibility of a multispecies model with annual structure implies a deep reorganization of all databases that feed the model. The re-calculation of multiple parameters that drives the dynamic of the stocks in the simulated populations is required, especially those related to the commercial fleet catches and consumption. In addition, the entire structure of the model must be modified so that the processes occur once a year, instead of 4 times as it was modeled so far. Finally the model has to be re-optimized, and the weight of the different likelihood components have to be re-estimated.

Preliminary results show estimates of total population abundance and biomass well below those obtained in the model with seasonal timestep and the single species stock assessment with XSA (Figure 6.2-10) by Ávila de Melo et al. (2017). Several modifications have been introduced in the configuration of the model, however this marked differences have not been dimished up to date. The most plausible explanation for these differences is that the growth process and the variability around average growth can not be adequately modeled if the year is not divided into at least four periods (Begley and Howell 2004).
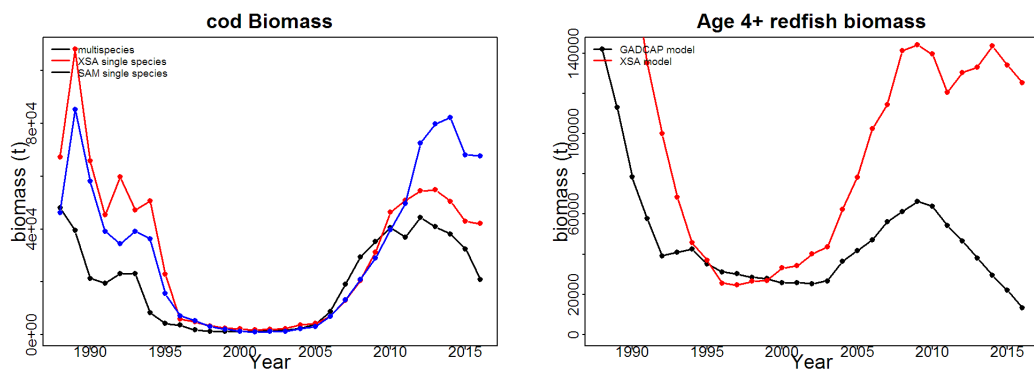
Figure 6.2-10.- Left panel : Total cod biomass estimated by single species models (XSA and SAM) and multispecies model GadCap with annual time steps. Right panel : Total redfish biomass at age 4+ estimated by single species models XSA and multispecies model GadCap with annual time steps.

- CESGA optimizers

The Supercomputing Center of Galicia, CESGA (Spain), from University of Santiago de Compostela (Spain) has developed a project that resulted in the implementation of two new optimization algorithms in Gadget: Particle Swarm Optimization (PSO) and Differential Evolution (DE). These methods have been improved with openMP parallelization, a self-tunning of configuration parameters and with additional diversification methods. The up-to-date results are very promising. Gadget with the new optimization framework is on average twice faster (Figure 6.2-11) and produces less variable parameter estimates when restarting the optimization from different initial values.

However, the new optimizer doesn't improve estimates of unstable models. The explanation to this is that the instability in the parameter estimates could simply be related to uncertainty, i.e. the objective function is flat in the neighborhood of the minima.

Currently some problems have been found when combining the PSO with Hooke and Jeeves. These difficulties are being studied, and when solved, this achievement may contribute in the development of GadCap in future projects, by allowing testing a higher number of model configurations due to its faster performance.

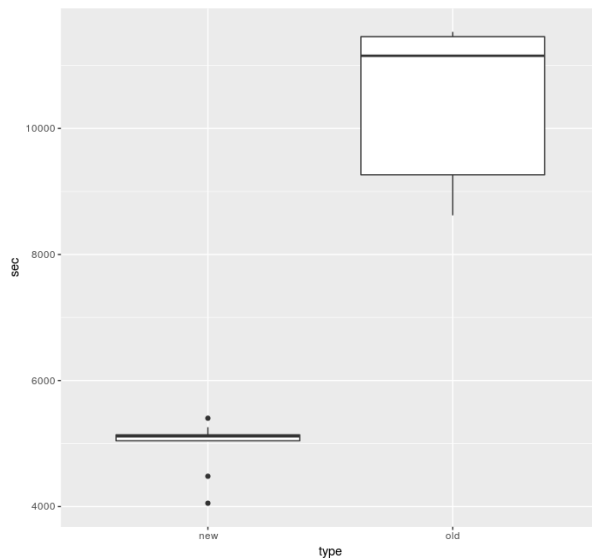**Figure 6.2-11.- Average time in seconds (horizontal black line within the box) needed to achieve convergence using the old (Hooke & Jeeves and Simulation Annealing) versus the new (Particle Swarm Optimization and Differential Evolution) optimization algorithms in gadget. The lower and upper limits of the box represent the 25 and 75 percentiles of the optimization time respectively.**

Sub-task 2.3 – Model assemblage

Cod, redfish and shrimp single species model settings

As explained in the previous section, the model configuration with one single time step has not perform satisfactorily. 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 four timesteps by year (seasonal timesteps). All the three stocks were modeled over the period from 1988-2016, 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 Table 6.2-3, Table 6.2-4 and Table 6.2-5 for cod, redfish and shrimp respectively.

As it was presented in the previous section, 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, for the separation of commercial catch between this two stocks strong asumptions have to be

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undertaken, 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 strong asumptions to separate redfish bewteen beaked and golden redfish during the late and early 1990s. More important, strong assumption has to be undertaken to separate 1-3 year old individuals (<15cm) between beaked and golden redfish. Due to these data limitations, the first option considered in this project SC05 was to include 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 in future research projects 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 diferential 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 posibility of splitting cod by sex.

Table 6.2-3.- 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.

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 annualy 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:

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

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.

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.

Table 6.2-4.- 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	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			
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.

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

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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.

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.

Table 6.2-5.- 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	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			
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.

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:

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

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 2 and 3) 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

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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 1), residual natural mortality was fixed as 0.35 based in the results of the analysis presented in the Subtask 2.2 section.

Assemblage of the multispecies model

Cod and redfish act as both predators and prey (Figure 6.2-12). 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.
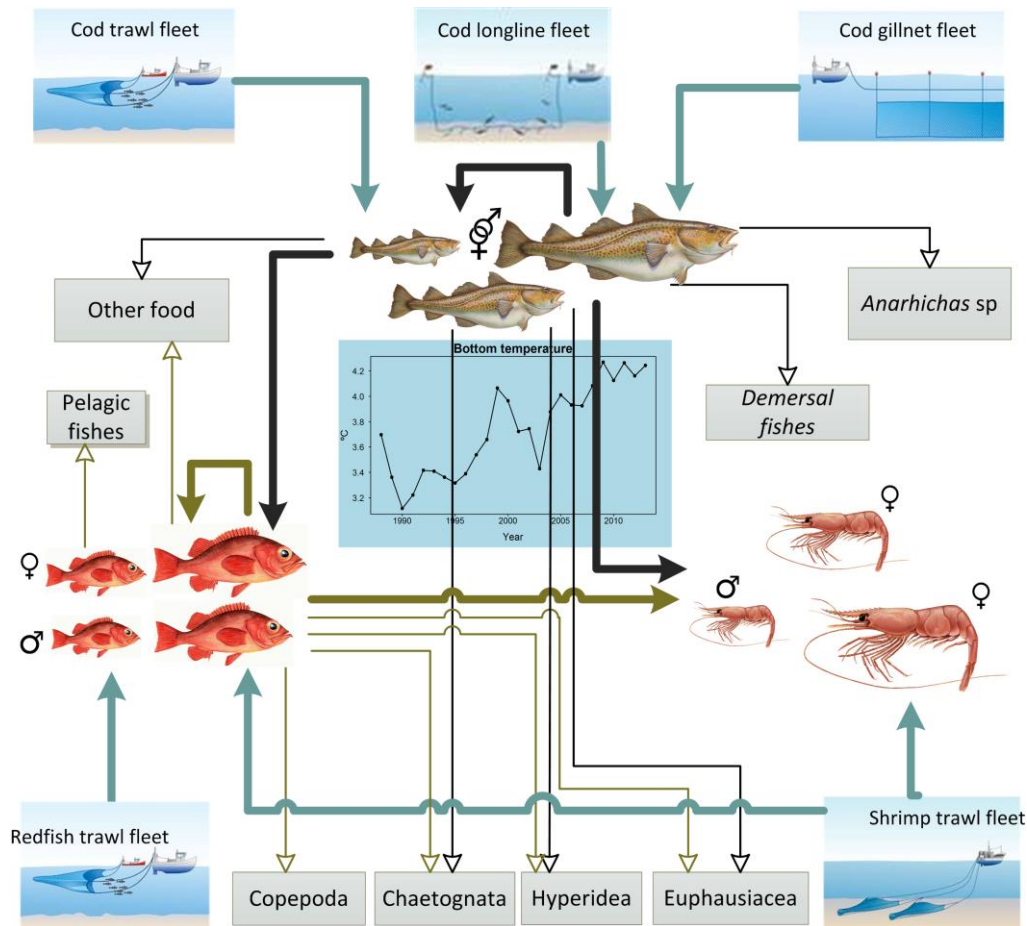
Figure 6.2-12.- Species interactions modeled in this study. Cod, redfish and shrimp are fully dynamically modeled, whereas species/prey groups in grey text boxes are incorporated as time series or constant values. The fleets fishing each species are also represented, as well as the effect of water temperature in total consumption.

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 ratio of fish surface and methabolic 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 optimice 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.

Model diagnostics

GadCap, once updated and improved, showed a high performance. Length distributions from survey and commercial fleets, total commercial catches and survey indices, catch at age, diet compositions were simulated very closely (see annex III). For this reason, the model GadCap was considered adequate for the assessment of the dynamic of the three stocks, as well as their trophic interactions over the period 1988-2016. In the next sections, GadCap was used to provide estimates of population biomass, abundance and recruitment.

Population estimates and mortality estimates

- Cod, redfish and shrimp stock dynamic

Model estimates of annual recruitment at age 1 (Figure 3.2-33), total abundance (Figure 3.2-34) and total biomass by maturity and/or sex state (Figure 3-49) 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 2011 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 2012, 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 is experiencig a marked decline.
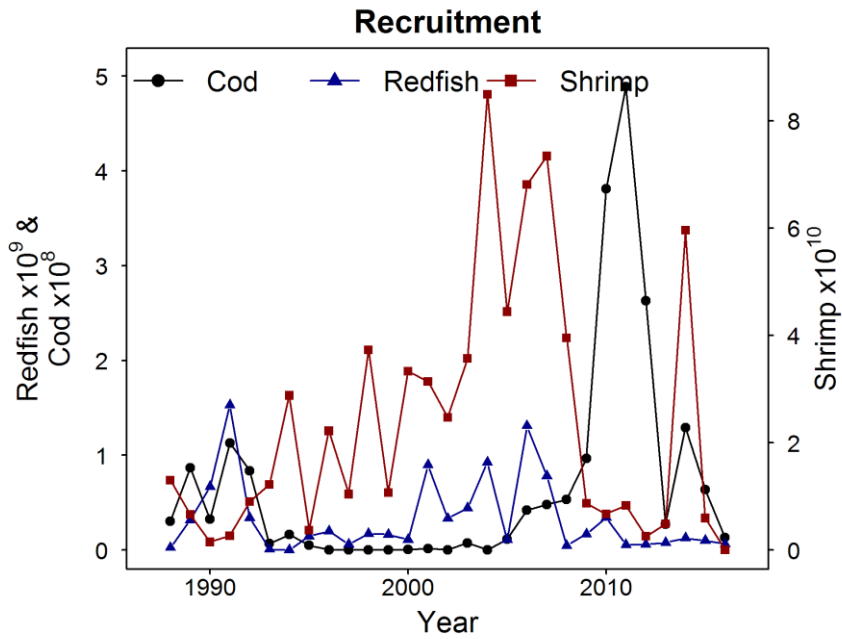
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Recruitment

Figure 6.2-13.- Annual recruitment at age 1 as estimated by the GADGET model for each of the three stocks.

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 did not translate 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.
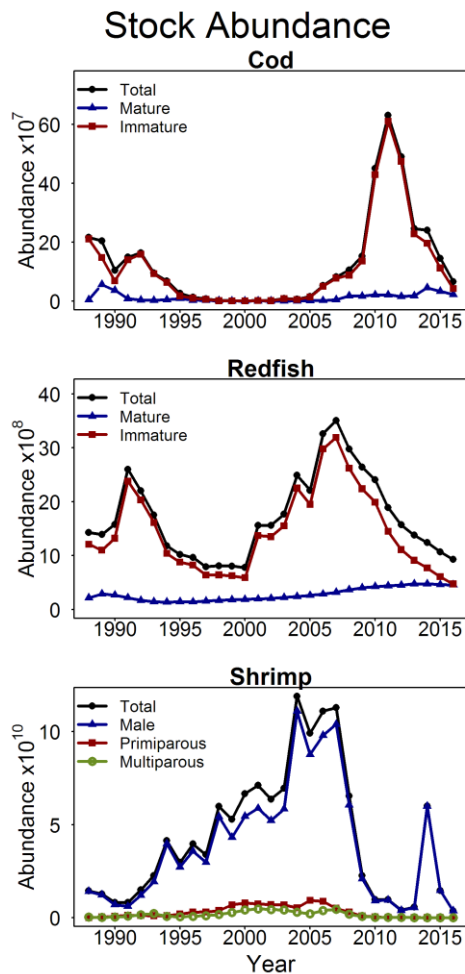
Figure 6.2-14.- Annual estimates of stock abundance, total and by maturity stage, for each of the three modeled stock (top: cod, middle: redfish, bottom: shrimp).

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.

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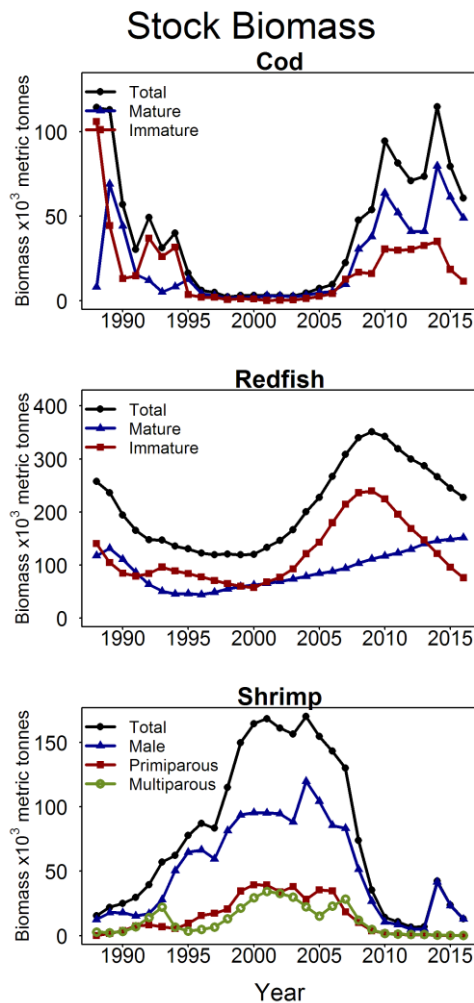"Multispecies Fisheries Assessment for NAFO"

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Figure 6.2-15.- Annual estimates of stock biomass, total and by maturity stage, for each of the three modeled stocks (top: cod, middle: redfish, bottom: shrimp).

- <u>Instantaneous and harvest rates by source of mortality</u>

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 3.2-36, 3.2-37 and 3.2-38). In cod cannibalism was the main source of mortality at age 1 all over the study period (Figure 3.2-36), 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).
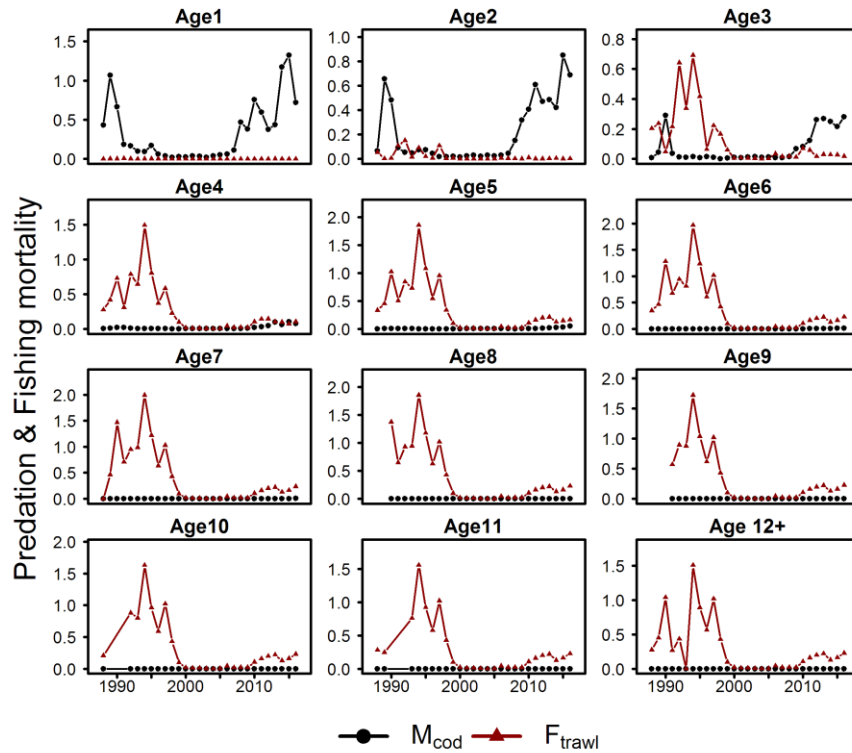
Figure 6.2-16.- Predation mortality by cod (M_pred by cod) and fishing mortality by age in the modeled cod stock. The "Age 12+" pannel shows the mortality rates for individuals of age 12 and older.

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 3.2-36). 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.
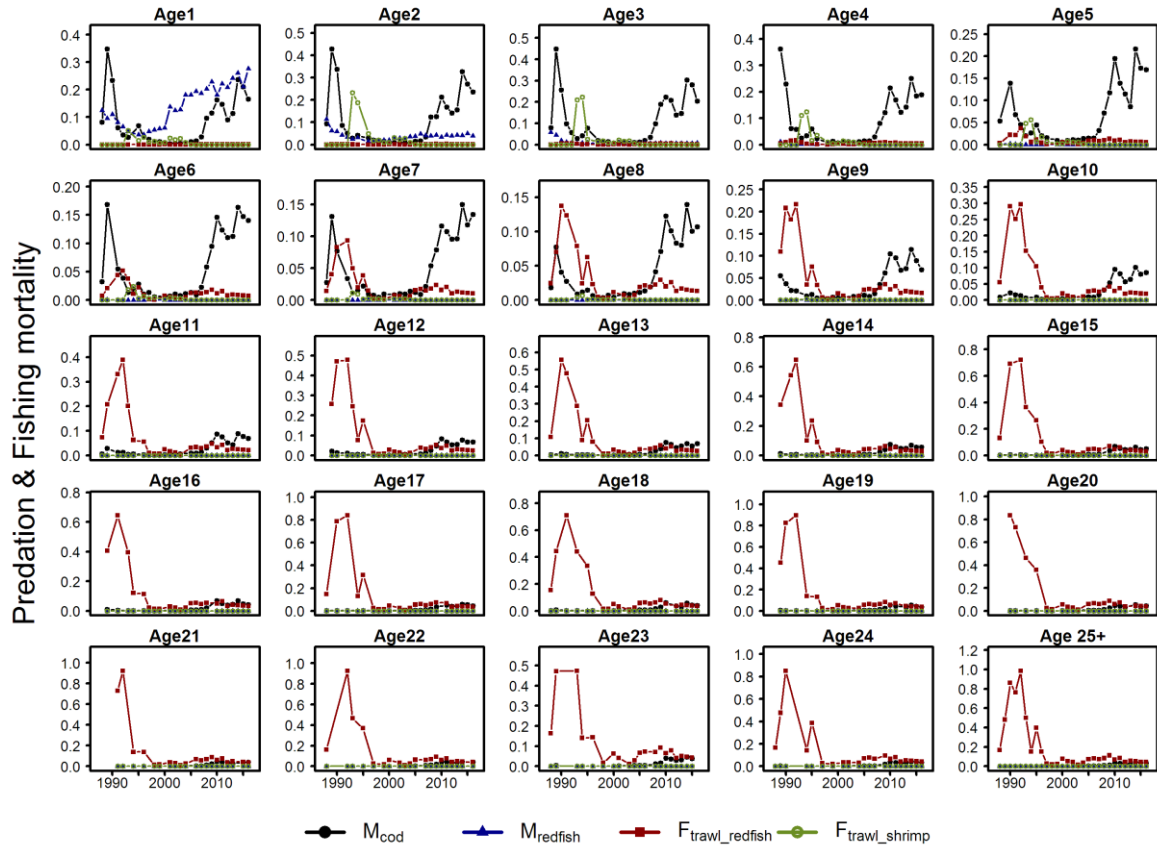
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Figure 6.2-17.- Predation mortality by age in the modeled redfish stock, by cod (M_pred by cod), by redfish (M_pred by redfish) and fishing mortality by the redfish trawl fleet (F_red_trawl) and the shrimp trawl fishery (F_shrimp_trawl). The "Age 25+" pannel shows the mortality rates for individuals of age 25 and older.

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 3.2-37), 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.
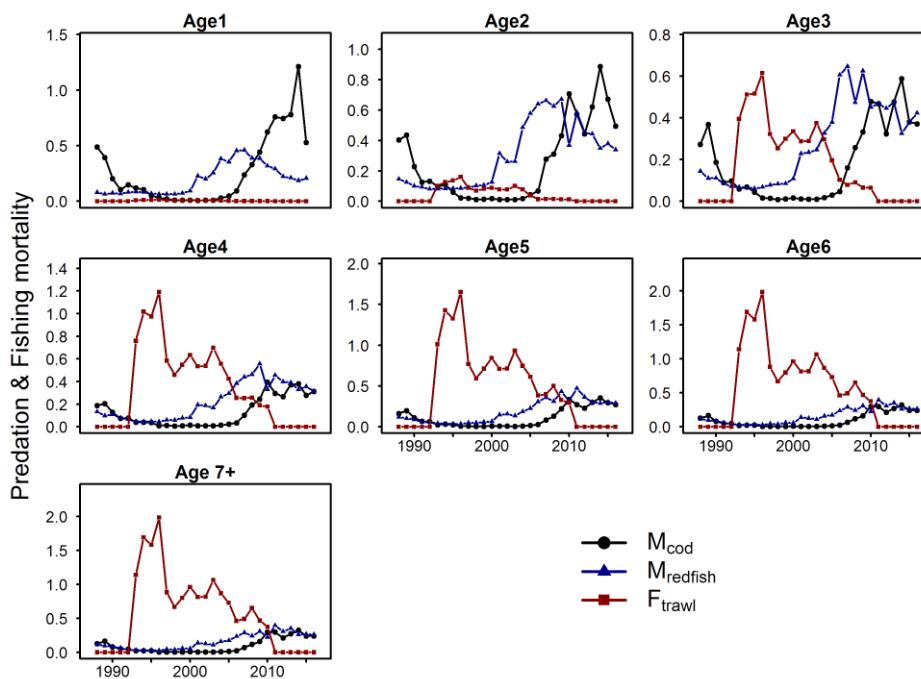
Figure 6.2-18.- Predation mortality by cod (M_pred by cod), by redfish (M_pred by redfish) and fishing mortality by the shrimp trawl fleet by age in the modeled shrimp stock.

6.2.5. Difficulties

As indicated in the previous sections, the main difficulties found in this Task 2, were related with the separation of redfish species into golden and beaked redfish. As it was made explicit in the project proposal, this reforms were explored. However, due to the lack of the approapriate data on due time, it has not been possible accomplish this task whiin this project SC05. In Task 6, a compilation of difficulties, gaps and possible improvements in future projects is presented.

6.3. TASK 3 – APPLICATION OF MULTISPECIES MODEL IN STOCK ASSESSMENT IN THE FLEMISH CAP

6.3.1. Summary

In this task, the multispecies model GadCap, once updated and improved in Task 2, was used for practical purposes in fisheries advice. First the estimates of natural mortality at age are used in the single species stock assessment model during the cod benchmark, next, reference points were estimated from a multispecies perspective, and the resulting HCRs were tested using an MSE framework where the multispecies model GadCap was included as operating model.

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The results of this Task 3 allow concluding that:

- Subtask 3.1:
    - Residual natural mortality (M1) seems to be higher than initially though for the Flemish Cap cod, as observed from the application of several methodologies, being on average around 0.35 at age.

    - There exist a strong variability in the predation mortality (M2) on cod, both at age and over time. This two factors are strong indicators of the need of considering alternative estimates of natural mortality (M1 and M2, residual and predation) for a proper assessment of the Flemish Cap cod, a better estimation of population dynamic in short term forecasts and accordingly, providing a more accurate catch advice.

- Subtask 3.2 and 3.3:
    - Combinations of HCRs designed under a single species approach were not precautionary for cod and shrimp in a framework where species interactions are directly modelled and simulated.

    - The risk analysis of HCRs combinations defined with multispecies criteria indicated that it is not possible maintaining the 3 stocks above B_{lim} at the same time. The reasons are the strong trophic interactions between the assessed stocks. Trying to maintain shrimp above Blim requires excessive fishing pressure on cod and redfish in order to reduce predation mortality, and this involves high risk of collapse on cod. On the contrary, maintaining cod above Blim involves high predation and high risk of collapse on shrimp and redfish.

    - Disregarding one stock may allow finding precautionary multispecies reference points for the other stocks. Disregarding cod would result on fishing redfish within precautionary levels. Disregarding redfish would allow fishing cod without collapsing the stock. However, this was not possible for shrimp. It is probable that the uncertainty in the recruitment process, taken randomly in this study have been determinant on this.

    - Precautionary HCRs for two stocks at once were only found when shrimp SSB in relation to B_{lim} was disregarded. Although there were not a high number of possibilities, there were a few combinations of HCRs that allowed fishing cod and redfish without collapsing the stocks. The estimated yield in the long term indicates that this strategies are in the line of the yields obtained for both stocks since the reopening of the cod fishery in 2010.

    - The results showed that the two stages HCRs for cod reduces predation and increases probability of cod and redfish being above B_{lim}. This result

supports that alternative two stage HCRs, or some other HCRs with other shapes, may increase the possible combinations of fishing pressure for these three stocks.

o The risk assessment indicated that the selected combinations of HCRs were still precautionary when the assessment error was included in the MSE. The assessment usually underestimates the real abundance at age, and, accordingly, the catch advice will always be below the real catch that the stock could support.

In the next sections, an extended description of the work conducted, the results and conclusions in the three subtasks 3.1, 3.2 and 3.3 is presented.

6.3.2. Objectives

This Task aims at:

- Estimating values of natural mortality for cod, redfish and shrimp that can be used in short term forecast projections with single species stock assessment models.
- Exploration of potential new reference points and Harvest Control Rules from a multispecies approach. Assemble a Management Strategy Framework that can be used to assess HCRs considering species interactions.

To accomplish this, Task 3 is divided in the following subtasks:

- Subtask 3.1.- Estimates of natural mortality (M1+M2) and use in single species short term forecast
- Subtask 3.2.- Explore single and multispecies reference points and HCRs
- Subtask 3.3.- Multispecies Management Strategy Evaluation

6.3.3. Methodology

Sub-task 3.1 – Estimates of natural mortality (M1+M2) and use in single species short term forecast

This subtask is connected with tasks 1 and 2 of the EU SC03 project *"Support to a robust model assessment, benchmark and development of a management strategy evaluation for cod in NAFO Division 3M"*. As part of this project SC03 a benchmark process took place to decide the model settings that will be used for the assessment and short term projections of the 3M cod.

The contribution of SC05 to this project SC03 was:

1. Providing estimates of natural mortality that were used during the 3M cod benchmark exercise as a more ecologically sounded value of M.

2. Providing estimates of natural mortality to be used in the short term forecast in support of catch advice for 3M cod (in case GadCap estimates of mortality are selected as the option to be used in the stock assessment).

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Different methods to estimate residual mortality (M1) were explored (see the *'Results'* section). Once an estimate of M1 was available, GadCap was reoptimized and estimates of total natural mortality (M1+M2) were provided to be used during the 3M cod benchmark meeting.

Subtasks 3.2.- Explore single and multispecies reference points and HCRs.

Harvest Control Rules (HCRs) are the basis for scientific advice in several management organizations, including NAFO, combining an approximation to Maximum Sustainable Yield (MSY) with a degree of precaution against recruitment overfishing and stock collapse. However, most of the work done when designing, evaluating, and implementing existing HCRs has been traditionally carried out in a single species context. However, due to multispecies technical and biological interactions, combining the use of a number of single-species HCRs within an ecosystem to provide catch advice may have unforeseen consequences. Changes produced by fishing in the biomass of key species in an ecosystem can be expected to impact on the natural mortality and productivity (and hence the outcomes of HCRs) of the direct predators and preys, as well as on competing species. Factors such as size selectivity or inter-annual variation on catches may perform differently in a single-species and multispecies analysis. A very important distinction has to be drawn between using multispecies models to assess single species HCRs, and HCRs designed explicitly to account for multispecies interactions. The current policy in NAFO is moving towards a more ecosystem-based approach to fisheries management. All this require HCRs to be evaluated in a multispecies context as a basis for sound management.

In this subtask, reference points in line with the precautionary approach (PA) and the Maximum Sustainable Yield (MSY) approach were estimated based in single and multispecies criteria. These reference points were used to define Harvest Control Rules HCRs. In the estimation of both precautionary and MSY reference points, the NAFO rules have been used as guidelines.

Criteria for the definition of Precautionary and MSY reference points in NAFO

NAFO Scientific Council (SC) Precautionary Approach (PA) framework started to be developed in 1997. This initial framework incorporated limit, buffer and target reference points, specified in terms of both fishing mortality and SSB. In 2003 a new PA framework was developed (NAFO 2004), describing zones of gradual increase in collapse risk and defined proposed management strategies and courses of action within each zone. These zones (Figure 6.3-1) were separated by limit and buffer reference points (called B_{lim}, B_{buf}, F_{lim} and F_{buf} and explainded bellow).
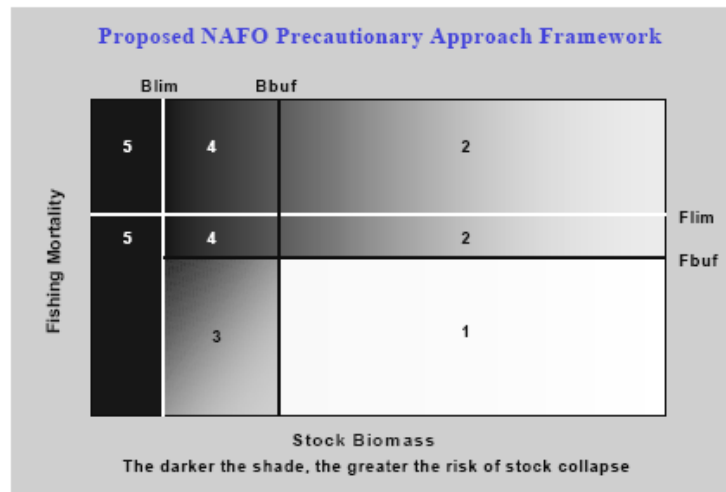
Figure 6.3-1.- Schematic depicting a revision to the proposed NAFO PA framework adopted by the Scientific Council in September 2003 (Taken from NAFO (2004)).

The reference points associated with the 2003 Framework were defined as follows (Figure 6.3-2):

Fishing Mortality Reference Points

• F_{lim} = F limit, is a fishing mortality rate that should only have a low probability of being exceeded (usually around 10% risk). F_{lim} cannot be greater than fishing mortality providing MSY (F_{MSY}).

• F_{buf} = F_{target}: F target, is a fishing mortality rate lower than F_{lim} that is required in the absence of analyses of the probability that current or projected F exceeds F_{lim}. It is a common approach in NAFO estimating F_{target} as $2/3*F_{lim}$. This is the approach that was followed in this project, since gadget is a deterministic type model that does not produce estimates of uncertainty.

Spawning stock biomass reference points

• B_{lim}: B limit, is a spawning stock biomass level, below which stock productivity is likely to be seriously impaired, that should have a very low probability of being violated (usually around 10% risk).

• B_{buf} = $B_{trigger}$: B trigger, is a stock biomass level above B_{lim} that is required in the absence of analyses of the probability that current or projected biomass is below B_{lim}.
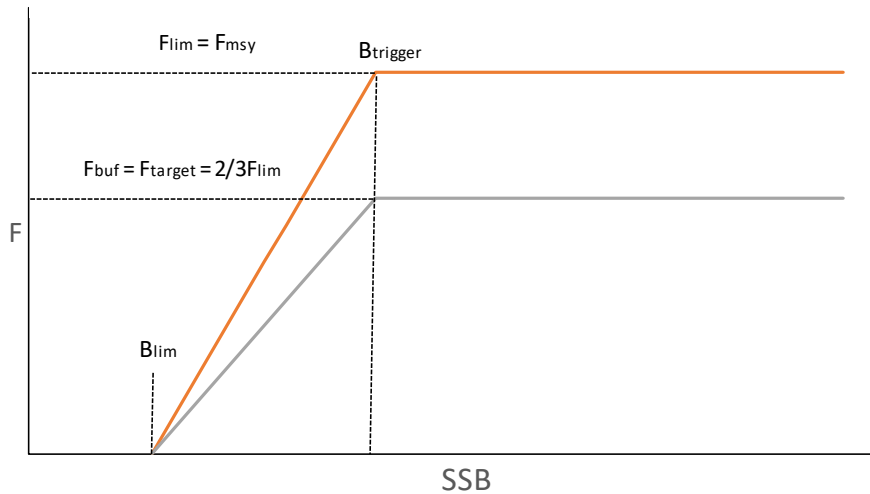
NAFO precautionary approach framework

Figure 6.3-2.- Reference points used in this study to define HCR following the NAFO precautionary approach framework.

In this study the NAFO PA framework (NAFO 2004) has been followed in the determination of the precautionary (B_{lim} and $B_{trigger}$) and MSY based reference points (F_{MSY} and F_{target}) to define single and multispecies HCRs. B_{lim} and $B_{trigger}$ were estimated for cod, redfish and shrimp using their respective SSB-Recruitment relationship, as it is explained in the next section. F_{MSY} and F_{target} were estimated for each stock from the long term simulations run using the multispecies model GadCap. The settings that allowed GadCap being used as a simulation model are explained in the next section. HCRs were designed in a way that F=0 when SSB≤B_{lim} (Figure 6.3-3), i.e. a traditional one stage hokey stick HCR. However, as it is presented later, two stage HCRs were also tested.

<u>Modelling the SSB-Recruitment relationship and the estimation of B_{lim} and $B_{trigger}$</u>

The SSB estimated annually in GadCap over the period 1988-2015 was used to model the recruitment estimated in the period 1989-2016, i.e. a one year delay between the SSB and the recruitment values that accounts for the fact that the recruitment in GadCap is modeled at age 1 for all the three stocks. There is little evidence in the available data to select the form of the SSB-recruitment function for the Flemish Cap stocks. However, the Ricker SSB-Recruitment model has been used due to its capacity to avoid unrealistic high estimates of recruitment produced by extremely high levels of SSB in some of the scenarios, as well as contributing to account for the cannibalistic behaviour observed in cod and redfish in the Flemish Cap (Pérez-Rodríguez et al, 2017).

$$R = \mu \, SSB \, e^{-\lambda \, SSB}$$

Where R is the recruitment in number of individuals at age 1, the SSB is the Spawning Stock Biomass, and μ and λ are parameters estimated when fitting the model.

The fitted Ricker SSB-Recruitment models for cod, redfish and shrimp were used in the estimation of their respective PA reference points. B_{lim_50}, B_{lim_75} and $B_{trigger}$ were defined as the SSB at which the recruitment was, respectively, 50%, 75% and 90% of the maximum value predicted by the fit model. For the calculation of MSY reference points, the SSB-

recruitment models were used as part of the model GadCap when running long term simulations, determining the number of recruits that entered in the population every year as a function of the SSB. When selecting the MSY reference points for each stock, in addition to the mean recruitment as a function of the SSB, the uncertainty around it was also considered, as it will be shown in section 3.3.3

Adapting GadCap for long term projections

GadCap is a gadget stock assessment model which structure has been created to assess the state and dynamic of the cod, redfish and shrimp Flemish Cap stocks and their respective fisheries as a function of the recruitment process, the fishing activity itself and the ecological interactions that occur between them (see section 3.2). In this Task 3, in order to estimate the MSY reference points (F_{target}) for cod, redfish and shrimp, GadCap has been used as a simulation model to run long term projections. Several different fishing pressure values have been used in these simulations with the intention of finding the F value that produce the highest productivity with the lowest ecological risk. In preparing the GadCap model to run forward simulations, several elements have to be modified in the structure of the model, and important asumptions have to be made in relation to ecological and biological processes.

The first element changed in the structure of GadCap was the time frame, which was modified to cover the period from 2017 to 2050. This time period was considered enough for the three stocks to reach the equilibrium in their dynamics, necessary to calculate the population and fisheries parameters that allow selecting an F_{target} for each stock.

Next, the Ricker SSB-Recruitment model described in the previous section, was incorporated to the structure of GadCap. When running the long term simulations, this model determined the new individuals that entered in the population at age 1 every year based in the level of the SSB in the previous year.

After setting the time period and the SSB-Recruitment, all the parameters needed to simulate the different processes affecting the dynamic of the three stocks were defined using the parameter values optimized when fitting GadCap to the historic period databases. These processes were: annual growth, length-weight relationship, maturation, sex change (from male to female primiparous shrimp), suitability of each prey for each of the predators, gear selectivity for the trawl fleets, residual natural mortality at age. The values for parameters defining these proceses were defined as the average of the values in GadCap during the historic period 2014-2016.

As part of this project, a preliminary study about the effect of density-dependent processes on growth in cod and shrimp was developed (see Annex II). The results indicate a significant effect of water temperature and biomass of the stock in the length at age 1 and 2. Including this process in the model GadCap for long term simulations would be very convenient. However this requires complex changes in the model structure that were not possible to address during this project SC05. This improvement may be included in future projects.

Deterministic long term forecast and selection criteria to define single and multispecies F_{target} reference points

Once the multispecies model GadCap was set up as described in the previous section, fishing activity was the only process to be defined, i.e. the level of fishing mortality F that each of the three trawl fleets (one per stock) was going to produce on each targeted stock in those

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long term simulations over the period 2017-2050. Running multiple independent simulation over this period with different fishing pressure allows assessing how the stock dynamic and the fishing catches (SSB and yield) changes over time as a function of F. This is the method used traditionally to find the optimal F (usually F_{MSY}) when using numerical models. In a single species approach, for each stock several levels of F need to be tested independently. In this work, 20 different values of fishing mortality F were simulated for cod, redfish and shrimp (Table 6.6-1**Error! Reference source not found.**). However, in a multispecies approach it is necessary that the effect of combined levels of F for all the stocks that show strong interactions is assessed, since the level of F in one stock will affect the productivity in the other stocks. In our study, this resulted in 20^3=8000 combinations of Fs, i.e. 8000 different long term forecast simulations to be performed.

Gadget is a deterministic model, and hence, for each combination of F the forecast simulation produced, by stock, a single estimate of catch, SSB, abundance at age, etc. Accordingly, the probability of a given combination of Fs to drive the SSB of each of the stocks bellow B_{lim} cannot be assessd with GadCap at this first stage. The risk assessment associated to each F level combination was conducted in a second stage using the multispecies MSE framework developed as part of the subtask 3.3 (see the next section). Despite of the limitations, the deterministic approach developed in this Task 3.2 can be used as a first step to reject those combinations of F that, already in a deterministic simulation, would bring the stocks bellow their respective B_{lim}.

In order to assess if a given combination of F would, in the equilibrium, bring the stocks bellow B_{lim} in a deterministic way, the mean SSB in the last 15 years of the simulated period (2035-2050) was estimated. The long term yield or catch associated to that combination of Fs was also assessed by estimating for each stock the mean catch during the that same period. This information (mean SSB and yield in the period 2035-2050) was used to select F_{target} for each of the three stocks to define candidate combinations of HCRs. As indicated, in a second stage the risk assessment considering uncertainty in some of the biological processes (at this stage uncertainty in the recruitment process) and error in the assessment will be considered to select the reference points and HCRs. As it is described in the next section, the approaches to define the candidate reference points are different from a single and multispecies approach.

Criteria to determine MSY reference points from a single-species perspective:

As the name indicates, in a single species approach, interactions between species are disregarded. Accordingly, there is no interest in considering the result of combining different values of F for the three stocks. For this reason, when assessing the performance of each of the 20 different F levels for each of the three stocks, the different fishing levels for the other two stocks are disregarded. In this process, the steps followed were:

1. Calculate, for each stock and each F level, the mean SSB and yield over the period 2035-2050 (average SSB and yield obtained in the 400 simulations of the 20x20 Fs of the other two stocks).
2. For each stock, select the F that produces the highest yield while SSB is above B_{lim} in a deterministic way. This is a candidate $F_{lim}=F_{MSY}$.
3. Estimate F_{target} as 2/3*F_{lim}: as explained above this is a standard procedure in NAFO when using a deterministic models like gadget.

Table 6.3-1- List of F values (20 values) tested for each of the three stocks considered in this study. All the possible combinations (8000 in total) were implemented in GadCap when running long term simulations over the period 2017-2050. The resulting estimates of yield and SSB were used to produce yield and SSB curves as a function of F, and serve to find MSY related F reference points.

F_{cod}	F_{red}	F_{shrimp}
0	0	0
0.05	0.015	0.015
0.1	0.03	0.03
0.15	0.045	0.045
0.2	0.06	0.06
0.25	0.075	0.075
0.3	0.09	0.09
0.35	0.105	0.105
0.4	0.12	0.12
0.45	0.135	0.135
0.5	0.15	0.15
0.55	0.165	0.165
0.6	0.18	0.18
0.65	0.195	0.195
0.7	0.2	0.2
0.75	0.225	0.225
0.8	0.25	0.25
0.85	0.275	0.275
0.9	0.3	0.3
0.95	0.325	0.325

<u>Criteria to determine MSY reference points from a multi-species perspective:</u>

As indicated above, whether a single or a multi-species approach is being developed, the precautionary reference points (B_{lim} and $B_{trigger}$) used when designing a HCR will be the same. However, the criteria for the determination of F_{target} values for each stock are very different in single and multispecies approaches. The basic and essencial difference is that in the multispecies approach there is not a single solution to define F_{target} as it is the case in the single species approach, but multiple potential valid combinations of F_{target} for the stocks under consideration. Which combinations of F_{target} are the most convenient will be determined based in the management objectives and the level of accepted ecological risk. Accordingly, a priori ecological, fisheries and management criteria has to be defined. As concluded in section 3.1, experience in previous projects indicated that the selection of management objectives, performance measures, constraints and the final HCRs should be agreed with all the stakeholders (Kempf et al. 2016, Rindorf et al. 2017c).

Since there are no specific a priori management objectives nor guidelines in this project for the selection of F reference points for the three species, a general approach has been taken. In this study, the selection of potential candidate F combinations for F_{target} was guided exclusively by ecological criteria. Those combinations of F that resulted in mean SSB above

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B_{lim} for one or more stocks in the long term (period 2035-2050) in a deterministic simulation were selected for a further step in the selection of candidate HCRs combinations. That step is presented in the next section and consisted on a risk analysis using the multispecies MSE framework to estimate the probability that each of those combinations of F_{target} drives one or more stocks below B_{lim} in the long term. In this study, a variety of posibilites is explored, and presented in the results section.

<u>One and two stage hockey stick HCRs</u>

The most common HCR is, as presented in Figure 6.3-3, a rule with a minimum level of SSB (B_{lim}) bellow which the adviced F becomes zero; and an SSB level ($B_{trigger}$) above which the adviced F is set constant at the level of F_{target}. Between $B_{trigger}$ and B_{lim} the adviced F decreases linearly. This is the so-called one stage hockey stick HCR, and is the one currently used in NAFO. A more innovative type of HCR is the so-called two stage hockey stick HCR, that includes a second set of B_{lim}, $B_{trigger}$ and F_{target} defining a second slope and flat areas for F advice as a function of SSB (Figure 6.3-3). This HCR was adopted by the Norwegian-Russian Fisheries Commission in 2016 for the management of the North East Atlantic cod (see section 3.1.3). This HCR produces higher F values at high stock sizes and is implicitly multispecies, as it aims to avoid excesive stock abundance that may reduced productivity due to increased natural mortality via cannibalism and negative density-dependent effects on individual growth and residual natural mortality.

Although the main effort in this study is focused on the standard single stage HCRs, with the intention of exploring new HCRs that take into account the species interactions, the two stage HCRs have also been tested. As presented in section 3.1, two stage HCRs are currently used for Barents Sea cod due to its capacity to avoid excesive predation, increasing the productivity of the stock. Hence, in first place several single stage HCRs have been tested for all the three stocks. Second, from those combinations of HCRs that succeeded in the risk analysis, a reduced number was used to set up two stage HCRs by adding a second set of B_{lim}, $B_{trigger}$ and F_{target} (the first set was taken from the one stage HCR). The second set of reference points were defined based the historic information. These two-stage HCRs were also tested in a probabilistic multispecies MSE framework.
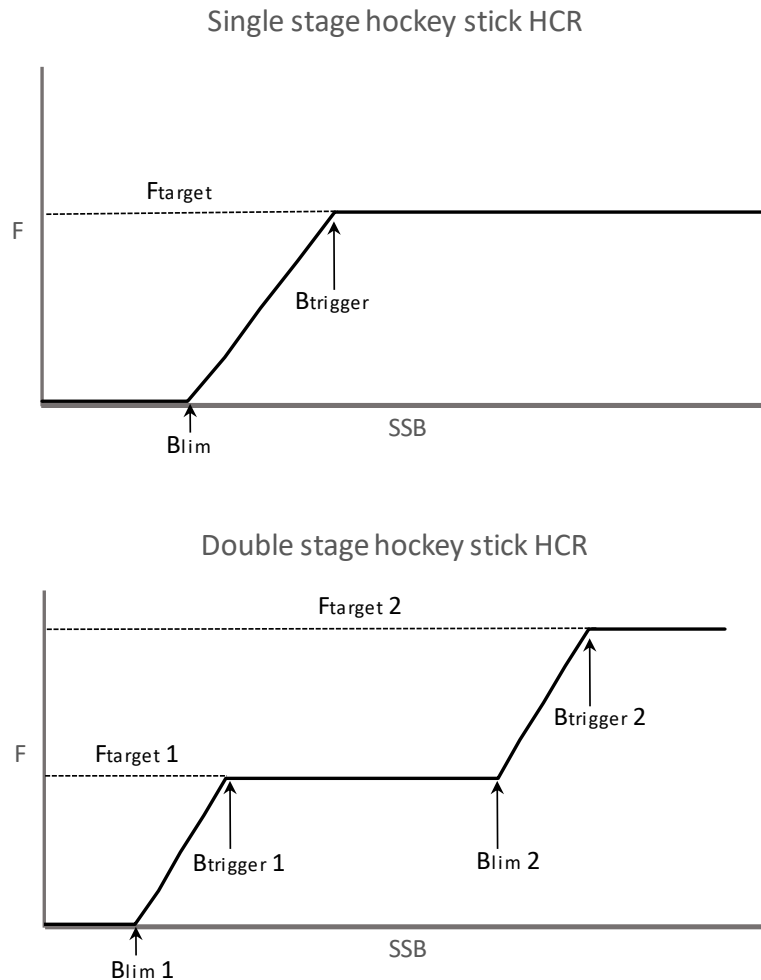
Single stage hockey stick HCR

Double stage hockey stick HCR

Figure 6.3-3.- One stage (upper pannel) and two stage hockey stick HCR (lower pannel), showing the reference points and the set up considered in this project.

Subtask 3.3.- Multispecies Management Strategy Evaluation framework and risk assessment

In this subtask a multispecies MSE framework was developed, where the multispecies model GadCap was used as an operating model (OM). This framework allows for an ecosystem approach when selecting the best management practices, by assessing the performance of single and multiespecies based HCRs when the species interactions are taken into account with the uncertainty in ecological, fisheries and management related processes. A full MSE has not been conducted in this study due to resources and time limitations, however, as a first step, uncertainty has been considered in the recruitment, the data-collecting and the stock assessment. In the next two sections, the steps followed for the development of the multispecies MSE framework and the simulations to assess the biological risk associated to the HCRs tested are presented.

a4a-FLR-MSE framework, adaptation for a multispecies approach

Management Strategy Evaluation (MSE) is a forward simulation framework for the development and comparison of alternative proposed management procedures (MP), considering the process, structural and observational uncertainty on stock dynamics,

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exploitation by fishing feets, the management decision making process and the implementation of managment measures. The major components in a fisheries management system, how they relate and interact, and their position in the fisheries management cycle are presented in Figure 6.3-4. The industry manage fleets of fishing vessels exploiting the fisheries resources. The scientific institutions collect data on both the industry activity and biological resources, build a model representing both fleets and stocks dynamics and conduct stock assessment to provide advice to the management body. Finally, the management body has the institutional responsibility of managing the resources, which requires the setting of appropriate regulations to steer and limit the activity of fishing.
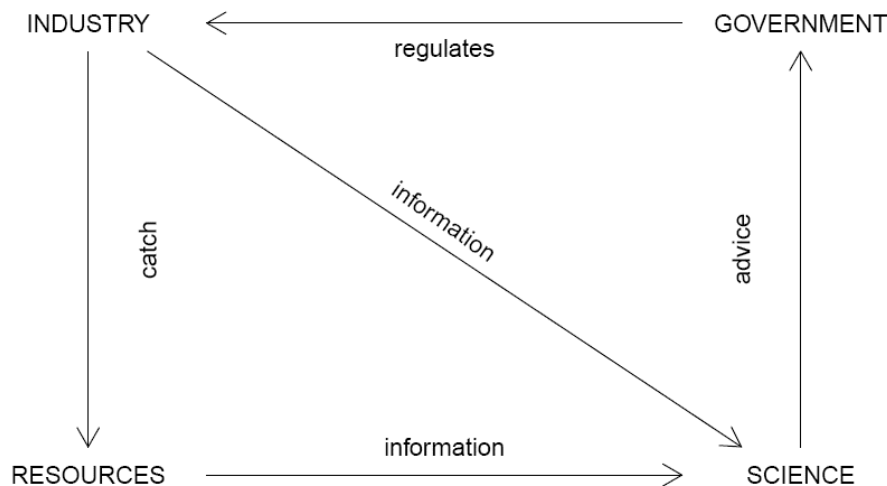

Figure 6.3-4.- Representation of the management cycle showing all the components that participate in the process that will result in the exploitation of marine resources. Science provide advice to managers, which take decisions that are implemented by the industry, affecting the stocks. Collection of data from commercial and scientific surveys will feed the scientific stock assessment, which will be used in a new management cycle.

For a proper evaluation of a MP, each of the elements of the management cycle has to be represented in a component of the MSE framework (Figure 6.3-5). The fleet and the stocks are embedded in an OM, which is the representation of the natural and fishery systems. On the other side, the MP includes the stock assessment process, carried out by scientific institutions and experts; and the management process, carried out by the governmental institutions based on scientific advice. Two other important components are the observation error model, which represents the process of collecting information for scientific purposes, and the implementation error model, which accounts for diferences between the intended results of the regulatory processes and the observed results.

The a4a approach to MSE[1] is to develop a set of common methods and procedures to build a minimal standard MSE algorithm. To implement the MSE, the FLR platform has been used with a modular design framework. The advantages of a modular design for MSE algorithms are the ability to easily reuse code across case studies. In that sense the a4a MSE modules (Figure 6.3-6) link back to the MSE parts showed in Figure 6.3-5, so that each element of the model maps to a single module.

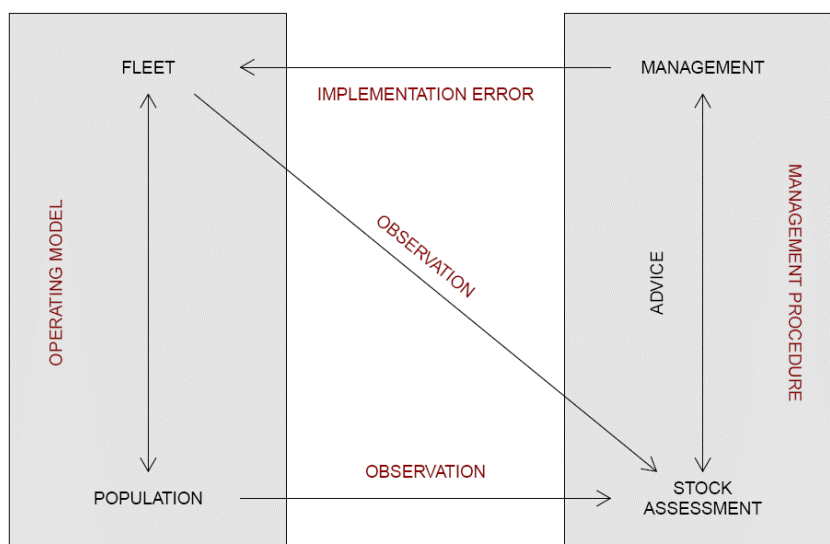---

[1] (http://www.flr-project.org/)

Figure 6.3-5.- Typical Management Strategy Evaluation framework containing all the elements of the management cycle

One of this modular components is the operating model (OM), that represents the natural and human system and allow simulating the dynamic of the population or populations of interest as well as their fisheries. It is commonly generated by formally conditioning on the available sources of data, through statistical fitting of a fishery and population model. The complexity of an OM can vary widely, from biomass dynamics models to ecosystem model with spatial components and seasonal time steps. The complexity of the OM will have a direct influence on the complexity of the management options that can be explored with it, and on the range of future robustness scenarios they can be tested against.

Figure 6.3-6.- The a4a-MSE algorithm showing all the different modules that simulates the management cycle.

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The a4a-MSE framewok includes a probabilistic a4a single species model as operating model (OM). This OM is designed to account for uncertainty about the functioning of the system (structural uncertainty), like growth, maturation, reprodution, natural mortality, etc., but also in other processes related with the fishery, like the selectivity functions, fishing effort, etc. Like in the real management cycle, in the MSE framework, this a4a OM provides information to the MP as result of simulated scientific surveys and commercial sampling programmes, that contains that uncertainty about the functioning of the system but also the noise introduced in the sampling process (observation error). All this uncertainty is transferred to the MP through an FLStock object, that contains information about stock abundance, mean length, mean weight and maturity at age in the stock, and information about the commercial fishery, like catch at age in numbers, mean weight, etc. This FLStock object with the information about the 'real' stock, the survey and the commercial catches is used in the MP to do the stock assessment, that will contain estimates of uncertainty. Within the MP framework, once the stock is assessed, the stock status in the next year is determined by projecting the populations in a short term forward simulation. The HCR is applied, an F value is decided based in the SSB, and this result in a catch advice. Finally, if there is no any other specification, this catch advice is used as Total Allowable Catch (TAC) in the Management part of the MP. This TAC goes through an implementation error model, where different elements can be taken into account, like technical interactions between species, or market limiting issues, that may produced differences in the final catch that will be provided to the OM. Once in the OM, the catch is taken over a whole year, in parallel to all the remaining processes affecting the dynamic of the stock (growth, maturation, reproduction and recruitment and natural mortality).

In this project SC05, the modular structure of the a4a-MSE framework was modified to to develop a multispecies MSE framework for the Flemish Cap cod, redfish and shrimp, that can be used to conduct risk assessments for different combinations of HCRs selected in the previous step (subtask 3.2). This part of the project was developed in tight collaboration with scientists of the department of demersal fish of the Institute of Marine Research IMR in Bergen (Norway) and the Joint Research Centre (JRC) of the European Commission in Ispra (Italy). The work developed as part of the project REDUS[1] (Reduced Uncertainty in Stock Assessments) by the IMR scientists in Norway was taken as the basis to continue working on during a stay at the JRC as part of the FLR/a4a internships programme. During this internship the a4a-MSE framework was modified in a very initial state, but this work was continued throughtout two different short stays at the IMR in Bergen.

For the purposes of the SC05 project, the a4a-MSE framework was deeply modified to 1) introduce in the OM module a gadget multispecies model (and specifically GadCap as a case study) 2) running several MPs in parallel, as many as stocks considered in the multispecies model 3) Include different sources of structural, process and observation uncertainty and error. At this stage, the structural uncertainty was only considered through the uncertainty in the recruitment process. Gadget is a deterministic model, while the a4a-MSE framework is designed to work with probabilistic models. This implied strong and deep changes in the structure and the mechanic of the simulations. In the *Results* section all the work done and the results obtained in adapting the a4a-MSE framework to the needs of a multispecies MSE are presented.

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[1] http://redus.no/en/projects/redus/

Introduction of uncertainty in the recruitment process in forward simulations: Random variability and Autorregressive model

Once the multispecies MSE framework (gadget-a4a-FLR) is assembled, with GadCap as OM, long term simulations of the whole management cycle were performed (see Figure 6.3-5). This multispecies MSE framework can be used for multiple purposes. Each of the elements of this multispecies MSE framework can be subjected to scrutiny. However, in the present study, the main goal is assessing the performance of a sub-selection of a set of HCRs that, from a deterministic point of view already indicated that the SSB for one or more stocks would not go bellow the established B_{lim} values (see previous section subtask 3.2). The multispecies MSE framework is used here to perform a risk analysis for that subset of HCRs given the current uncertainty in the prediction of the recruitment and the known error in the assessment process (see next section).

In order to assess the importance of recruitment uncertainty in the risk associated with a given combination of HCRs for the three stocks, it is necessary introducing variability in the number of recruits that a given level of SSB will produce every year during the long term simulations (period 2017-2050). Although there are different ways to do that, in our study we chose the option of estimating a '*year factor*' as the residuals from the optimized Ricker model for each of the three stocks, calculated as the ratio between the observed recruitment (output from GadCap) and the predicted recruitment (Ricker model). The year factor can be thought of as representative of the deviations from the recruitment expected due to the SSB level, produced by the effect of particular annual environmental conditions in the recruitment success of each stock. These time series of year factor can then be used to simulated long time series of year effects over the period 2017-2050. Each of these time series of year factors will produce variability in the SSB-Recruitment relationships between years, by multiplying the parameter α of the fitted Ricker model for each stock times the year factor (equation 5).

$$Recruitment = year\_factor \ x \ \alpha SSBe^{-\mu SSB} \qquad (5)$$

The uncertainty in the SSB-Recruitment relationship is traditionally the most important source of uncertainty when running forward simulations, and hence, the risk assessment of different management strategies is highly sensitive to the assumptions made to produce stochasticity in the recruitment process when running long term simulations. In this study, for each of the three stocks, 100 time series of year factors over the period 2017-2050 were produced by randomly selecting with replacement from the year factors estimated in the historic period. These 100 time series of year factors for each of the three stocks were then be provided to the GadCap operating model (OM) in the multispecies MSE framework to run 100 forward simulations over the period 2017-2050. Each of these 100 time series of year factors will produce variability in the SSB-Recruitment relationships and hence will produce 100 of different dynamics in the three exploited stocks, in their fisheries, trophic interactions and population structures. In summary, this will bring variability to the effect of a set of HCRs in the population dynamic, allowing for a risk analysis.

Calculation of the assessment error

In the assembled gadget-a4a-MSE framework two different ways of simulating the assessment within the MP have been designed: 1) stock assessment with single species a4a model ; 2) 'shortcut option' stock assessment (ICES 2008). For simulation purposes, in this project SC05 only the shortcut option has been used. The shortcut assessment option consist

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on taking the information about the SSB directly from each of the three stocks in the OM, i.e. the 'real' SSB, and apply an assessment error to that SSB. This will result in SSB calculations that is expected to be close to the values that the actual assessment conducted by the NAFO SC would have estimated.

In order to use the shortcut option it is necesary estimating the error in the assessment of the SSB by the currently aproved stock assessment methods in NAFO. The approach followed in this study has been, for each of the stocks, analyzing the retrospective patterns obtained in the last year that the stock assessment has been conducted. The mean error at age has been calculated as the ratio between the estimated abundance at age in the last year of each retrospective pattern and the abundance at age estimated for that year in the most updated assessment. In addition to the mean ratio by age, the variance-covariance matrix of the ratios between the different ages was also estimated. The mean ratio at age and the variance-covariance matrix defines a multivariate distribution of the error between ages, that allow producing every year in the long term simulations new error ratios sampled randomly but with certain covariance bewteen ages. During the long term simulations, every year the information about the 'real' abundance at age for each stock coming from the OM in the MSE framework, will be transformed by multiplying it times the sampled ratio. The abundance at age including the assessment error is then multiplied times the mean weight at age and the proportion of mature at age, producing an estimate of the SSB. The necessary data to estimate the mean and variance-covariance matrix of the assessment error was provided by the designated stock assessors for cod and redfish. In the case of shrimp the assessement is currently based in the survey index and hence there is not an assessment model that allow estimating the assessment error. In this case it was assumed that the assessment error for cod was applicable.

6.3.4. Results

Sub-task 3.1 – Estimates of natural mortality (M1+M2) and use in single species short term forecast

Estimate of residual natural mortality M1

A direct output of GadCap multispecies model are the M2 values (predation mortality), that is estimated as result of the diet composition, consumption estimate, predator-prey length relationship, number of predators and number of prey. However, M1 (residual natural mortality) is still a portion of remaining M that has to be provided to the model as fixed values. Estimating M internally during model optimization is extremely difficult, and often impossible, due to the interaction of M with the optimization of recruitment, growth and fishing catchability at age. For this reason, M1 has to be estimated externally using an alternative methodology.

Different methods to estimate the M1 have been explored:

1.- Catch curve methods

2.- Longevity method

3.- Loglikelihood score selection.

Regarding the catch curve method, different approaches were applied: Chapman-Robson, Chapman-Robson corrected, Heincke, Linear Regression, Poisson model, Random intercept

Poisson and Weighted Linear Regression (Millar 2014, Smith et al. 2012). The criteria presented in Smith et al. (2012) were used to select the range of ages to be considered in the analysis, and the cohorts finally included in the study were selected based in the level of fishing effort and predation that those cohorts experienced. The R package Fishmethods was used to estimate the average Z over the group of selected ages.

The longevity method to estimate M1 is presented in Hewitt and Hoenig (2005). This method is based in the assumption that the average M at age value is that one that allows that 1.5% of the individuals recruited in a cohort reach to the age defined as maximum longevity. For the Flemish Cap cod it was selected that this age is 12 years, based in the knowledge that the longevity in the Flemish Cap cod is shorter than in other cod stocks in the Northwest Atlantic. The range of cohorts used to estimate the Z (M1 for these cohorts) that would bring the percentage of the individuals at the beginning of the time series to the 1.5% was the same as those used for the catch curves methods (1998 to 2002). The multispecies model GadCap, version 87 was used to make this calculations.

The last method used to find the best estimate of M was the loglikelihood score selection. Different values of M1 (constant for all ages over time) ranging from 0.05 to 0.5 were tested in the models GadCap_87, and parameters were re-optimized. The M1 that led to the lower loglikelihood score was selected as the candidate M1 value.

The application of the criteria presented in Smith et al. (2012) resulted in an age range from 4 to 8. The range of cohorts selected to estimate the M1 was from 1996 to 2002 based in the fact that for these cohorts, the fishing mortality at ages 4 to 8 was negligible due to the directed cod fishing moratoria, and cannibalism predation mortality was not relevant, based in the information available for the diet composition. Hence, it may be assumed that the estimated average Z mortality with these catch curve methods for the range of ages 4-8 and cohorts 1996-2002 is representative of the M1. The logarithm of the EU survey abundance by age is presented in Figure 6.3-7. The application of the different catch curve methods produced a wide range of Z values, ranging from 0.4 to 1.29 (Table 6.3-2).
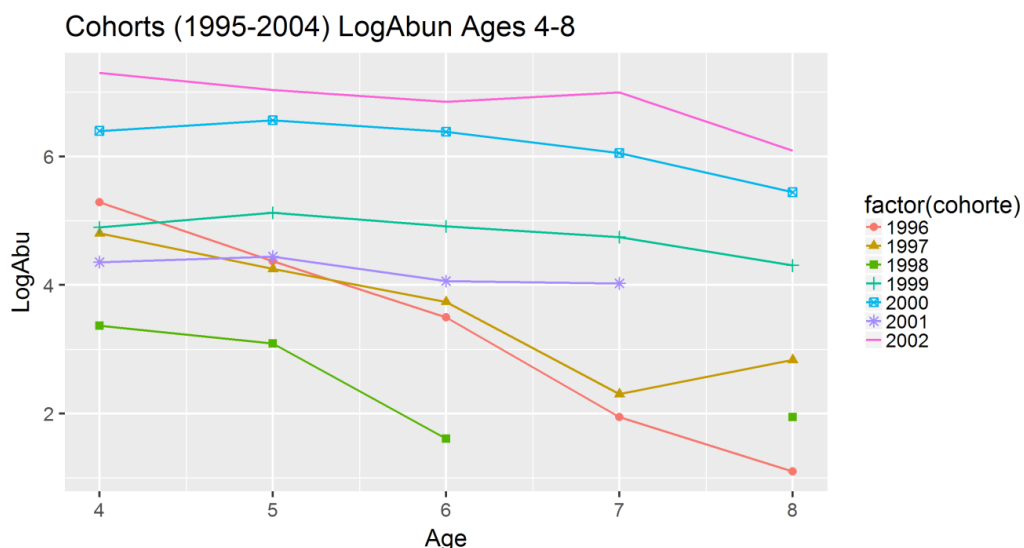

Figure 6.3-7.- Logarithm of the abundance at age estimated during the EU Flemish Cap survey for the different cohorts used in the catch curve analysis and for the range of ages 4 to 8.

Table 6.3-2.- Average Z for the group of cohorts 1996-2002 estimated using the different catch curve methods for the group of ages 4 to 8.

Catch curve method	Average Z
Chapman-Robson	0.644285714
Chapman-Robson CB	0.641428571
Heincke	0.484285714
Linear Regression	0.407142857
Poisson Model	0.627142857
Random-Intercept Poisson	1.295714286
Weighted Linear Regression	0.411428571

In the case of the longevity method, the maximum longevity of the Flemish Cap cod was set at age 12 and the range of cohorts from 1998 to 2002. The percentage of the individuals at age 1 that reached the longevity age is shown in Table 6.3-3 for a range of different M1 values. This table shows that the M1 value that bring the percentage of the individuals at the beginning of the cohort to the 1.5% at age 12 would be a value between 0.30 and 0.35. By interpolation the M1 value is 0.3215.

Finally, the loglikelihood score profile indicated that the model with the lower loglikelihood score was the one with a constant M1=0.4 by age and year (Figure 6.3-8).

Since the different catch curve methods produced highly variable values, more relevance was given to the longevity and the log-likelihood methods. Based in the results of these two methods, the final value selected was M1=0.35, as an intermediate value between both methods.

Table 6.3-3.- Percentage of the recruited number of individuals at age 1 that reach age 12 (maximum longevity)

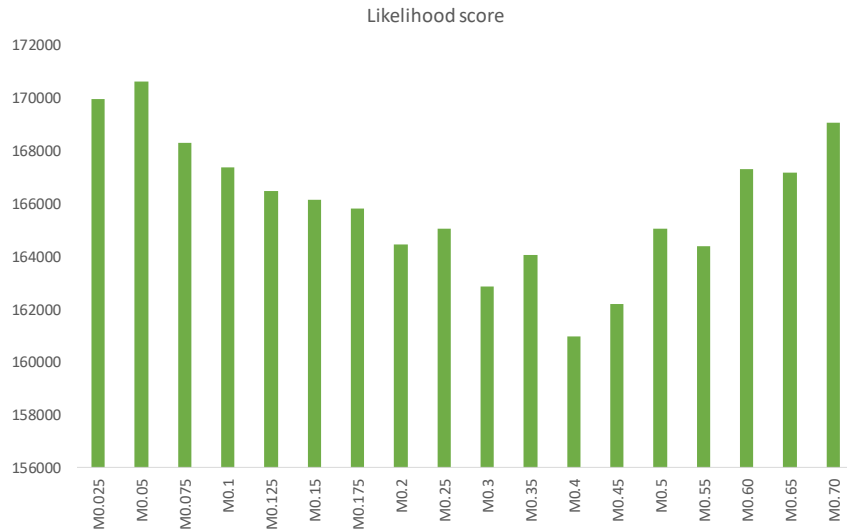| Cohort	M_0.17	M_0.20	M_0.25	M_0.30	M_0.35	M_0.40	M_0.45	M_0.50
1996	9.57	7.5	4.56	2.69	1.59	0.93	0.54	0.31
1997	11.48	8.74	5.1	2.92	1.69	0.98	0.56	0.32
1998	11.24	8.58	4.98	2.86	1.64	0.95	0.55	0.31
1999	8.14	6.21	3.6	2.07	1.17	0.67	0.39	0.22
2000	6.5	4.93	2.85	1.62	0.9	0.51	0.29	0.16
2001	4.71	3.57	2.04	1.14	0.63	0.35	0.19	0.1
2002	2.61	1.96	1.12	0.6	0.31	0.17	0.09	0.04
Averag	7.75	5.9271	3.4642	1.9857	1.1328	0.6514	0.3728	0.20857

Likelihood score

Figure 6.3-8.- Loglikelihood score resulting of applying different values of M1 by age and year during the optimization of GadCap.

Estimate of total natural mortality (M1+M2)

Once the M1 value was determined externally with the alternative methods explained above, the matrix with the total natural mortality (M1+M2) by age and year was estimated. The model GadCap version 87 was used. The M1 was fixed at 0.35 in this model, and parameters were reoptimized. With these settings, the resulting M at age an year was estimated as the sum of M1=0.35 and the M2 estimated from the estimates of consumption predation and initial population every year. The estimated natural mortality is presented in Table 6.3-4.

This estimates of total M at age and year were used as fixed values in the statistical catch at age model assessed during the 3M cod benchmark meeting in Lisbon (see the working document https://www.nafo.int/Portals/0/PDFs/sc/2018/scr18-025.pdf, deliverable 5.1 (see table with the list of Deliverables in section 4 of this report)). The model diagnostics and population estimates (SSB, total Biomass, recruitment and F at age) result of using different values of M (constant at age and year ; variable at age but constant over time ; variable at age and year using GadCap) were compared and assessed by the experts attending the benchmark. During the 2018 June NAFO Scientific Council meeting the final strategy to define M values in the 3M cod stock assessment model was decided.

Table 6.3-4.- Total M (Mresid + Mpred) estimated with the model GadCap once Mresid is fixed as 0.35 for all ages and years.

age	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
1	0.766	1.125	0.91	0.455	0.479	0.406	0.41	0.471	0.392	0.373
2	0.397	0.842	0.656	0.41	0.374	0.389	0.395	0.419	0.385	0.362
3	0.358	0.388	0.581	0.367	0.355	0.355	0.36	0.357	0.362	0.358
4	0.352	0.356	0.368	0.361	0.352	0.351	0.351	0.351	0.351	0.353
5	0.35	0.351	0.353	0.351	0.351	0.35	0.35	0.35	0.35	0.35
6	0.35	0.35	0.351	0.35	0.35	0.35	0.35	0.35	0.35	0.35
7	NA	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
8	0.35	NA	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
9	0.35	0.35	NA	0.35	0.35	0.35	0.35	0.35	0.35	0.35
10	0.35	0.35	NA	NA	0.35	0.35	0.35	0.35	0.35	0.35
11	0.35	0.35	0.35	NA	NA	0.35	0.35	0.35	0.35	0.35
12	0.35	0.35	0.35	0.35	0.35	NA	0.35	0.35	0.35	0.35

age	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
1	0.362	0.367	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
2	0.359	0.363	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
3	0.351	0.353	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
4	0.351	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
5	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
6	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
7	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
8	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
9	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
10	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
11	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
12	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35

age	2008	2009	2010	2011	2012	2013	2014	2015	2016	
1	0.35	0.35	0.876	0.822	0.581	0.592	1.441	1.425	0.809	
2	0.35	0.35	0.692	0.683	0.622	0.656	0.693	0.894	0.789	
3	0.35	0.35	0.412	0.457	0.506	0.497	0.517	0.48	0.527	
4	0.35	0.35	0.365	0.37	0.392	0.403	0.384	0.415	0.392	
5	0.35	0.35	0.352	0.354	0.356	0.363	0.361	0.364	0.373	
6	0.35	0.35	0.35	0.351	0.352	0.353	0.353	0.356	0.356	
7	0.35	0.35	0.35	0.35	0.35	0.351	0.351	0.352	0.352	
8	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	
9	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	
10	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	
11	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	
12	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	

Subtasks 3.2.- Explore single and multispecies reference points and HCRs.

Precautionary reference points: B_{lim} and $B_{trigger}$

As indicated in the methodology section, the SSB estimated annually in GadCap over the period 1988-2015 was used to model the recruitment at age 1 in the period 1989-2016 using a Ricker SSB-Recruitment model. The fit model for cod and redfish showed the typical dome shaped Ricker model shape, with recruitment decreasing at higher values of SSB (Figure 6.3-9). However, for shrimp this pattern was not observed in the range of SSB of the historic period.
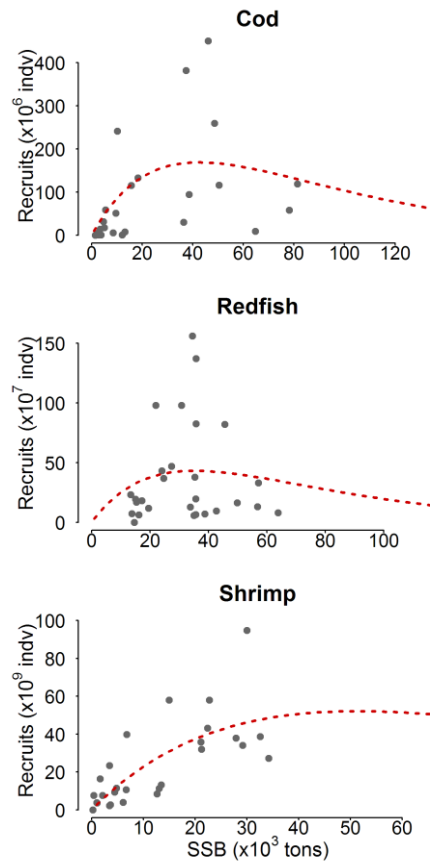
Figure 6.3-9.- SSB-Recruitment values obtained from the model GadCap over the period 1988-2016 (grey points) and the fitted Ricker model (red dashed lines) for the Flemish Cap cod, redfish and shrimp.

The fit Ricker SSB-Recruitment models were then used to estimate the precautionary reference points, B_{lim_50}, B_{lim_75} and $B_{trigger}$, defined as the SSB at which the recruitment is, respectively, 50%, 75% and 90% of maximum predicted recruitment (see Figure 6.3-10. The criteria followed to define the precautionary reference points were different for each of the three stocks, and this is something that may be subjected to discussion. However, as a first step, in this study it was decided that B_{lim} for shrimp would be taken as the SSB at B_{lim_50} (10206 tons), while for cod B_{lim} would be taken as the SSB at B_{lim_75} (17906 tons). The reason is that it was deemed that for cod B_{lim_50} (9892 tons) was an excesively low SSB value based in what have been previously defined as reference points for cod (González-Troncoso et al. 2013). For shrimp, B_{lim_50} was aproximately four times higher that the B_{lim} value (2564 tons) defined for the survey index stock assessment (Casas-Sánchez 2012), and this value was consider appropriate based in the relationship between the biomass survey index and the estimated total stock biomass (aprox 5 times higher stock biomass than survey index). In relation to redfish, both the B_{lim_50} and B_{lim_75} seemed very low in relation to the observed values over the historic period. For this reason, the criteria used for redfish was changed, and B_{lim} was considered for this stock the level of SSB for which the first above average recruitment was observed (see Figure 6.3-10, right bottom panel), while $B_{trigger}$ was defined the SSB at maximum recruitment. Following this criteria, B_{lim} was defined at 22027 tons and $B_{trigger}$ at 35361 tons. The Table 6.3-5 shows the B_{lim} and $B_{trigger}$ to be used in the HCRs for each of the three stocks in this study.

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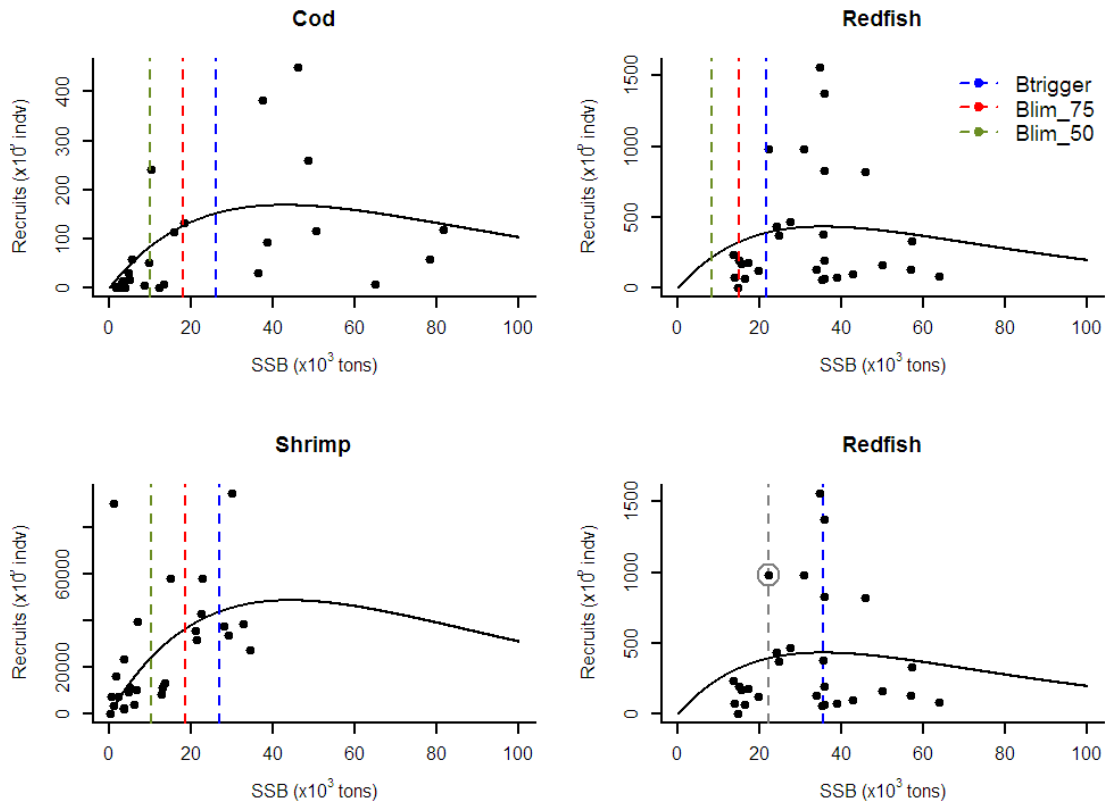
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Figure 6.3-10.- SSB and recruitment values result of GadCap over the historic period (black points) and fitted Ricker SSB-Recruitment model (black line). The Vertical lines represent the B_{lim_50} (green dashed line), B_{lim_75} (red dashed line) and $B_{trigger}$ (blue dashed line), defined as the SSB at which the recruitment is, respectively, 50%, 75% and 90% of maximum predicted recruitment. The right-bottom panel shows the special criteria followed to define the precautionary reference points in redfish. The grey line an the grey circle indicates the B_{lim}, as the SSB at which it was observed the first recruitment value above the average in the historic period. The Blue dotted line in this case is $B_{trigger}$, defined as the SSB at maximum recruitment.

Table 6.3-5.- B_{lim} and $B_{trigger}$ finally selected for each of the three stocks following the criteria described in the text.

Stock	B_{lim}	$B_{trigger}$
cod	17906	25943
redfish	22027	35361
shrimp	11864	31114

Deterministic long term forecast and definition of single and multispecies F_{target} reference points

As described in the methodology section, in the process of finding the candidate F_{target} for the HCRs, 20 different values of F were defined for each species, resulting in 8000 different combinations for the three stocks. The adapted GadCap was coupled to the fitted Ricker SSB-Recruitment models. Since recruitment uncertainty was not considered at this stage, each SSB level would produce an only value of recruitment for each stock. Once the 8000 long term simulations were run, the mean SSB and mean Yield over the period 2035-2050 was

estimated for each stock. From Figure 6.3-11 to Figure 6.3-13 the mean long term SSB and yield are shown for each of the three species as a function of the fishing pressure applied to the three stocks.

For the cod stock, the impact of changes in fishing pressure on redfish didn´t seem to have an important effect when the fishing pressure on shrimp is low. However, when fishing pressure on shrimp is increased there is a decline in cod mean SSB as the F on redfish is increased. But interestengly, it is when the fishing pressure on shrimp is increased when the most important differences in the estimated mean long term cod SSB is observed. This is especially evident when the fishing pressure on cod is low. This negative effects on cod SSB in the long term simulation as result of a higher fishing pressure on redfish and shrimp is due to the increased cannibalism occuring on cod when the availability of these prey stocks is reduced due to the high fishing pressure. In the case of fishing pressure on cod, as expected, the SSB decreased as the F on cod was increased. It is interesting to note that the fishing pressure that cod is able to stand before the SSB (in a deterministic way, without uncertainty ranges around it) goes bellow the B_{lim} (17906 tons) is very high. Specifically in the three F shrimp values presented in the Figure 6.3-11, cod SSB was below B_{lim} only when F was above 0.8. Variations in the mean long term cod yield showed a similar pattern to that explained in relation to the SSB, i.e. increased fishing pressure on redfish and shrimp produced reduced productivity on cod, being especially evident when both F on shrimp and redfish was high. However, unlike the SSB, the increase of fishing pressure on cod showed a dome shaped curve, irrespective of the F value applied for redfish and shrimp. The maximum yield for cod was always observed when the F for cod was between 0.45 and 0.65.

In the case of the redfish stock, the mean long term SSB was very independent of the fishing pressure applied on shrimp. However, it was extremely dependent on the F applied on cod (Figure 6.3-12). For a given F value on redfish, the lower the F on cod the lower the redfish long term SSB. In different words, higher fishing pressure on cod allows higher F on redfish before the redfish SSB declined below the B_{lim}. The results indicate that the absence of fishing on cod could bring redfish below B_{lim} even at very low fishing pressure. However, it is important highlighting that those SSB and Yield values obtained in situations that have not been observed before should be taken with caution, as it is the case for a scenario of very low fishing on cod when cod is at very high biomass level. In relation to the fishing pressure on redfish, increasing the F lead to lower values of SSB, but this relation was highly dependent on the fishing activity on cod. Regarding the long term yield for redfish, it also showed the typical dome shape as a function of fishing effort. This shape was independent of the fishing pressure on shrimp, but it was very dependent on the fishing pressure on cod. The higher the F on cod the higher the peak of yield for redfish. Unlike for cod, in redfish the peak of yield was always observed at low F values, being usually between 0.1 and 0.2.

Shrimp, due to its trophic role being a very important prey of two dominant species in the Flemish Cap, showed (in the SSB and Yield) a high sensitivity and dependency on the fishing strategies selected for these two predators. Only when fishing pressure on cod was very low or, interestingly, very high, the mean shrimp SSB in the long term could achieve values above the B_{lim}. At intermediate levels of fishing pressure on cod, the shrimp SSB was bellow B_{lim} independently of what fishing pressure was set on redfish (Figure 6.3-13). The reason for this pattern is that cod is a main predator of shrimp, and hence very intense fishing on cod would benefit the development of the shrimp stock, and would bring the SSB above B_{lim}. However, cod is also a main predator for redfish, which in turn is also a main predator for shrimp. For this reason a low fishing pressure on cod would involve high predation on redfish

and hence a decrease in redfish stock (as it was already indicated in the previous paragraph). That decrease in redfish biomass would allow also an increase in the shrimp SSB above B_{lim}. However, as indicated above, this is a scenario that has never being observed before and hence the model is getting into the extrapolation territory, which should be taken with caution. In both cases (high or low fishing pressure on cod) the long term shrimp SSB was very dependent on redfish fishing pressure: low fishing pressure did not allowed shrimp SSB above B_{lim}. The long term mean yield on shrimp showed also a dome shape as a function of F on shrimp, but only when, as indicated for the SSB, the fishing pressure on cod was either very high or very low. The peak on the shrimp stock was hence very dependent on the fishing pressure on cod and redfish, but, in any case was always very low (bellow 0.15).
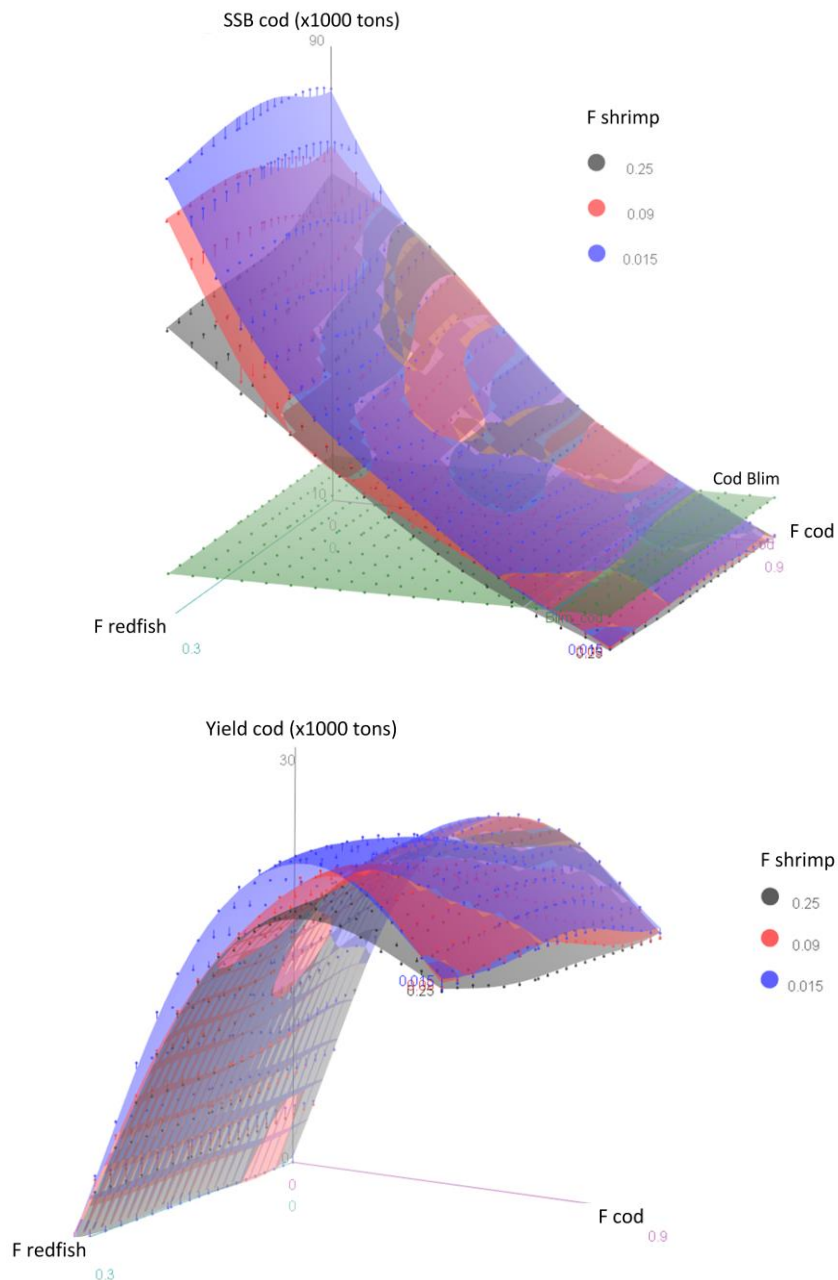

Figure 6.3-11.- Mean SSB (upper panel) and Yield (lower panel) for the cod stock at the end of the forecast simulation period (2035-2050). The figures show the SSB and Yield values for the combination of 20 different F values of cod, 20 F values of redfish and 3 values of F for Shrimp. In this figures, the remaining 17 fishing mortality values for shrimp have been ommited for clarity and simplicity of the figures.
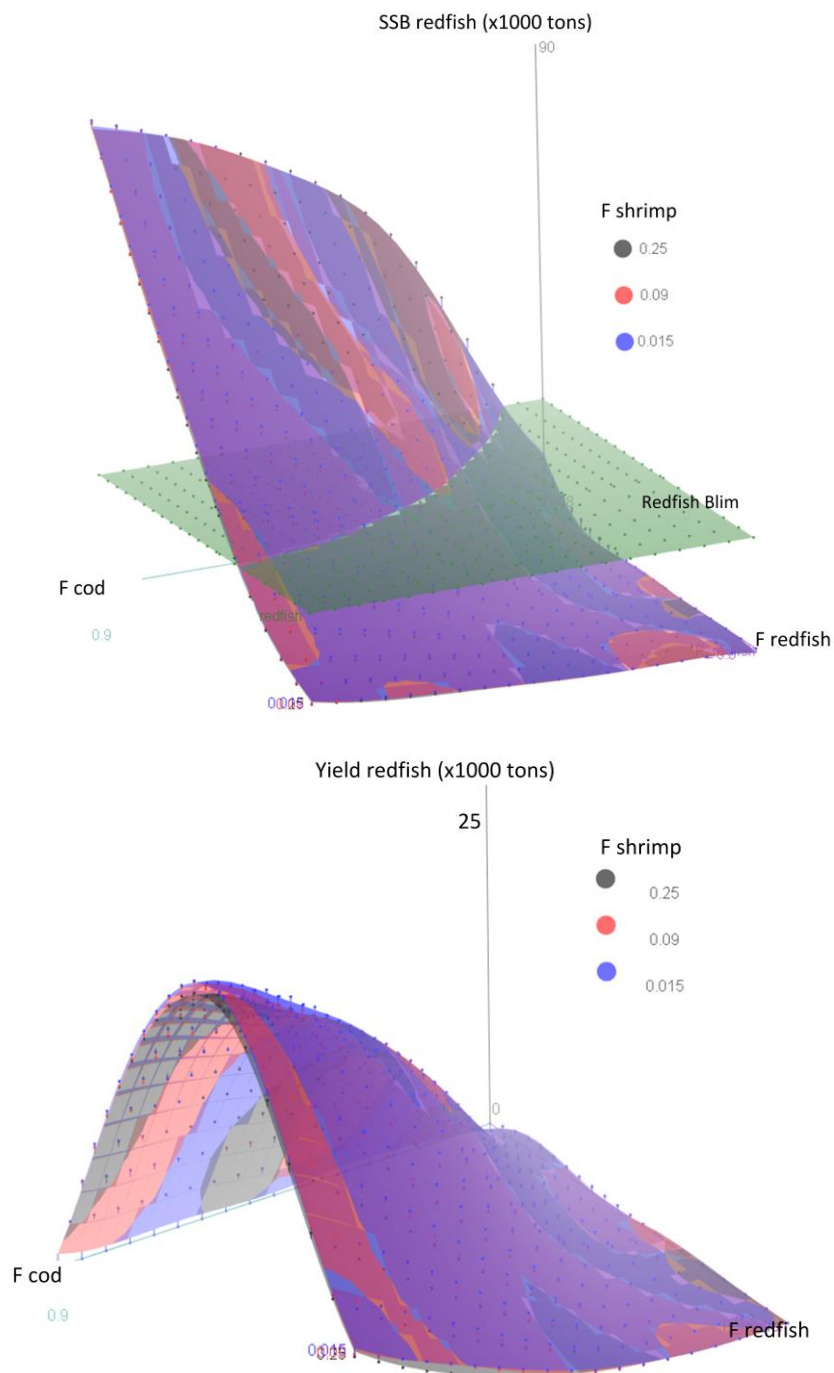
Figure 6.3-12.- Mean SSB (upper panel) and Yield (lower panel) for the redfish stock at the end of the forecast simulation period (2035-2050). The figures show the SSB and Yield values for the combination of 20 different F values of cod, 20 F values of redfish and 3 values of F for Shrimp. In this figures, the remaining 17 fishing mortality values for shrimp have been ommited for clarity and simplicity of the figures.
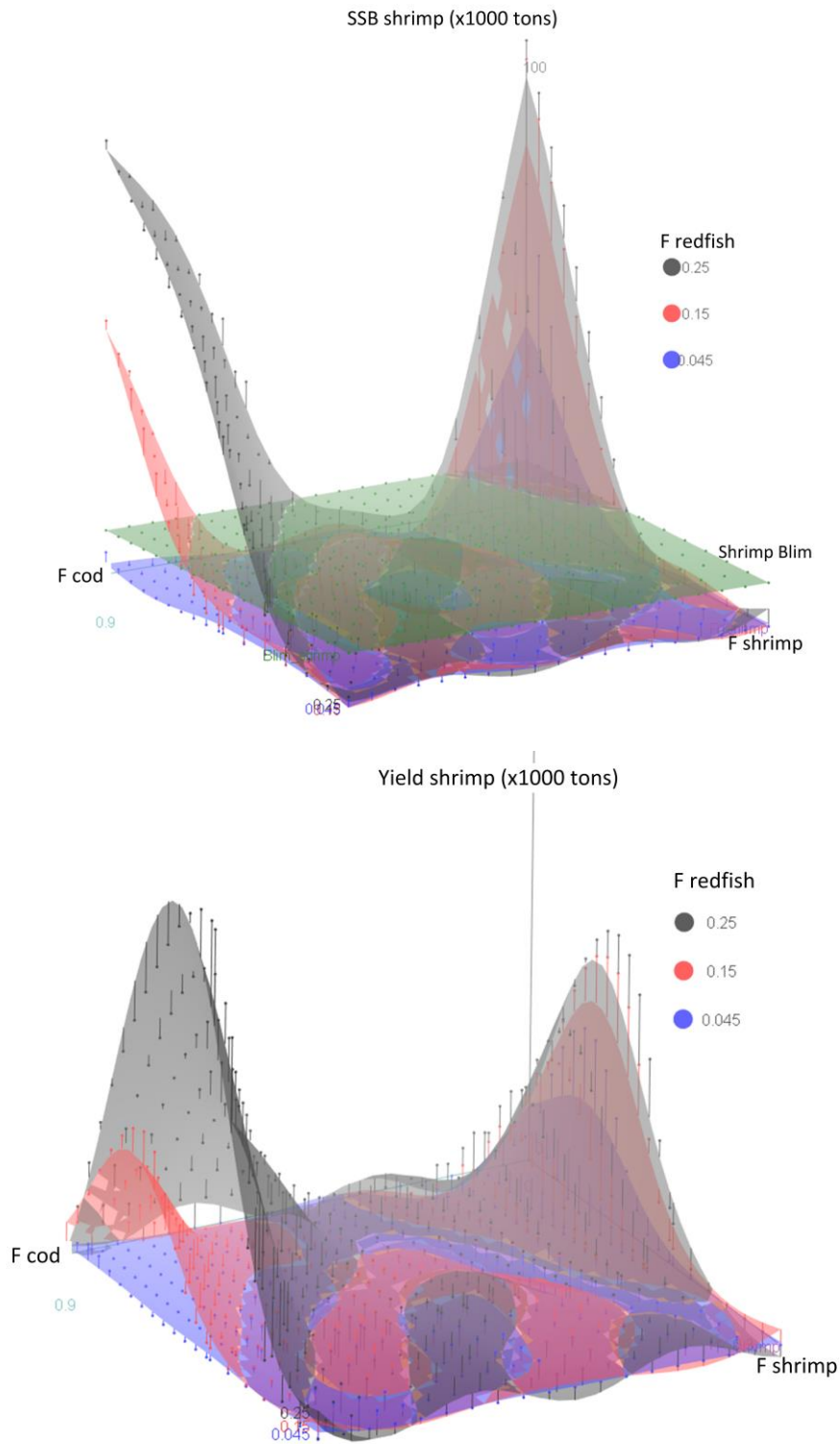
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Figure 6.3-13.- Mean SSB (upper panel) and Yield (lower panel) for the shrimp stock at the end of the forecast simulation period (2035-2050). The figures show the SSB and Yield values for the combination of 20 different F values of cod, 20 F values of shrimp and 3 values of F for redfish. In this figures, the remaining 17 fishing mortality values for redfish have been ommited for clarity and simplicity of the figures.

Once the long term SSB and yield have been calculated for each combination of fishing pressures (F_{cod}, $F_{redfish}$ and F_{shrimp}), the next step is selecting those HCRs that produce the highest and sustainable yields. However, as explained in the methodology section, the way the single and multispecies approaches will use all the information showed in figures 3-12, 3-13 and 3-14 is very different. In the next sections the procedures used in both approaches are explained in depth and the F reference points and hence the HCRs are estimated from a single and multispecies perspectives.

- <u>Single species based reference points</u>

In a single species approach all that variability in the long term mean SSB and yield as a function of the fishing pressure on the three stocks is disregarded. In this study, in order to simulate that approach, for each of the 20 different F levels tested for each species the mean SSB and Yield was estimated, and the yield and SSB curves were plotted disregarding the variability due to different management strategies in other species (Figure 6.3-14). Based in this approach, the F_{MSY} is selected as the F value that produces the highest yield while the SSB is above B_{lim}. The resulting F_{MSY} is, as explained in the methodology section, a limit to the fishing pressure, and usually a lower value is used as F_{target}. It is a standard in NAFO that the F_{target} is calculated as 2/3 of F_{MSY}. Both F_{MSY} and F_{target} are presented in Table 6.3-6.
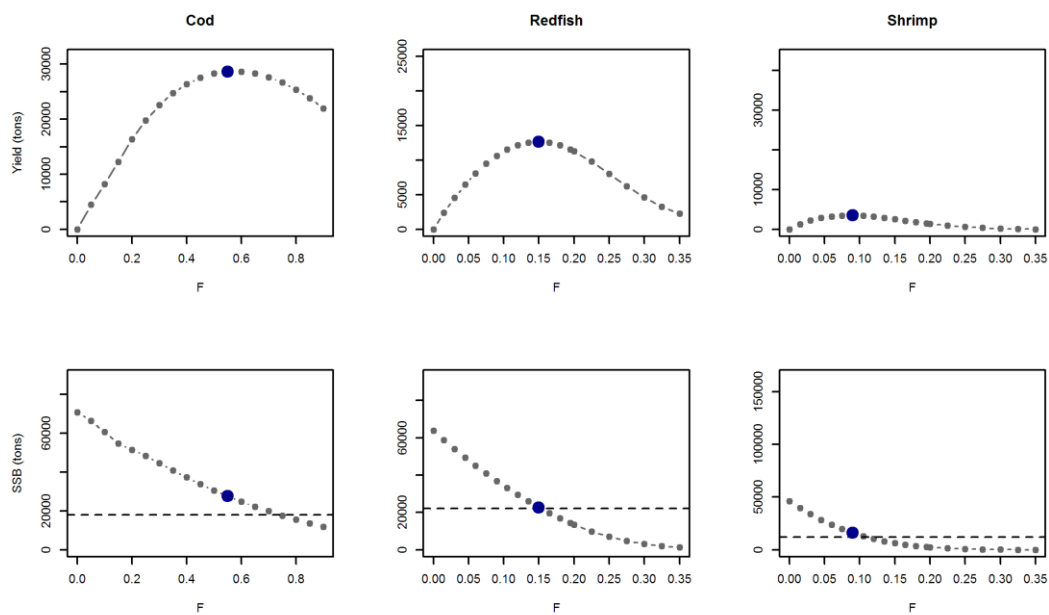

Figure 6.3-14.- Average SSB and Yield in the equilibrium (years 2035-2050) by F level tested during the long forecast simulations.

Table 6.3-6.- F_{MSY}, F_{target}, mean long term yield and mean long term SSB (both in tons) for the Flemish Cap cod, redfish and shrimp and estimated with a single species approach.

Stock	F_{MSY}	F_{target}	Yield	SSB
cod	0.55	0.367	28652	27605
redfish	0.15	0.1	12669	22689
shrimp	0.09	0.06	3463	16050

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- <u>Multispecies based reference points</u>

In the multispecies approach the value of F_{target} for a stock is decided considering the F_{target} for the rest of species, following a list of management objectives that must be defined a priori by all the stakeholders. In this study the criteria have been based exclusively on biological aspects, following as much as possible the NAFO precautionary approach defined for a single species approach. Five different criteria have been defined to select combinations of F_{target}:

1. Combinations of F_{target} (and hence HCRs) that allowed the SSB being above B_{lim} at the end of the simulation period (2035-2050) for all the 3 stocks.

2. Combinations of F_{target} for which at the end of the simulation period cod and redfish SSB is above their B_{lim}, but disregarding the estate of the SSB for shrimp.

3. Combinations of F_{target} for which at the end of the simulation period shrimp and redfish SSB is above their B_{lim}, but disregarding the estate of the SSB for cod.

4. Combinations of F_{target} for which at the end of the simulation period shrimp and cod SSB is above their B_{lim}, but disregarding the estate of the SSB for redfish.

5. Combinations of F_{target} for which at the end of the simulation period shrimp SSB is above their B_{lim}, but disregarding the estate of the SSB for redfish and cod.

Those combinations of F_{target} that already in a deterministic way fulfilled these criteria (see Table 6.3-7 for a sinoptic presentation of these criteria) have been selected to perform a probabilistic risk analysis (see next section subtask 3.3).

Table 6.3-7.- Synoptic presentation of the different criteria followed to select combinations of F_{target} candidate to be tested in a risk analysis. They symbol + means that in that criteria the SSB for that stock had to be above B_{lim} at the end of the long term simulation period (2035-2050), while the symbol – indicates that for that stock the SSB was allowed to be either abover or bellow its established B_{lim}, i.e. that stock was disregarded when deciding the candidate F_{target} combination.

Criteria	Cod	Redfish	Shrimp
1	+	+	+
2	+	+	-
3	-	+	+
4	+	-	+
5	-	-	+

Out of 8000 F combinations, only 96 comply with the criteria 1, i.e., the restriction of keeping all the three stocks at the same time above their respective B_{lim} values at the end of the simulation period. From all these 96 combinations a subset of 13 were selected, which were representative of the range of Fs applied for each of the three stocks that fulfilled this criteria 1 (see Table 6.3-8), maintaining all stocks above B_{lim} at the same time. The complete table with the 96 possible combinations was provided as part of the deliverable 3.2 (see List of Deliverables table in section 4 of this report). It is important to note that the F values for cod and redfish were very high, and very close to the B_{lim} (see Figure 6.3-15).

Table 6.3-8.- Reduced selection of F combinations from all those that resulted in SSB higher than Blim in the equilibrium for all the three stocks, cod, redfish and shrimp (criteria 1).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
1	3 stocks above B_{lim}	0.55	0.18	0
1	3 stocks above B_{lim}	0.6	0.165	0
1	3 stocks above B_{lim}	0.65	0.165	0
1	3 stocks above B_{lim}	0.65	0.165	0.015
1	3 stocks above B_{lim}	0.65	0.165	0.03
1	3 stocks above B_{lim}	0.65	0.195	0
1	3 stocks above B_{lim}	0.65	0.195	0.015
1	3 stocks above B_{lim}	0.65	0.195	0.03
1	3 stocks above B_{lim}	0.65	0.195	0.045
1	3 stocks above B_{lim}	0.65	0.195	0.06
1	3 stocks above B_{lim}	0.75	0.2	0
1	3 stocks above B_{lim}	0.75	0.2	0.06
1	3 stocks above B_{lim}	0.75	0.2	0.075

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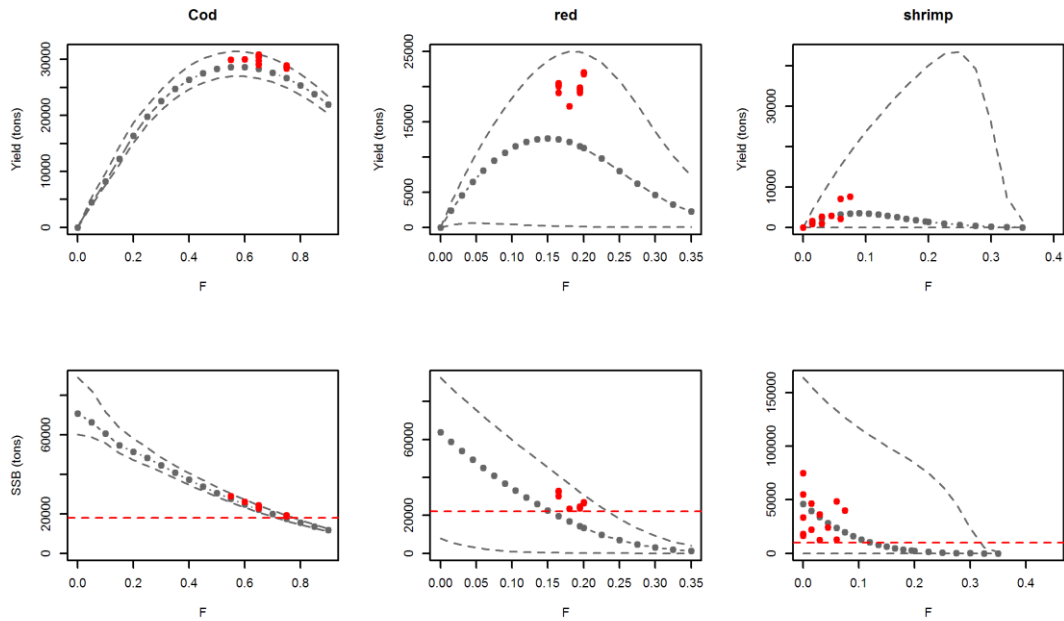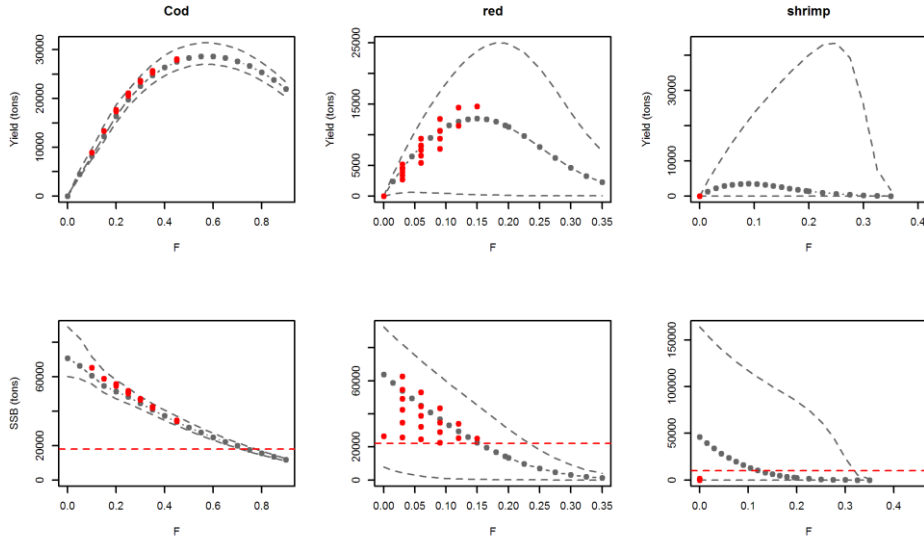"Multispecies Fisheries Assessment for NAFO"

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Figure 6.3-15.- Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F values selected following the criteria 1 and presented in Table 6.3-8.

However, when the restrictions were released by allowing the shrimp stock going below its B_{lim} (criteria 2), the number of combinations of Fs for which the SSB in cod and redfish was maintained above B_{lim} was increased substantially, with 2595 possible combinations (see the attached excel document 'Combinations_F_Selection_Criteria_2.xlsx'). It is not possible conducting a risk analysis to all those combinations, and hence, a reduced number of 19 combinations were selected (Table 6.3-9). It was decided that in the selected F combinations, for simplicity the F values for shrimp would be set to zero. The reason is that in all the 2595 combinations, catches for shrimp were very low, and hence, in practice the shrimp fishery wouldnt have occurred. As it can be observed in the Figure 6.3-16, even when the F was set to zero for shrimp the SSB was clearly bellow the Blim.

When the state of the cod SSB was disregarded, a total of 365 F combinations maintaind redfish and shrimp SSB above their respective B_{lim} values in a deterministic way. For risk analysis in subtask 3.3 (see next section), a subset of 17 F combinations were selected (Table 6.3-10). The selected combinations showed that for cod, in a deterministic way, the fishing pressure brought the SSB bellow or very close to B_{lim} (Figure 6.3-17). The complete table with the 365 possible combinations of F for the three stocks was provided as part of the deliverable 3.2 (see List of Deliverables table in section 4 of this report).

Table 6.3-9.- Reduced selection of F combinations from all those that resulted in SSB higher than B$_{lim}$ in the equilibrium for cod and redfish, but disregarded the state of the SSB for shrimp (criteria 2).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
2	Disregard shrimp SSB	0.1	0	0
2	Disregard shrimp SSB	0.15	0.03	0
2	Disregard shrimp SSB	0.2	0.03	0
2	Disregard shrimp SSB	0.2	0.06	0
2	Disregard shrimp SSB	0.25	0.03	0
2	Disregard shrimp SSB	0.25	0.06	0
2	Disregard shrimp SSB	0.25	0.09	0
2	Disregard shrimp SSB	0.3	0.03	0
2	Disregard shrimp SSB	0.3	0.06	0
2	Disregard shrimp SSB	0.3	0.09	0
2	Disregard shrimp SSB	0.35	0.03	0
2	Disregard shrimp SSB	0.35	0.06	0
2	Disregard shrimp SSB	0.35	0.09	0
2	Disregard shrimp SSB	0.35	0.12	0
2	Disregard shrimp SSB	0.45	0.03	0
2	Disregard shrimp SSB	0.45	0.06	0
2	Disregard shrimp SSB	0.45	0.09	0
2	Disregard shrimp SSB	0.45	0.12	0
2	Disregard shrimp SSB	0.45	0.15	0

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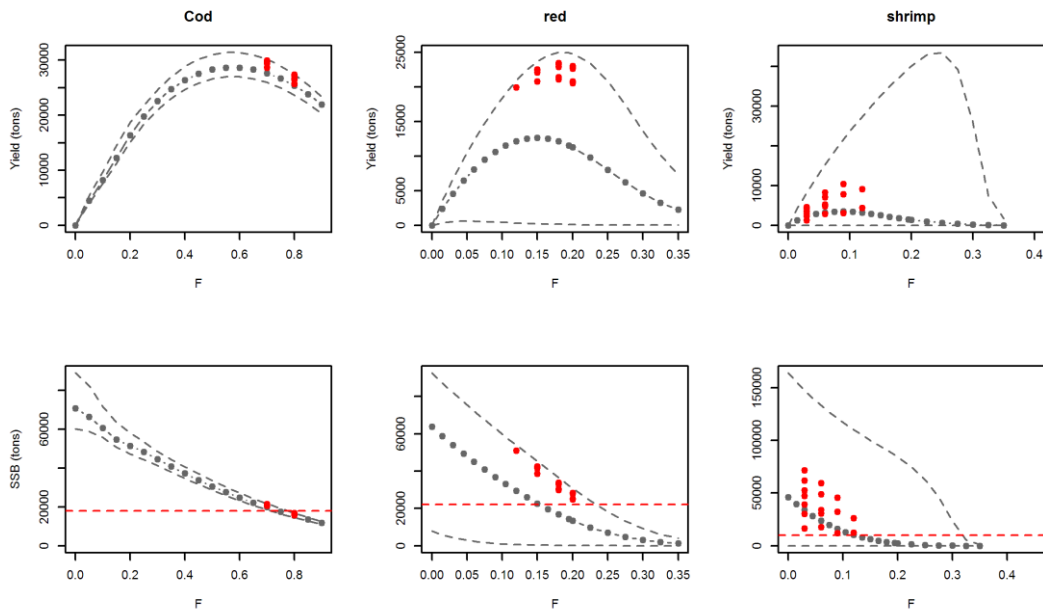"Multispecies Fisheries Assessment for NAFO"

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Figure 6.3-16.- Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F values selected following the criteria 2 and presented in Table 6.3-10.

Table 6.3-10.- Reduced selection of F combinations from all those that resulted in SSB higher than Blim in the equilibrium for shrimp and redfish, but disregarded the state of the SSB for cod (criteria 3).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
3	Disregard cod SSB	0.7	0.15	0.03
3	Disregard cod SSB	0.7	0.18	0.03
3	Disregard cod SSB	0.7	0.18	0.06
3	Disregard cod SSB	0.7	0.2	0.03
3	Disregard cod SSB	0.7	0.2	0.06
3	Disregard cod SSB	0.8	0.12	0.03
3	Disregard cod SSB	0.8	0.15	0.03
3	Disregard cod SSB	0.8	0.15	0.06
3	Disregard cod SSB	0.8	0.15	0.09
3	Disregard cod SSB	0.8	0.18	0.03
3	Disregard cod SSB	0.8	0.18	0.06
3	Disregard cod SSB	0.8	0.18	0.09
3	Disregard cod SSB	0.8	0.18	0.12
3	Disregard cod SSB	0.8	0.2	0.03

3	Disregard cod SSB	0.8	0.2	0.06
3	Disregard cod SSB	0.8	0.2	0.09
3	Disregard cod SSB	0.8	0.2	0.12

Figure 6.3-17.- Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F selected following the criteria 3 and presented in Table 6.3-10.

When the state of the SSB for redfish is disregarded (criteria 4), again the number of possible F combinations is higher, with 1068 combinations that allow maintaining the SSB for cod and shrimp above their respective B_{lim}. From these 1068 possible combinations, a subset of 40 F combinations was selected (Table 6.3-11), for which a risk assessment will be performed in the next section. In a deterministic way it is already evident that these combinations resulted in the redfish SSB being much lower than B_{lim} (Figure 6.3-18), and producing a very low yield, while for cod and shrimp the SSB was above B_{lim}, in line with the criteria. In cod, with the exception of a few F combinations, most of the cases the SSB was much larger than B_{lim}. The complete table with the 1068 possible combinations of F for the three stocks was provided as part of the deliverable 3.2 (see List of Deliverables table in section 4 of this report).
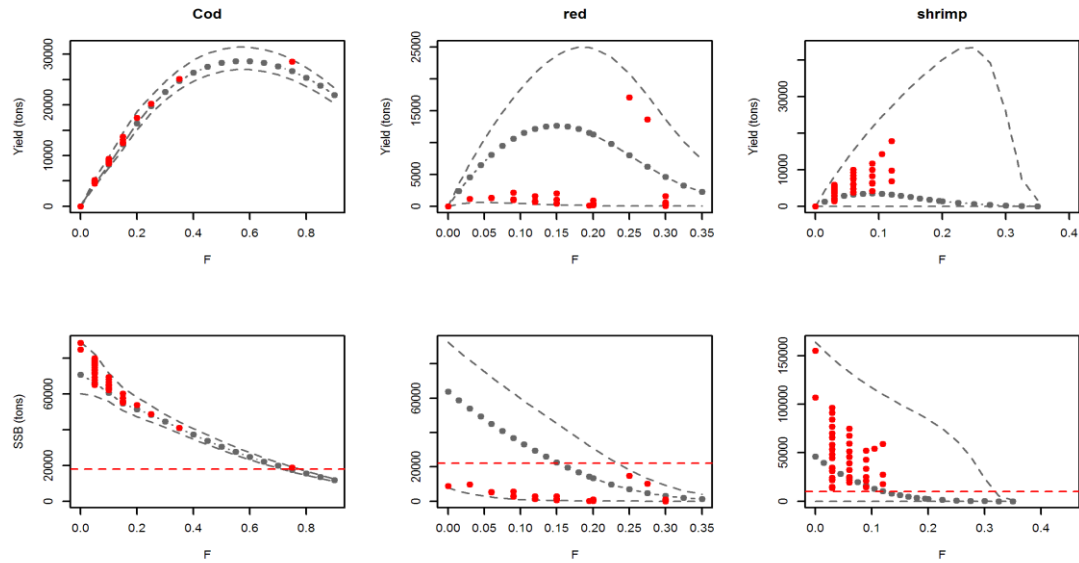
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Figure 6.3-18.- Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F selected following the criteria 4 and presented in Table 6.3-11.

When the state of both cod and redfish was disregarded (criteria 5), 1604 F combinations resulted in shrimp SSB above its established B_{lim}. A subset of 21 F combinations was selected for risk analysis (Table 6.3-12). In these combinations, the deterministic long term simulations showed that in the equilibrium the SSB for redfish was bellow B_{lim} most of the cases, while for cod, it was close to B_{lim} in several combinations, but never below it (Figure 6.3-19). The complete table with the 1604 possible combinations of F for the three stocks was provided as part of the deliverable 3.2 (see List of Deliverables table).

Table 6.3-11.- Reduced selection of F combinations from all those that resulted in SSB higher than Blim in the equilibrium for shrimp and cod, but disregarded the state of the SSB for redfish (criteria 4).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
4	Disregard redfish SSB	0	0	0
4	Disregard redfish SSB	0	0.195	0
4	Disregard redfish SSB	0.05	0.03	0.03
4	Disregard redfish SSB	0.05	0.06	0.03
4	Disregard redfish SSB	0.05	0.06	0.06
4	Disregard redfish SSB	0.05	0.09	0.03
4	Disregard redfish SSB	0.05	0.09	0.06
4	Disregard redfish SSB	0.05	0.09	0.09
4	Disregard redfish SSB	0.05	0.12	0.03

4	Disregard redfish SSB	0.05	0.12	0.06
4	Disregard redfish SSB	0.05	0.12	0.09
4	Disregard redfish SSB	0.05	0.15	0.03
4	Disregard redfish SSB	0.05	0.15	0.06
4	Disregard redfish SSB	0.05	0.15	0.09
4	Disregard redfish SSB	0.05	0.2	0.03
4	Disregard redfish SSB	0.05	0.2	0.06
4	Disregard redfish SSB	0.05	0.2	0.09
4	Disregard redfish SSB	0.05	0.2	0.12
4	Disregard redfish SSB	0.05	0.3	0.03
4	Disregard redfish SSB	0.05	0.3	0.06
4	Disregard redfish SSB	0.05	0.3	0.09
4	Disregard redfish SSB	0.05	0.3	0.12
4	Disregard redfish SSB	0.1	0.09	0.03
4	Disregard redfish SSB	0.1	0.12	0.03
4	Disregard redfish SSB	0.1	0.15	0.03
4	Disregard redfish SSB	0.1	0.15	0.06
4	Disregard redfish SSB	0.1	0.2	0.03
4	Disregard redfish SSB	0.1	0.2	0.06
4	Disregard redfish SSB	0.1	0.3	0.03
4	Disregard redfish SSB	0.1	0.3	0.06
4	Disregard redfish SSB	0.1	0.3	0.09
4	Disregard redfish SSB	0.15	0.15	0.03
4	Disregard redfish SSB	0.15	0.2	0.03
4	Disregard redfish SSB	0.15	0.3	0.03
4	Disregard redfish SSB	0.15	0.3	0.06
4	Disregard redfish SSB	0.2	0.3	0.03
4	Disregard redfish SSB	0.25	0.3	0.03
4	Disregard redfish SSB	0.35	0.3	0.03
4	Disregard redfish SSB	0.75	0.25	0.105
4	Disregard redfish SSB	0.75	0.275	0.12

Table 6.3-12.- Reduced selection of F combinations from all those that resulted in SSB higher than Blim in the equilibrium for shrimp, but disregarded the state of the SSB for cod and redfish (criteria 5).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
5	Disregard cod and redfish SSB	0.2	0.275	0.03
5	Disregard cod and redfish SSB	0.2	0.35	0.03
5	Disregard cod and redfish SSB	0.2	0.35	0.06
5	Disregard cod and redfish SSB	0.35	0.275	0.03
5	Disregard cod and redfish SSB	0.35	0.35	0.03
5	Disregard cod and redfish SSB	0.5	0.275	0.03
5	Disregard cod and redfish SSB	0.5	0.275	0.06
5	Disregard cod and redfish SSB	0.5	0.35	0.03
5	Disregard cod and redfish SSB	0.5	0.35	0.06
5	Disregard cod and redfish SSB	0.5	0.35	0.09
5	Disregard cod and redfish SSB	0.7	0.2	0.03
5	Disregard cod and redfish SSB	0.7	0.2	0.06
5	Disregard cod and redfish SSB	0.7	0.275	0.03
5	Disregard cod and redfish SSB	0.7	0.275	0.06
5	Disregard cod and redfish SSB	0.7	0.275	0.09
5	Disregard cod and redfish SSB	0.7	0.275	0.12
5	Disregard cod and redfish SSB	0.7	0.35	0.03
5	Disregard cod and redfish SSB	0.7	0.35	0.06
5	Disregard cod and redfish SSB	0.7	0.35	0.09
5	Disregard cod and redfish SSB	0.7	0.35	0.12
5	Disregard cod and redfish SSB	0.7	0.35	0.18

Figure 6.3-19.- Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F selected following the criteria 5 and presented in Table 6.3-12.

Subtask 3.3.- Multispecies Management Strategy Evaluation framework and risk analysis.

Running long term simulations with 8000 combinations of F for the 3 stocks (20 F levels per stock determining the fishing pressure on each scenario) has allowed identifying candidate HCRs combinations. In total, with the 5 different criteria considered, a total of 110 combinations of F have been selected for risk analysis. The deterministic long term forecasts conducted in subtask 3.2 have shown already that for some of these combinations, the SSB of one or more stocks get very close to their respective B_{lim} in the long term equilibrium. The risk analysis will show if, when the uncertainty in the recruitment and the error in the assessment processes are considered, these combinations of F will still maintain the stocks above B_{lim} with high probability. In the next sections the first multispecies MSE framework assembled for the NAFO area is presented. Then, this framework is used to perform a risk assessment of the selected HCRs combinations. This multispecies MSE frameworks is also used to test the performance of two stage HCRs in comparison to one stage HCRs. The ecological trade-offs result of different management objectives are described.

Adaptation of the a4a-MSE framework

In the development of a gadget-a4a-MSE framework four main modifications have been introduced:

- Introduction of the multispecies model GadCap as OM
- Parallel MPs
- Implementation of a "shortcut" assessment option with assessment error
- Integration of the MSE framework in a loop to account for uncertainty in the recruitment process and the assessment error.

Introducing these four main modifications in the a4a-MSE framework involved considerable challenges. The first challenge was replacing the single species a4a model with the gadget multispecies model GadCap as an operational model. The a4a-MSE belongs to the FLR project and is an R package. For this reason it was necesary creating another R package that was able to interact and execute gadget as well as serving as bridge between gadget and a4a-MSE. This package has been called gadgetR[1] and provides the user with a two-way interface to Hafro's Globally applicable Area Disaggregated General Ecosystem Toolbox (Gadget)[2]. GadgetR enables user to explicitly control the gadget simulation steps as well as modify and inspect the gadget internal objects (such as recruitment parameters, fleet consumption amount, among others) at any point in time during the simulation. The R package gadgetR takes the output from gadget and formats it in the way needed by the a4a framework, that is, the FLR class objects FLstock and FLindices, to be used by the observation error model and the stock assessment within the MP. In turn, the information contained in the output of the MP and the implementation error model, which is contained in a fwdControl class object, is modified by gadgetR to the format that can be used by a gadget. The package gadgetR was developed at the Institute of Marine Research in Bergen (Norway) as part of the REDUS project[3].

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[1] https://github.com/REDUS-IMR/gadget

[2] http://www.hafro.is/gadget/

[3] http://redus.no/en/projects/redus/participants

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Once the package gadgetR allowed the integration of a gadget model (specifically the multispecies model GadCap) as operating model (OM) within the a4a-MSE framework (hereafter gadget-a4a-MSE), and the interaction with the observation error model, the MP and the implementation error model, the next step was modifying the code and the structure of the a4a-MSE framework to create multiple MPs, as many as stock in the multispecies model, that can be run in parallel during the long term simulations. This modification of the gadget-a4a-MSE was carried out during the internship at the Joint Research Centre in ISPRA[1] and the two short stays at the Institute of Marine Research[2] in Bergen. In the case of GadCap, the gadget-a4a-MSE framework was modified to run three MPs in parallel: cod, redfish and shrimp MPs (Figure 6.3-20). This modification also required changing the code and the structure of the gadget-a4a-MSE framework so it would produce three different FLStock and FLIndices class objects (one per species) coming out from the OM GadCap every year with information from the real stock, real fisheries and scientific surveys respectively. These class objects after going through 3 different observation error models, will be used in the three separate MPs that will eventually result on independent TACs for cod, redfish and shrimp. Whithin each of the three MPs, each stock will have a different stock assessment (so far designed to be an a4a catch at age assessment model or a shortcut option), a different HCR (with different values for B_{lim}, $B_{trigger}$ and F_{target}), and separate management decisions, that, after passing through their respective implementation error model, will indicate the fleets in the GadCap OM the catch that has to be targeted for each of the three stocks.
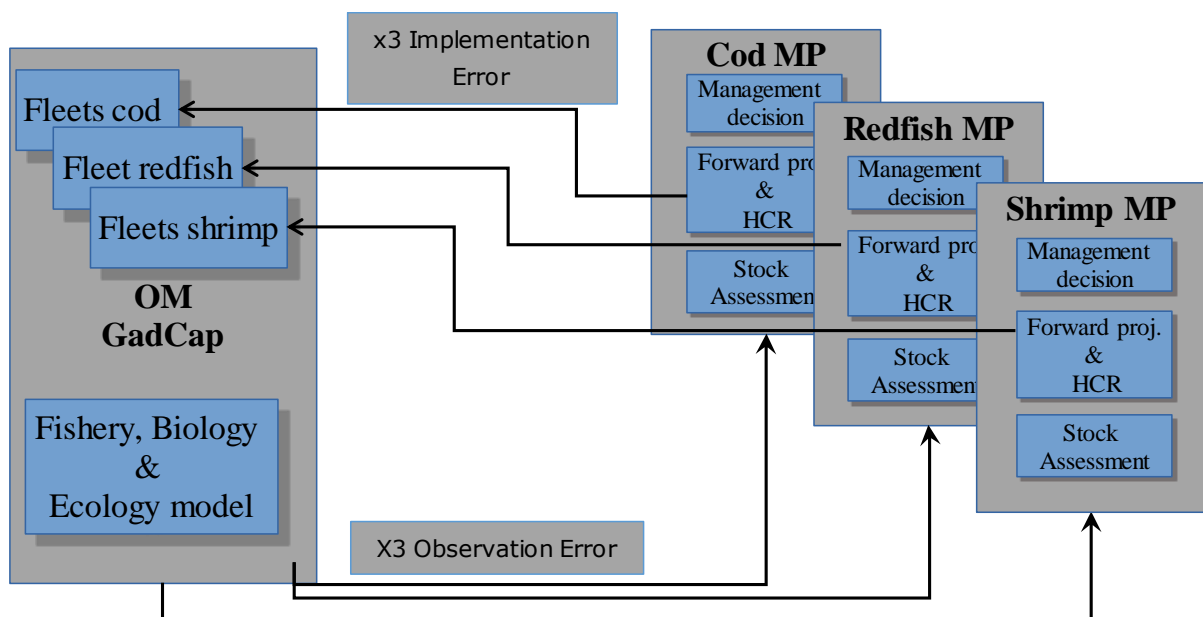
Figure 6.3-20.- Multispecies gadget-a4a-MSE framework. The multispecies model GadCap developed as part of Task 2 was used as OM. Uncertainty on the knowledge of the system was expressed as SSB-Recruitment uncertainty in the OM. Uncertainty in the MP

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[1] https://ec.europa.eu/jrc/en/about/jrc-site/ispra

[2] http://www.imr.no/en

As indicated in the methodology section, although the possibilities for stock assessment within the gadget-a4a-MSE framework include the a4a catch-at-age statistichal assessment model, in this project the shortcut assessment was used instead. In this study, two options were possible for the shortcut assessment. The first option was 'no error shortcut', and, as the name indicates, no any error was applied to the SSB provided by the OM. Hence, this may be considered a perfect assessment option. The second option was a 'truth plus error shortcut' option, and consisted of multiplying the abundance at age in the assessment year provided by the OM times an error value. This error is estimated as described in the methodology section, the mean ratio of the difference between the estimated abundance at age in the last aproved assessment for each of the three stocks, and the abundance at age estimated in the retrospective pattern. This ratio is usually close to 1, but can be lower or higher. A ratio higher than one means that usually the estitamed abundance in the assessment is higher than in reality, and the opposite when the ratio is smaller than one. With the exception of ages 2 to 3 in cod, and 11 to 15 in redfish, in both stocks the estimated ratio was lower than 1 for most ages (see Table 6.3-13 and Table 6.3-14)

Table 6.3-13.- Mean ratio of the difference between the estimated abundance at age for cod in the last aproved assessment for each of the three stocks, and the abundance at age estimated in the retrospective pattern.

age	meanratio
1	0.920441
2	1.160129
3	1.133066
4	1.02969
5	0.955309
6	0.951849
7	0.940828
8	0.944203
9	0.944203
10	0.944203
11	0.944203
12	0.944203

In addition to the mean ratio at age, the analysis of relationship in the ratio between ages over time in the retrospective pattern allows estimating a variance-covariance matrix. Assuming a multivariate normal distribution, the mean ratio at age and the variance-covariance matrix were used during the long term simulations to produce new values of assessment error at age every year, considering the covariance of this ratio bewteen ages.

Finally, the last important challenge was creating a framework that allow assessing the uncertainty in the recruitment process. In order to assess the importance of recruitment uncertainty in the risk associated with a given combination of HCRs for the three stocks, it is necessary introducing variability in the number of recruits that a given level of SSB will produce every year. This was achieved with the integration of the gadget-a4a-FLR tool within

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a framework that would run simulations one after another, using, at each time a different time series of 'recruitment success' level. Although there are different ways to create these time series of recruitment success, in our case these time series were produced in two steps. First, once the Ricker model was optimized, a year factor was calculated as the ratio between the observed recruitment (output from GadCap, grey points in Figure 6.3-9) and the values predicted by the fitted Ricker model (red dotted line in Figure 6.3-9). The estimated year factors (Figure 6.3-21) have been assumed in this work representative of the effect of the annual environmental conditions in the recruitment success of each stock. These environmental conditions may have been water temperature or other oceanographic factors, but also predation, diseases or any other factor affecting survivorship of early recruits. Second, time series of year factors were produced for cod, redfish and shrimp by selecting randomly and with replacement between these estimated values for each of the three species. The length of these time series was enough to cover the long term simulation period, i.e. from 2017 to 2050.

Table 6.3-14.- Mean ratio of the difference between the estimated abundance at age for redfish in the last aproved assessment for each of the three stocks, and the abundance at age estimated in the retrospective pattern.

age	meanratio
1	0.972452
2	0.972452
3	0.972452
4	0.788327
5	0.823222
6	0.842748
7	0.972452
8	0.942793
9	0.921678
10	0.910833
11	1.017579
12	1.050842
13	1.003778
14	1.007053
15	1.019722
16	0.893988
17	0.821866
18	0.932904
19	0.932904
20	0.932904
21	0.932904
22	0.932904
23	0.932904
24	0.932904
25	0.932904

As presented in the methodology section, during the long term simulation, the gadget-a4a-MSE framework will use these time series, one at a time, to produce variability in the relationship between the SSB and the recruitment every year by multiplying the year factor times the parameter α of the Ricker model. This resulted in SSB-Recruitment curves similar in shape, but with different level of recruitment for a given SSB value.

In this work, 100 time series of randomly selected year factors were produced and used to run 100 simulations over the period 2017-2050 using the MSE framework with each of the selected combinations of HCRs. This number of time series was consider enough to assess the risk of the SSB reaching values below B_{lim} due to the uncertainty and variability in the recruitment process.
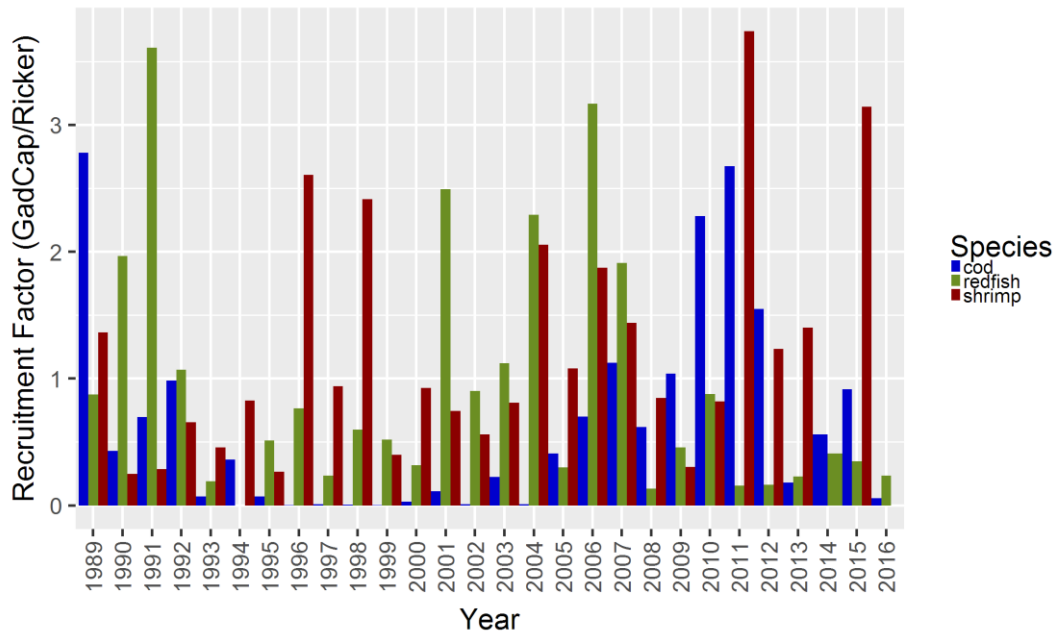

Figure 6.3-21.- Estimated annual factor for SSB-Recruitment relationship. These values result of dividing the recruitment estimated with GadCap in section 3.2 by the predicted recruitment with the fitted Ricker model. These annual factors are assumed to reflect the environmental conditions affecting recruitment and were used to change annually the Richer SSB-Recruitment curve.

Risk assessment of single species and multispecies one stage HCRs combinations considering recruitment uncertainty

The MSE framework was used to perform the risk analysis. The 'no error shortcut' option was used as a first option in the risk assessment for all the selected combinations of HCRs. The 'truth plus error shortcut' option was used for a reduced number of HCRs combinations, with the intention of assessing if the selected best combinations of HCRs are still precautionary when the assessment error is considered.

To avoid excessive and unrealistic population growth during the long term simulations, limitations were introduced to the population growth of shrimp and redfish. This was done by introducing a carrying capacity in the OM, based on the maximum population sizes observed in the historical period. It was assumed that the collapse of cod allowed its prey stocks shrimp and redfish, reaching values that may be close to the maximum carrying capacity. To simulate this limitation to population growth, a source of extra mortality has been introduced in the shrimp submodel when it approached 150000 tons of total biomass, and a source of extra mortality for the redfish submodel when it was approaching a SSB of 70000 tons. For cod, it has not been necessary, since cannibalism has worked as a source of mortality limiting the productivity of the stock.

Data are shown in graphs and figures, but original excel tables can be provided upon request.

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- Single species based HCRs combinations

When the HCRs selected based in single species criteria were used in long term simulations, the uncertainty in the SSB-recruitment relationship produced that the SSB would go bellow the B_{lim} in all the three stocks all over the simulated period 2017-2050 (Figure 6.3-22), but specially on shrimp and cod. In the equilibrium (over the period 2035-2050), the probability of being below B_{lim} at least one year was clearly above the 10% limit considered in NAFO to be precaturionary in cod and shrimp, while in redfish the combinations of HCRs maintained the stock in the safe zone, with less than 10% of the simulations being below Blim at least one year (Table 6.3-15).
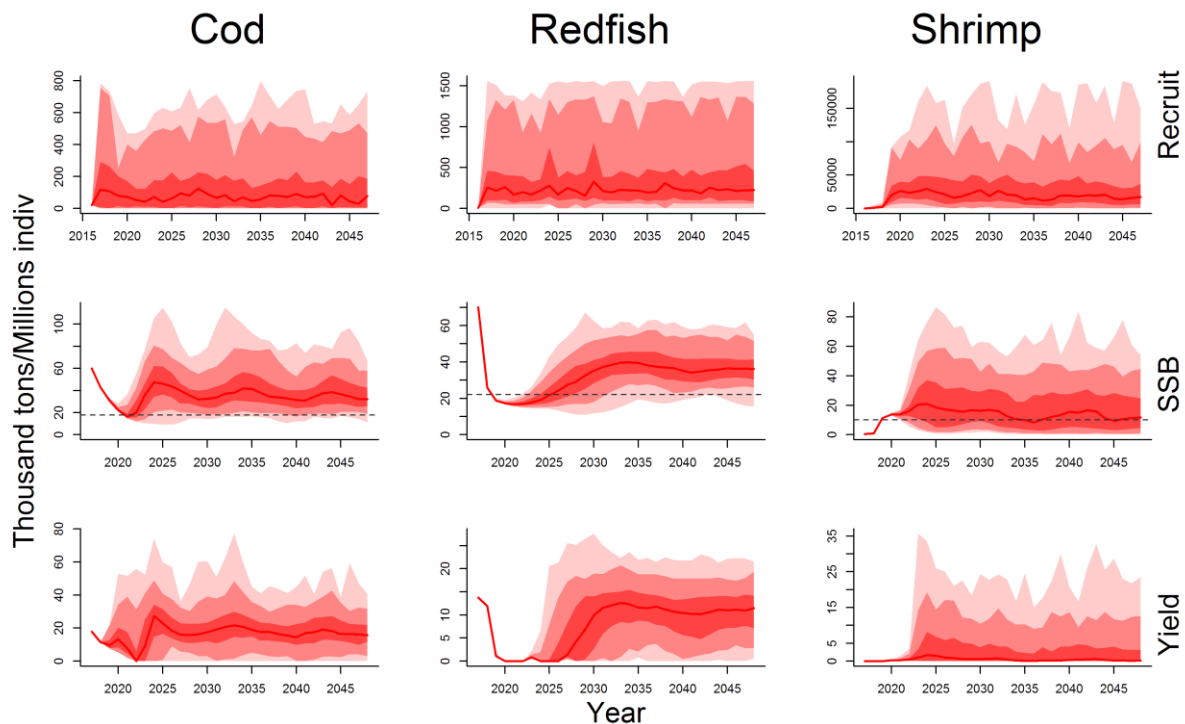
Figure 6.3-22.- Long term simulations using the multispecies MSE framework with GadCap as an OM, while in the MP, the HCRs defined with single species considerations are used to define the fishing quota annualy. The red line defines the median Recruit, SSB and yield. From darker to clearer, the coloured areas define the 25-75, the 5-95 and the 0-100 percentiles. These ranges of uncertainty were produced by running 100 simulations, each of them with a different time series of year effects in the SSB-Recruitment relationship.

Table 6.3-15.- Results of the risk analysis on the HCRs defined with single species criteria candidate to maintain the three stocks above Blim when the recruitment uncertainty is included in the long term simulations. The second column shows the F_{target} for each of the stocks in the selected combinations. The third column shows the probability (proportion of the 100 simulation runs) of being below Blim in the long term (period 2035-2050). The forth column shows the median yield and the last column the interannual variability in the catch, as percentage of difference in relation to the median yield.

Species	F_{target}	Perc_below_B_{lim}	Median_Yield	Interannual_variance
cod	0.353	26	16719	23
redfish	0.1	4	11021	12
shrimp	0.067	77	2730	81

- Multispecies based HCRs combinations: 3 species above B$_{lim}$

When taking into account the species interactions, the first management objective that was decided as part of this simulation exercise was maintaining the 3 stocks above B$_{lim}$. In the Table 6.3-16 the different HCR combinations as well as the risk of being below B$_{lim}$ as a percertange over the 100 simulation runs are shown. The results indicate that none of these HCR combinations were precautionary for cod and shrimp, while for redfish the probability of being below B$_{lim}$ was lower than 10%. Despite the high risk of collapse, the median yield over the period 2035-2050 was high for cod. However, the percentage of interannual variability (percentage of the median yield) was very high, being usually above 100% due to the frequent collapses and closures of the fishery. The low risk of collapse, high median yield and low interannual variability for redfish was probably due to the released predation from a collapsed cod.

- Multispecies based HCRs combinations: disregarding shrimp

The candidate combinations of HCRs selected when the level of SSB on shrimp in relation to its B$_{lim}$ reference point is disregarded showed better performance than those combinations of HCRs intended to maintain the three stocks above B$_{lim}$. Although none of the options were precautionary for shrimp, some combinations maintained cod below or around the 10% probability, while a larger number allowed redfish to be at precautionary levels (Table 6.3-17). But the most interesting output is that there was a number of combinations for which the probability of being below B$_{lim}$ was lower or slightly higher than 10% both for cod and redfish at the same time (e.g. combinations 5 and 6). Hence, when the shrimp is disregarded it is possible finding combinations of HCRs that allow exploiting cod and redfish within the precautionary constraints. With these HCRs combinations yield values are comparable to the TACs for Flemish Cap cod and redfish in the last years (see (Ávila de Melo et al. 2017, González-Troncoso 2017), and the interannual variability is lower than 20% of the median yield.

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Table 6.3-16.- Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain the three stocks above Blim when the recruitment uncertainty is considered in the simulations. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

HCR_combi	F_{target}			Risk_below_B_{lim}			Median_yield			Interannual_variance		
	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0.55	0.18	0	81	3	40	17118	15547	0	62	11	0
2	0.6	0.165	0	92	2	38	16798	15762	0	100	11	0
3	0.65	0.165	0	92	1	39	17649	14870	0	48	12	0
4	0.65	0.165	0.015	93	1	40	16835	15687	0	99	13	0
5	0.65	0.165	0.03	93	1	43	14398	15894	0	134	13	0
6	0.65	0.195	0	92	1	36	16755	15705	1526	101	11	55
7	0.65	0.195	0.015	92	1	37	16764	15641	1673	100	13	58
8	0.65	0.195	0.03	92	1	41	16687	15642	2812	101	11	54
9	0.65	0.195	0.045	93	1	44	16658	15595	3067	100	13	47
10	0.65	0.195	0.06	92	1	49	16552	15536	4189	100	13	52
11	0.75	0.2	0	99	1	35	16520	15469	5146	99	13	63
12	0.75	0.2	0.06	100	1	51	13888	15648	5616	162	13	69
13	0.75	0.2	0.075	100	1	53	13826	15577	6411	170	13	257

Table 6.3-17.- Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain cod and redfish above Blim while disregarding shrimp when the recruitment uncertainty is considered in the simulations. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

HCR_combi	F_{target}			Risk_below_B_{lim}			Median_yield			Interannual_variance		
	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0.1	0	0	9	66	75	7528	0	0	16	0	0
2	0.15	0.03	0	9	53	76	10410	2459	0	17	38	0
3	0.2	0.03	0	11	22	78	12729	3322	0	17	22	0
4	0.2	0.06	0	9	30	73	12788	5246	0	17	27	0
5	0.25	0.03	0	13	6	82	14712	4022	0	18	10	0
6	0.25	0.06	0	14	15	73	14768	6527	0	18	13	0
7	0.25	0.09	0	14	23	67	14783	7750	0	19	22	0
8	0.3	0.03	0	18	3	79	16039	4586	0	20	8	0
9	0.3	0.06	0	18	5	72	16135	7685	0	20	11	0
10	0.3	0.09	0	17	10	66	16197	9418	0	20	13	0
11	0.35	0.03	0	25	1	78	16876	5062	0	23	5	0
12	0.35	0.06	0	25	1	72	17003	8602	0	23	6	0
13	0.35	0.09	0	27	4	65	17069	10667	0	23	9	0
14	0.35	0.12	0	27	6	58	17112	11570	0	23	12	0
15	0.45	0.03	0	51	0	77	17429	5610	0	32	4	0

16	0.45	0.06	0	51	0	69	17594	9629	0	32	5	0
17	0.45	0.09	0	51	0	58	17693	12244	0	32	6	0
18	0.45	0.12	0	51	2	54	17807	13525	0	32	9	0
19	0.45	0.15	0	50	2	48	17910	13733	0	32	12	0

- <u>Multispecies based HCRs combinations: disregarding redfish</u>

The HCRs combinations where the redfish state in relation to B_{lim} was disregarded while prioritizing cod and shrimp resulted in very low probability of cod SSB being bellow B_{lim} (less than 10%) with the exception of those combinations where the F_{target} for cod was above 0.35. However, shrimp did not get risk lower than 45% in any of these combinations, and redfish risk of being below Blim was very high (above 80%), with the exception of those combinations for which the risk was higher for cod (see HCRs combinations 38-40 in Table 6.3-18). Yield in redfish was relatively low, and interannual variability high (above 100% in most cases) in those years for which the risk was high, while the opossite pattern was observed in HCR combinations 38-40. For shrimp yield was always low in comparison to historical catches (Casas-Sánchez 2017), and interannual variability was above 50%, although it was higher when yield was high, due to the higher risk of collapse result of higher fishing pressure. Interannual variability was low in cod in all HCRs combination, excepting 39-40 when F_{target} was high (Table 6.3-18). Cod yield increased when F_{target} on cod was higher, however, it was clear that, for each level of F_{target} on cod, yield decreased when the F_{target} on redfish and shrimp was increased. This was the result of an increased cannibalism on cod in reaction to a lower availability and higher collapse risk of prey (redfish and shrimp) due to higher fishing removals.

- <u>Multispecies based HCRs combinations: disregarding cod</u>

In those HCRs combinations selected when the state of cod SSB in relation to B_{lim} was disregarded, the risk of being bellow B_{lim} for cod was, as expected, very high (Table 6.3-19). Still the yield was high for cod, but this was at the cost of a extremely high interannual variability (often closed fishery), usually above 200% of the median yield. On the contrary, for redfish the risk was very low due to the release from cod predation, resulting in an increased productivity and hence higher yield for the fishery. However, shrimp did not benefitted from these scenarios, probably due to the high predation from redfish.

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Table 6.3-18.- Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain cod and shrimp above Blim while disregarding redfish when the recruitment uncertainty is considered in the simulations. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

HCR_combi	F_{target}			Risk_below_B_{lim}			Median_yield			Interannual_variance		
	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0	0	0	5	96	54	0	0	0	0	0	0
2	0	0.195	0	4	99	39	0	287	0	0	153	0
3	0.05	0.03	0.03	9	90	63	4101	798	3062	16	768	113
4	0.05	0.06	0.03	7	92	58	4117	1131	3359	16	88	69
5	0.05	0.06	0.06	8	93	64	4046	1102	5613	16	209	80
6	0.05	0.09	0.03	7	95	55	4126	1259	3516	16	220	82
7	0.05	0.09	0.06	8	95	62	4053	1224	6000	16	183	76
8	0.05	0.09	0.09	8	94	66	3994	1196	7715	16	170	90
9	0.05	0.12	0.03	7	98	52	4136	1294	3658	16	112	69
10	0.05	0.12	0.06	8	97	61	4058	1256	6269	16	116	81
11	0.05	0.12	0.09	8	97	65	3997	1223	8082	16	103	94
12	0.05	0.15	0.03	7	99	49	4143	1220	3821	16	148	71
13	0.05	0.15	0.06	7	99	61	4061	1179	6466	16	167	70
14	0.05	0.15	0.09	8	99	62	3998	1163	8360	16	130	88
15	0.05	0.2	0.03	8	99	48	4155	977	3981	16	131	58
16	0.05	0.2	0.06	9	100	55	4079	974	6723	16	129	71
17	0.05	0.2	0.09	10	100	63	4007	950	8616	16	133	92
18	0.05	0.2	0.12	10	100	68	3948	948	10009	16	125	92
19	0.05	0.3	0.03	9	100	46	4173	676	4270	16	329	56
20	0.05	0.3	0.06	9	100	52	4096	647	7095	16	255	72
21	0.05	0.3	0.09	10	100	57	4019	657	9079	16	127	75
22	0.05	0.3	0.12	10	100	63	3953	663	10612	16	126	89
23	0.1	0.09	0.03	9	85	64	7540	2799	2363	16	86	89
24	0.1	0.12	0.03	9	90	61	7545	2819	2521	17	102	78
25	0.1	0.15	0.03	10	91	61	7554	2796	2664	17	193	79
26	0.1	0.15	0.06	10	91	66	7455	2744	4467	17	189	94
27	0.1	0.2	0.03	11	91	58	7576	2479	2830	17	197	163
28	0.1	0.2	0.06	11	91	63	7469	2447	4711	17	125	87
29	0.1	0.3	0.03	11	96	54	7598	1759	3055	17	261	69
30	0.1	0.3	0.06	11	96	62	7485	1717	5185	17	148	98
31	0.1	0.3	0.09	11	96	66	7371	1666	6526	17	170	109
32	0.15	0.15	0.03	8	78	63	10429	4792	2016	17	118	86
33	0.15	0.2	0.03	8	82	62	10447	4460	2205	17	82	81
34	0.15	0.3	0.03	8	87	57	10496	3802	2425	17	237	66
35	0.15	0.3	0.06	9	88	60	10378	3787	4029	17	93	77
36	0.2	0.3	0.03	10	67	58	12859	6163	2190	17	74	78
37	0.25	0.3	0.03	14	50	59	14819	8009	2129	19	64	73
38	0.35	0.3	0.03	27	18	53	17165	11186	2477	23	32	98
39	0.75	0.25	0.105	100	1	55	13953	15454	7994	172	16	170
40	0.75	0.275	0.12	100	1	57	13831	15409	8489	173	19	83

Table 6.3-19.- Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain redfish and shrimp above Blim while disregarding cod when the recruitment uncertainty is considered in the simulations. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

| HCR_combi | F_{target} | | | Risk_below_B_{lim} | | | Median_yield | | | Interannual_variance | | |
	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0.7	0.15	0.03	97	1	49	12656	15500	2436	241	7	47
2	0.7	0.18	0.03	97	1	44	16121	15703	2790	125	10	52
3	0.7	0.18	0.06	97	1	51	12489	16121	2973	275	9	65
4	0.7	0.2	0.03	97	1	44	16163	15697	3091	188	12	53
5	0.7	0.2	0.06	97	1	50	12530	16186	3299	262	12	53
6	0.8	0.12	0.03	100	0	55	16136	15685	3264	104	14	50
7	0.8	0.15	0.03	100	0	46	12671	16111	3439	259	13	52
8	0.8	0.15	0.06	100	0	55	12463	16015	4953	255	9	48
9	0.8	0.15	0.09	100	0	63	15811	15572	5200	99	12	67
10	0.8	0.18	0.03	100	0	40	12596	16039	5530	246	12	50
11	0.8	0.18	0.06	100	0	48	15808	15567	5482	98	14	56
12	0.8	0.18	0.09	100	0	58	12755	15988	5764	243	13	54
13	0.8	0.18	0.12	100	0	64	12210	15914	6054	246	10	79
14	0.8	0.2	0.03	100	0	41	12316	15916	6833	240	12	56
15	0.8	0.2	0.06	100	0	47	12544	15862	7187	238	13	79
16	0.8	0.2	0.09	100	0	54	12130	15746	7441	244	12	97
17	0.8	0.2	0.12	100	0	63	12308	15673	7830	241	13	128

- <u>Multispecies based HCRs combinations: disregarding cod and redfish</u>

The HCRs combinations where cod and redfish were ignored regarding to their SSB in relation to B_{lim}, were expected to result in a lower collapse risk for shrimp. However, the simulations showed that the risk of shrimp SSB being below B_{lim}, despite being lower than in previous scenarios for some HCRs combinations, it was still very high, far from the precautionary limits (Table 6.3-20). This may be related with the fact that, when the F_{target} and hence the risk of collapse was low for cod, the predation on shrimp was high. And, when F_{target} was high on cod, the redfish benefited of that, and even when the fishing pressure was high the risk of colapse was relatively low, involving high predation on shrimp.

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Table 6.3-20.- Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain shrimp above Blim while disregarding cod and redfish. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

HCR_combi	F_{target}			Risk_below_B_{lim}			Median_yield			Interannual_variance		
	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0.2	0.275	0.03	10	65	58	12843	6267	2152	17	63	70
2	0.2	0.35	0.03	10	75	57	12877	5808	2284	17	85	77
3	0.2	0.35	0.06	11	75	62	12715	5791	3843	18	81	140
4	0.35	0.275	0.03	27	17	53	17140	11257	2417	23	30	106
5	0.35	0.35	0.03	27	22	52	17205	11064	2562	23	42	85
6	0.5	0.275	0.03	71	4	42	17796	14236	2899	39	19	63
7	0.5	0.275	0.06	72	4	49	17717	14112	4835	40	19	79
8	0.5	0.35	0.03	71	8	38	17899	14200	3120	38	27	47
9	0.5	0.35	0.06	72	10	44	17726	14088	5203	40	27	61
10	0.5	0.35	0.09	72	10	55	17622	13965	6551	40	28	110
11	0.7	0.2	0.03	97	1	44	16136	15685	3264	104	14	50
12	0.7	0.2	0.06	97	1	50	15808	15567	5482	98	14	56
13	0.7	0.275	0.03	97	2	38	16128	15636	3600	98	20	38
14	0.7	0.275	0.06	97	2	45	15854	15489	5922	99	20	43
15	0.7	0.275	0.09	97	2	52	15606	15355	7371	99	20	54
16	0.7	0.275	0.12	97	2	56	15479	15257	8095	100	20	79
17	0.7	0.35	0.03	97	12	34	16255	15474	3791	98	32	39
18	0.7	0.35	0.06	97	13	44	15991	15348	6346	99	32	45
19	0.7	0.35	0.09	97	14	52	15665	15227	7810	99	33	53
20	0.7	0.35	0.12	97	14	55	15485	15116	8587	99	33	111
21	0.7	0.35	0.18	98	16	64	15243	14928	9339	119	33	106
22	0.4	0.5	0.03	36	90	39	18000	10343	3023	25	129	57
23	0.4	0.5	0.06	35	91	47	17825	10249	5022	25	120	76
24	0.4	0.5	0.09	38	91	56	17658	10257	6327	25	116	145

<u>Risk assessment of one stage HCRs combinations considering the error in the stock assessment (in addition to the recruitment uncertainty).</u>

The result indicate that the selected HCR are more precautionary for cod when the error in the assessment is included in the simulations (Table 6.3-21). The reason is that the retrospective pattern indicated that the assessment tend to underestimate the real biomass of the stock (see Table 6.3-13). Accordingly, the adviced quota is lower than what it could be based in the real stock biomass. This lead to a higher survivorship of the cod stock, and then lower risk of being below B_{lim}. However, although the retrospective pattern in redfish also indicated a tendency to underestimate the real population biomass (see Table 6.3-14), the fact that cod biomass is higher produces a higher predation on redfish. This produces a decrease in productivity of redfish and hence higher probability of being below B_{lim}. In any case, the differences are relatively minor in comparison with the risk assessment without considering the error in the assessment.

Table 6.3-21.- Selection of HCRs for comparison of risk analysis results when the assessment error is considered in the shortcut assesment ('truth plus noise shortcut') in relation to when the error is disregarded ('no error shortcut').

HCR combi	Type	F_{target}			Risk_below_B_{lim}		
		cod	red	shrimp	cod	red	shrimp
1	disregard redfish	0.2	0.3	0.03	7	60	63
2	disregard redfish	0.35	0.3	0.03	22	14	51
3	disregard shrimp	0.25	0.03	0	12	8	83
4	disregard shrimp	0.3	0.03	0	17	2	82
5	disregard shrimp	0.3	0.09	0	18	7	67
6	B_{lim} 3 sp	0.65	0.195	0	99	1	33
7	disregard cod	0.8	0.2	0.03	100	3	38
8	disregard cod and redfish	0.7	0.35	0.03	97	6	28

Risk assessment of two stage multispecies HCRs

A two stage HCR was designed (Figure 6.3-23) using the reference points of the one stage HCR ($F_{target1}$, $B_{trigger1}$ and b_{lim1}) to define the first section of the HCR. A second group of reference points was introduced in this HCR ($F_{target2}$, $B_{trigger2}$ and b_{lim2}) based in previous experience about the dynamic of cod. The values selected for these reference points have been chosen as tentative possible values, with the aim of testing the differences in the performance of one versus two stage HCRs when extra mortality is applied on cod once the stock is abouve a given SSB value. However, values for this second set of references points should be subjected to a more exhaustive process in order to find the best possible combination of reference points.
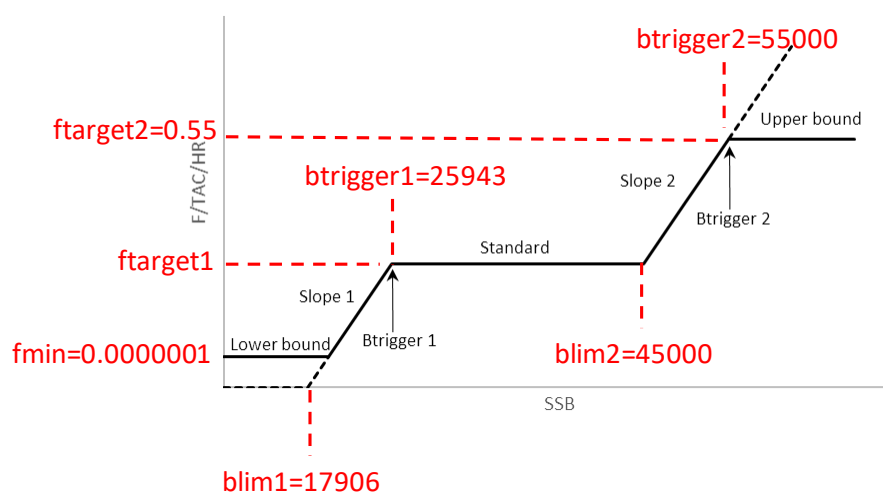
Figure 6.3-23.- Two stage HCR designed to decide the TAC on cod that will be decided within the MSE framework depending on the cod SSB.

The results indicate that a two stage HCR advicing a higher catch when cod SSB is above 45000 tons would result in a clear reduction of the risk of being below B_{lim} for redfish, due to the lower predation from cod (Table 6.3-22). There is also a lower risk of being below B_{lim} for cod, although the difference is not as important as for redfish. For shrimp, there is also a slight benefit in some HCRs combinations, although it is minor in comparison with the high risk of collapse.

Table 6.3-22.- Comparison of probability, for the three stocks, of SSB being below their respectives Blim when a single versus a two stage HCRs is used for cod.

		F_{target}		Perc_B_{lim}_cod		Perc_B_{lim}_redfish		Perc_B_{lim}_shrimp	
comb.N	cod	redfish	shrimp	one-stage	two-stage	one-stage	two-stage	one-stage	two-stage
1	0.25	0.03	0	13	10	6	0	82	82
2	0.25	0.06	0	14	11	15	0	73	75
3	0.25	0.09	0	14	12	23	2	67	65
4	0.35	0.12	0	27	28	6	2	58	54

6.3.5. *Difficulties*

In this project SC05, substantial advancements have been achieved in the design and definition of HCRs that account for trophic interactions. In addition, by the first time in the NAFO area it has been developed an MSE framework with the capacity to assess the performance of management strategies accounting for ecological interactions. However, there still room for improvement in future projects. Difficulties, gaps and suggested future work for improvement in future projects is presented as part of Task 6.

6.4. TASK 4 – EVALUATION OF ECONOMIC IMPLICATIONS OF TRADE-OFFS

6.4.1. *Summary*

This section is divided in two parts. The first one analyzes the existing bioeconomic models and contrast them against the necessities to deal with a full integrated bioeconomic analysis of a multispecies approach-based management in the NAFO 3M area. The second part performs a bioeconomic analysis of selected multispecies HCRs and analyse them from the existing trade offs in the, time, variability of the output and fleets involved, dimensions.

The main conclusion from the first part is that, although models exist, none of them fit exactly to the desired objective of a full integrated bioeconomic analysis of multispecies HCRs. However, a tool that is currently under development, based on integrating two (sub) models such as GADGET and FLBEIA, in such a way hat the first is the (biological) operating model of the second, is likely to be the appropriate one for the NAFO bioeconomic advice.

In the second part, an economic analysis of the HCRs is presented. Although considering the limitations derived from non-use of a full integrated model, several conclusions have been

obtained. These conclusions have been presented from the perspective of the trade offs arrising from the selection of one HCR against other comparable one. It has been obtained that while one HCR can be the most appropiate (in terms of economic performance) for one MS fleet, it is not, necessarily, the most appropriate for the remaining EU fleets of the fishing area. In that sense from the fleet dimension there is not a first best option, for all the EU fleets involved in the 3M NAFO fishery. The same conclusion is obtained when long term vs short term economic indicators are considered or even when indicator's variability is considered.

Another important result that has been obtained is when the one stage vs two stage Shrimp HCRs are compared. In this comparison it has been obtained how a good design of a HCR (the 2 stage HCR) is superior in all the dimensions considered (fleet, time and variabibility).

Some recommendations have been given from the point of view of the results obtained. Financial indicators are dependant on the catch profile of each fleet. If one fleet is very dependant on one species and if the HCR disregards this species, economic results will reflect it. Adittionaly, it should be also considered the variability of the results. When analysing long term strategies, variability of an economic indicator is relevant because investment decisions of the fishing firms are more likely to happen under future stable environments. Therefore, it is worth considering the absolute results vs their variability, trade offs. Finally, results also show that under the application of different HCRs, no overcapacity is appreciated, in the sense that resource rent is not altered by changing (decreasing) the number of vessels of the individual fleets.

6.4.2. Objectives

In Task 4.1 the HCRs outputs arewere analysed in order to define the best modelling approach to cope with the economic evaluation and the availability of economic data. A review work is addressed, where the main source of information is the paper Integrated Ecological-Economic Fisheries Models – Evaluation, Review and Challenges for Implementation (Nielsen et al, 2018) where an extensive review of all the up-to-date economic fisheries models in Europe, North America and Australia has been conducted. An analysis of the challenges to use a full coupled model is also provided. In the case where any existing model could be applied, an analysis of the requirements to deal with the economic evaluation is produced and used as an input to the next task.

In Task 4.2, fleets, data requirements and data sources are identified, and available economic data collected to perform an economic evaluation of the arising trade-offs of the multi-species HCRs executed. This is done using an ad-hoc approach) Results are provided including the uncertainty estimates derived from the modelling output coming from tasks 2 and 3 and from the fleets' financial results perspective point of view. These results are evaluated considering the trade-offs among different fleets and from the point of view of the management system in place. Within the conclusions, recommendations on the best approaches to go forward on the economic evaluation are given.

6.4.3. Methodology

Sub-task 4.1 – Identification and description of the existing economic data and the ecological-economic models suitable to be applied on multispecies assessment

The fishery system comprises a dynamic interplay between the biological part of the system and the economic (or broader ''human'') part. Economics is one of the conditioning factors of fishing activities. The fish, i.e. the biological resource, can naturally exist without the

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fishery, but the fishery cannot exist without the fish, whilst there is an obvious economic interest in exploiting the biological resource. Integrated analyses of the economics and biology of the exploitation of natural resources applied to fisheries is a relatively recent branch of economics. The field is known as bio-economics (Clark 1976) and it has been developing since the end of the 1950s from the work of Gordon and Schaefer (Gordon 1953, 1954, Schaefer 1954, Schaefer 1957).

The need to combine biology and the economics of fisheries comes from external factors, which impact on both. Generally, there is a close link between the resource and the resource user that can be described – in a simplistic way – as the fishing mortality, which results from the extractive activity (even if it is broader than this). Due to this link, external factors, which affect the biological side (e.g., nutrients, hydrographical conditions and biological interactions such as predator-prey relationship) will also impact the economic side of the whole fisheries system. The reverse is also true: external factors, which affect the economic side (e.g., management, fuel costs) will also have an impact on the biological system. In other words, the necessity of a bioeconomic model and integrated approaches comes from the fact that both systems (biology and economy) are interrelated.

What is a bioeconomic model?

A bioeconomic model is a mathematical representation of biological and economic systems, which typically links economic and biological components and parameters together (Prellezo 2010). The biological component represents the natural resource, whilst the economic component characterises resource users, e.g. fishers, consumers or society in general (Da-Rocha et al. 2017).

Types of models

Models can be classified in terms of what they do (simulate or optimize) or in terms of their complexity.

On one hand, simulation models strive to simulate a system by projecting a set of biological and economic variables or parameters into scenarios. On the other hand, when optimizing them find optimal solutions to an objective function under certain economic and/or biological constraints. When optimizing it should be considered that a single dimension can be considered as the objective (i.e. maximize resource rent) or consider multiple dimensions, in where the final outcome is to drive the system (fishery) to a desired area (instead of a point) in where several multi-dimensional objectives are compatible. An important remark is that, it could be the case that the area in which several (conflicting) objectives coexist could be empty. That is, it is not always possible to meet all the objectives at the same time.

Complexity is another issue when deciding which model should be used. End to end ecosystem models tempt to determine multiple factors affecting species growth, including interactions among them (i.e. predator-prey relationships) but also other factors affecting their growth and evolution. Fisheries bioeconomic models are on the other side of the complexity stream. They normally start from the fleets and they are modelled down (to catch stocks) and up to produce profits, based on assumption on market prices, costs, selectivity and effort allocation and intensity.

In both sides of the complexity stream, it should be noted that model's parameterization is key, and that it can drive the results obtained. This will depend on the data quality and the knowledge we have on the fishery. In any case it is always a time-consuming procedure.

Integration

The manner in which the biological and economic subcomponents of fisheries models are linked is crucial for success.

Fish production arises from the application of labour and capital services (physical capital, technology and energy) to the natural resource in a fishery. Thus, when trying to understand a fishery, it is essential to consider biological and economic forces. Integrating different disciplines allows us to integrate possible feedbacks between the biological and economic components. For example, one could conclude from data, that an increase in the input (e.g. vessels, days at sea, etc.) leads to an increase in the output (harvest). However, detailed knowledge of the biology shows that the biological productivity of a fish resource is limited and increases in input do not necessarily lead to long-term increases in output (harvest). Moreover, intricate density dependant interactions in the biology of a species or the fishery, may lead to a system with non-linear relationships between input (e.g. effort) and output (e.g. catch).

Additionally, changes in economic variables (e.g. prices, costs, capital investment and interest rates) will affect fishing mortality through modifications in fishing behaviour; and fishing mortality directly affects the stock size and ultimately stock dynamics.

The complexity of the feedback mechanisms is a hindrance. The models tend to interrelate (feedback) the biological and economic features using complex assumptions. The feedback processes used by these models rely on the levels of catches not coinciding with the advised level (output-based regulations) or on the non-linear relationship between the fishing effort and fishing mortality (the so called hyperstability) in the input based regulated systems. This might happen as a result of the overall selectivity changes, the different evolution of the individual fleets, the tactical behaviour of the fleets (including different objectives or different spatial behaviour), and/or the changes in the capacity of the fleets. However, if the economic aspects of the model are not correctly modelled this feedback process cannot be properly captured. The estimation of the economic performance leading from the current stock status (often far from the intended target) to a biologically ideal status implies substantial changes for many of the stocks. This is well beyond the scope and, in many cases, out of range of most projection models. This is an extremely important issue; given that some projections can be based on strong assumptions in terms of factors availability (except fishing opportunities) and can potentially ignore the likely impact of these factors on stock-rebuilding strategies (or the other way around).

Bioeconomic models that are focused on a single stock, by definition, ignore dynamic interactions with other stocks. Other bioeconomic models evaluate several stocks, e.g. stocks included in a mixed fishery. This can have the form of several independent single species assessments (multi-stock), or assessments which take biological interactions between stocks such as predation (multi-species models).

Independent single assessments are more related to what is happening in the current advisory process (i.e. ICES, NAFO). Advices are given at individual stock status. Under this approach, any (or almost any) reference or target point can be obtained by regulating fishing pressure

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(using TACs or effort limitations). This contrasts with multispecies assessments in which the interspecies interplay through, for example, predator-prey relationships, could end up in a more constrained solution space, in which reference points that were plausible at individual stock level, cannot be always obtained.

In conclusion, it can be stated that meeting an objective at individual stock/species level is not necessarily compatible with a multi-species approach. This statement will have important consequences on the NAFO HCRs evaluation as described in subtask 4.2.

Subtasks 4.2.- Trade-offs between different fleet-sectors within and among countries (special interest in the EU countries)

The methodology of this subtask is divided in two parts: Firstly the available data is described including fishing effort, catches and financial performance of the fleet and used to describe the fishery itself. Secondly and using this data, financial results of the fleets of the likely consequences of each HCR on the financial performance of the different EU fleets fishing the NAFO area 3M are evaluated. These results are focused on the trade offs among the indicators selected and also on the variability (due to the existing uncertainty) of these indicators.

Available data

Capacity data

Capacity data was available through the NAFO secretary. It included: number of vessels by EU country, individual length and gross tonnage (GT) for the period 2013-2017 and individually for each NAFO area (3M, 3L, 3M and 3O).

6 different EU Member States (MS) have had activity in the 3M area in the period 2013-2017. In the year 2014, it peaked the maximum with 27 vessels, with 22 vessels in 2017. In terms of the MS, in 2017, Spain with 10 and Portugal with 9 were the MS with higher number of vessels in this area. Poland and Lithuania only had presence in the year 2014. Figure 6.4-1 presents the evolution of the fleet in this period.
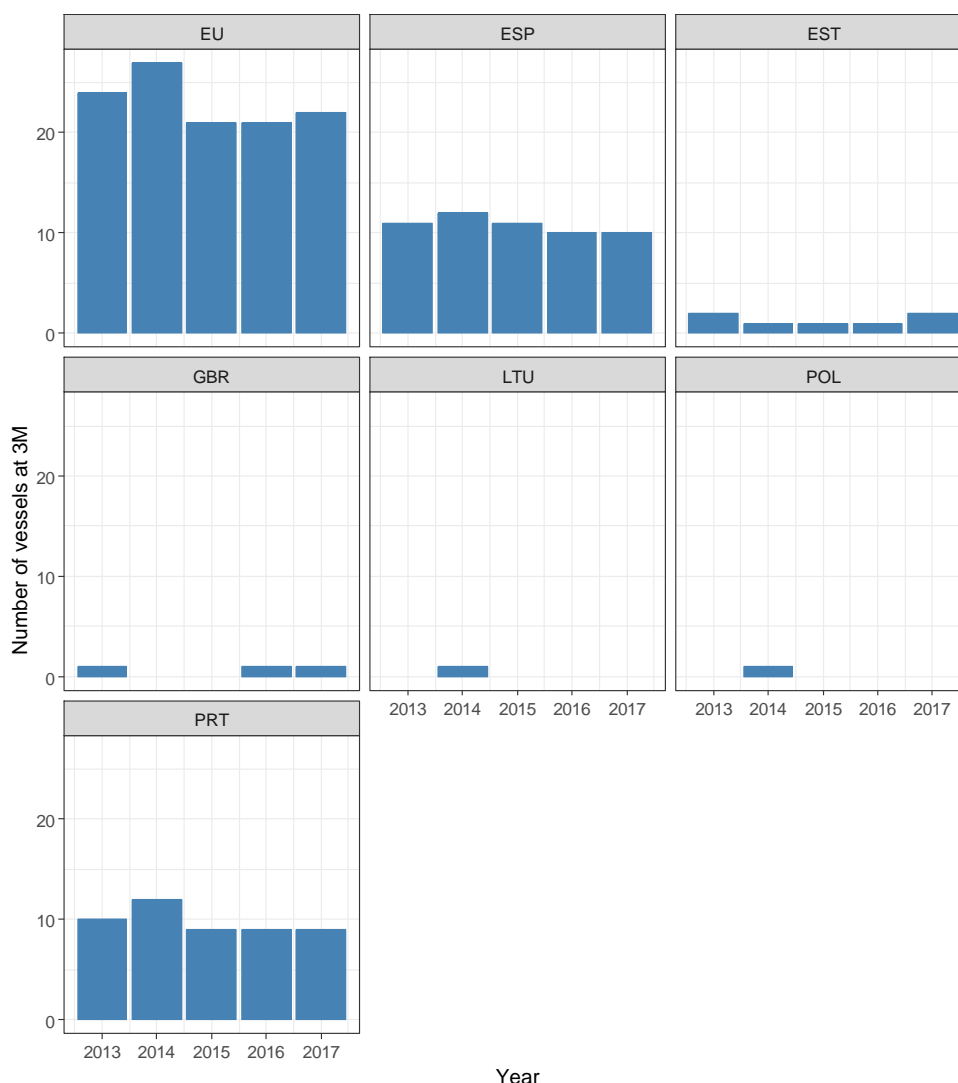
Figure 6.4-1.- Evolution of the number of vessels in the period 2013-2017 in the NAFO 3M area of the EU fleet and by Member State.

EU vessels had an average length ranging from 57m (Spain) to 82m (UK). In GT terms, UK vessels had the highest average with 3690 GT while Spain had the lowest with 1157 GT.

<u>Fishing effort data</u>

Fishing effort data was available through the NAFO secretary. It included: days of presence in the area for the period 2013-2017 of each EU fishing vessel and individually for each NAFO area (3M, 3L, 3M and 3O).

In terms of the presence (days at sea) of the EU vessels in the NAFO 3M area, the number of fishing days decreased from 1624 in 2013 to 1457 in 2017. In this case Portugal with a total of 698 days and Spain with 496 are the main EU contributors to the total fishing effort of EU vessels in NAFO 3M area. The evolution of fishing effort is displayed in Figure 6.4-2, 3M area is not the only NAFO fishing area of the EU fleet. The same vessels also have activity in areas 3N, 3L, 3N and 3O (see annex III for the evolution of the fishing effort in other NAFO areas).

<u>Data for landings</u>

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Landings data was available through the NAFO secretary. It included: landings by species for each EU vessel, for the period 2013-2017 and individually for each NAFO area (3M, 3L, 3M and 3O).

In the period 2013-2017 the EU Fleet landed, on average, 16800 tonnes per year. With the highest amount landed in the year 2017 (18191 tonnes) and the lowest in 2016 (15667 tonnes). The main EU contributor was Portugal with approximately 10000 tonnes per year followed by Spain with 4300 tonnes per year.

On average Cod (COD) accounted for approximately the 53% of the total landings in weight of the period analysed, followed by Redfishes (RED) with a 33.8% and Greenland halibut (GHL) with a 7.3%. Northern prawn was not captured in this period. The evolution of the landings by species and MS are presented in Figure 6.4-3.

However, area 3M is only reflecting part of the activity of the EU fleet. As it can be seen in Table 6.4-1, it is relevant to note how Cod is only a main target species in the area 3M. This implies that any HCR altering the productivity of Cod in this area will have an important effect on the financial results of the fleets.

Table 6.4-1. Average (period 2013-2017) length and GT of EU vessels with activity in the NAFO 3M area.

Member State	Average Length	Average GT
Estonia	68 m	1385
Lithuania	62 m	1943
Poland	60 m	1805
Portugal	76 m	1889
Spain	57 m	1157
United Kingdom	79 m	3316
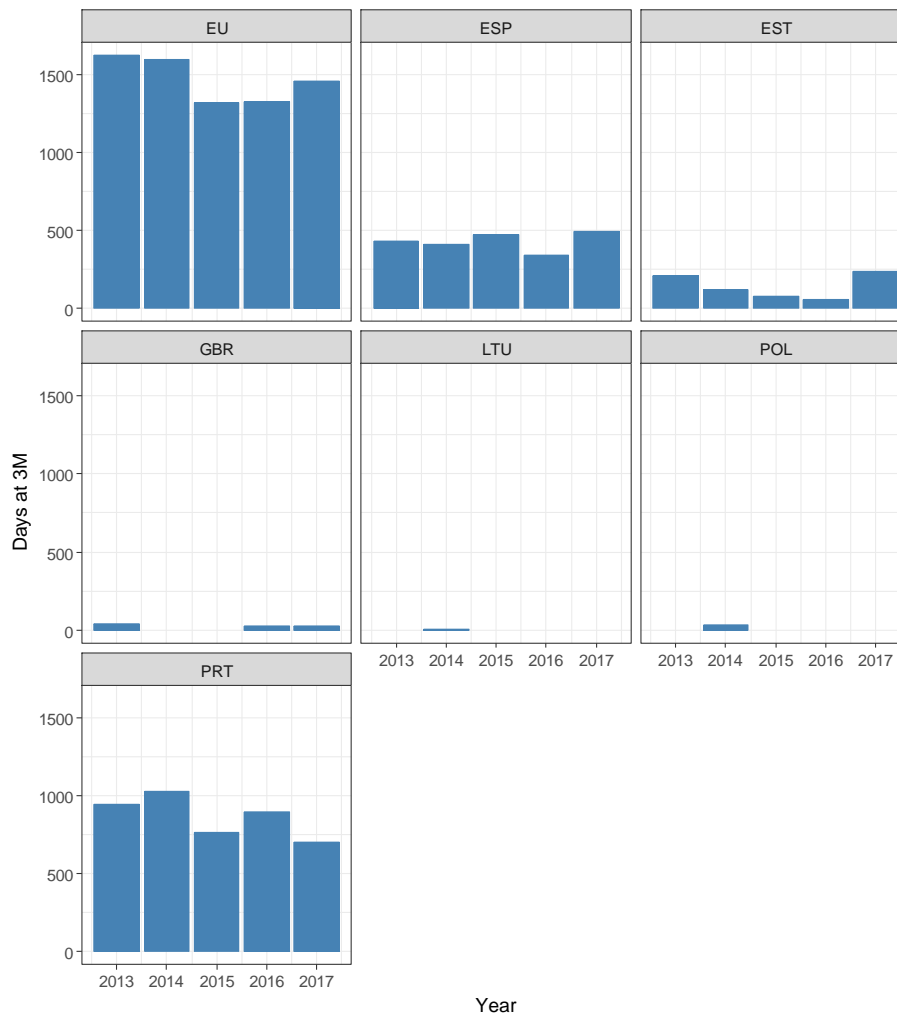
Figure 6.4-2. Evolution of the days of presence in the NAFO 3M area the period 2013-2017 of the EU fleet and by Member State.

Figure 6.4-3. Landings of the EU fleet by species and year in the NAFO 3M area in the period 2013-2017.

Table 6.4-2. Main target species (period 2013-2017) by NAFO fishing area.

NAFO AREA	Main target species	Secondary target species
3M	Cod	Redfishes
3L	Greenland Halibut	Redfishes
3L	Skates	Greenland Halibut
3O	Redfishes	Skates

In other NAFO areas, the same vessels target different species (Table 6.4-2). Greenland Halibut in 3L, skates in 3L and Redfishes in 3O. It should be noted that each fleet is targeting different species. For example, Portugal has the highest dependency on Redfishes of all EU fleets, while UK fleets are only (or almost only) fishing Cod.

Data for Prices

Prices for the area 3M were obtained from the Annual Economic Report on the EU Fishing Fleet of the 2018 year (STECF 2018), which was the latest report available, presenting data of the year 2016 and prior. All monetary values were updated to the 2015-year prices using the Consumer Price Index (CPI) deflator obtained from Eurostat time-series of harmonised CPI. This implies that all results are provided using this reference. In all cases an attempt was made to relate landed quantity with price and to provide a differentiation among the different MSs. However, with the available data it was not possible to obtain statistical significative differences. Adittionaly, prices could also be affected by the availability of substitute fish (elasticity of substitution) or by imports of the same species. However, no attempt was made to consider these effects. Therefore, the assumption taken was that the available susbstitutes and imports, remained constant along the simulation period.

For cod, there are not big differences between the two main fishing MS (Portugal and Spain) in terms of the market prices. The difference, in average, between the two MS is lower than 1%. In terms of the year to year changes, this difference is around 4% (in real price terms). An analysis of the inverse demand was performed to try to relate prices with quantity landed. Results showed that, with the available data, it was not possible to significantly relate price to quantity landed. Therefore, in the projections of the different HCRs it was assumed an average price for cod of 2325€/tonne, for all MS and for the whole simulation period.

There are not big differences between the two main fishing MS (Portugal and Spain) in terms of the market prices for Redfishes. The difference, in average, between the two MS is lower than 5%. However, in terms of the year to year changes this difference is quite high (for Spain there is deviation of around 50%), although the analysis of the inverse demand showed that, with the available data, it was not possible to significantly relate price to quantity landed. Therefore, in the projections of the different HCRs it was assumed an average price for Redfishes of 2485€/tonne, for all MS and for the whole simulation period.

Given that the shrimp fishery has been closed in recent years, the average values of the areas 3N,L and O were used (2662€/tonne for all MS).

For other species, from Figure 6.4-2, it can be seen that, although not so relevant in terms of the total volume of landings, other species were caught by the EU fleet operating the NAFO 3M area. Ex-vessel prices used for these species are presented in Table 6.4-3 (obtained from the Annua Economic Report of the EU fleet (AER 2018)).

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Table 6.4-3. Ex vessel prices for other species used in the projection. Average 2010-2017 in 2015 prices value. When price was not available (NA) it was assumed equal to 1000 €/tonne. Source AER 2018.

Species	Price (Euros/ tonne)
Blue antimoral (ANT)	6189
Atlantic wolfish (CAA)	450
Dogfish (DGX)	1157
Threadfin rockling (GDE)	4644
Greenland halibut (GHL)	3105
Greenland shark (GSK)	NA
Haddock (HAD)	2826
Atlantic halibut (HAL)	2480
Red hake (HKR)	1293
White hake (HKW)	1574
Marine fishes nei (MZZ)	1241
American Plaice (PLA)	2354
Beaked redfish (REB)	3115
Roughhead grenadier (RHG)	2703
Roundnose grenadier (RNG)	2249
Dogfish sharks (SHX)	NA
Raja rays nei (SKA)	2049
Northern shortfin squid (SQI)	NA
Witch flounder (WIT)	2580

Approach taken to conduct bioeconomic simulations

A first attempt of producing financial results comparison among different HCRs has been undertaken in this Task 4.2.

It should be noted that the objective of the HCRs is pre-defined (a biological reference point or a conservation strategy), which implies that from the modelling perspective it is worth to simulate, in contrast to optimize (see Task 4.1). That is, from the projections performed the question what if, instead what's best, is answered.

The fishery system is simulated projecting a set of biological, transversal (fishing effort) and economic variables and parameters into scenarios, to evaluate alternative management strategies. Capacity excess (number of vessels), is also assessed by altering the number of vessels (which otherwise are fixed) and computing the resource rent obtained with the base case (capacity fixed and equal to the historical average).

The approach taken has been the same as the one used in the long term management plan of Bay of Biscay anchovy evaluation performed by the STECF (Sánchez S et al. 2018). This implies that the evaluation has been done coding and ad-hoc program, following, when possible, the main features of bioeconomic models such as FLBEIA (Garcia et al. 2017) and FISHRENT (Salz et al. 2011).

As in these two models, the link between biology and economy is implemented via a Cobb–Douglas production function (Cobb and Douglas 1928). In this function a bi-non-linear relationship is assumed between the two inputs, fishing effort and total stock biomass, and the produced catch. This is done for each species (s) and fleet (f).

$$h_{s,f}(E_f, X_s) = q_{s,f} \cdot E_f^a X_s^b \qquad (1)$$

where, h is harvest, X biomass, E effort (days of presence) and a and b are the effort and stock size elasticities, respectively.

HCRs are considered exogenous, i.e. there is not integration between economy and biology. This last will require a bio-economic model with a biological OM using Gadget, as explained in Task 4.1. This implies that h (landings) and X (abundance-stock size-) along the simulation path are predefined by the biological simulations performed using each HCR. Biomass (abundance) is assumed to be common to all fleets in the area, but harvest is not. Available fishing possibilities by stock and harvest control rule were distributed among fleets, using the average TAC share of each fleet in the last three years for which data was available (2015-2017). Using this distribution and parameters q, a and b *(estimated) for each fleet*, the required days of presence by fleet to catch the catch share provided by each HCR was obtained.

However, days of presence estimated for each species included in the HCR can differ and, in particular, they will depend on the discards allowed. Therefore, a set of scenarios, standard in the multispecies simulation literature (Salz et al. 2011, Ulrich et al. 2011), were considered, to consider these possibilities in the discard regimen.

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- *Min* scenario, where the effort of the fleet is limited by the first TAC share exhausted (by fleet). No discards due to overquota occur;
- *Max* scenario, where the effort of the fleet is limited by the last TAC share exhausted (by fleet). Discards due to overquota occur for al species except for the the species for which the last TAC share is exhausted;
- *2017* scenario, where the effort is fixed and equal to the effort (by fleet) of the year 2017. Discards are, on average, equal to the historical period.

None of the three possibilities are perfect to simulate the financial results of the fleets. While the Min scenario is the most restrictive, the Max scenario is the less. 2017 scenario assumes that no changes are derived in terms of the effort deployed by the fleets, independent of the HCR applied.

TAC shares by fleet are converted into revenues, multiplying the TAC share by the harvest allowed by the HCR by the prices (fixed) of each species. Those species that are part of the catches and landings of the fleet in the area 3M but not included in the HCRs (see Table 6.4-3), are projected using the value per unit of effort (VPUE). This last is obtained dividing the landings multiplied by the prices of each (none HCR) species by the historical days of presence.

Effort (fishing days) was calculated from the species included in the HCRs and then, compute the corresponding value of landings considering the stock size (for those included in the HCRs) and without considering it (for the other stocks that are part of each fleet's landing portfolio).

From the AER, the main economic indicators of the fleet are derived (using the average of period 2014-2016) with the following transformations:

- Crew cost are related to landings, which can be interpreted as a share system, which quite common in fisheries.
- Fuel costs and other variable costs are related to the days at sea. The total variable costs are reconstructed multiplying the average value by the days of presence in the 3M area estimated using equation 1 (by fleet and species and mixed fishery scenario).
- Fixed costs and capital costs (depreciation and opportunity) are related to days at sea by NAFO area. The total fixed and capital costs are reconstructed by multiplying the average value obteined from the AER for the segment (DTS>40m) by the ratio days of presence in the 3M area estimated using equation 1 (by fleet) divided by the days of presence in the areas 3M, N, L and O).

Using this logic, we created the financial performance indicators in the area NAFO 3M at vessel level, which is related to the catch possibilities allowed by each HCR.

The indicators selected to describe the financial performance of the fleets were:

- Gross Value (GV): This is the first economic identity, and probably the most used. Calculated by multiplying landings by ex-vessel prices, it is normally

used to interpret different conservation strategies with a different mix of target species;

- Value added (GVA): Stands for the contribution to the Gross Domestic Product (GDP). GDP is calculated as the indicator paying the labor remuneration, the capital remuneration, and the depreciation of the productive capital;
- Full equity profit (FEP): It is an economic long-term indicator (note that from now we are not talking in terms of expenses but on costs). FEP is defined as the profit that the boat owner would have obtained if there were no debt. It is normally included in the firm's accounts;
- Net Profit (NP): Is the "economic" version of FEP, where capital opportunity cost is considered.

An economic interpretation of any of the indicators above can be given considering their present value. As an example, present valu of the Gross Value (GV) takes the form:

$$PV(GV) = \frac{\sum_{t=2017}^{t=2048} GV_t}{(1 + \partial)^t}$$

Where ∂ is the discount-factor which operates as follows: $\partial = 0$, implies that equal value is given to all gross revenues (present and future) and a discounting factor above $\partial > 0$, implies that the future gross revenue is discounted. It compares different HCRs form the time perspective, that is, if they prioritize the future or the present. Present value is able to show if an extreme conservation strategy is worth or not, or, in general, provide the timing perspective of the conservation preferences.

The Schaefer production (eq. 1 when a=b=1) implies that an increase in stock biomass leads to an increase in the catch at the same rate, when keeping the fishing effort unchanged. The underlying assumption is that the fish stock is homogeneously distributed in the ocean, and the abundance of fish changes linearly. A similar assumption is related to the fishing gear, assuming it to fish with a predefined probability function of fish abundance. Alternatively, a Cobb-Douglas (eq. 1 when a≠1 & b≠1) production function has been suggested by several authors and some empirical work have been carried out on the North-East Arctic cod (Hannesson, 1983; Flaaten, 1987).

As explained above parameters a and b are the effort-output and stock-output elasticities (b indicates the degree of schooling behaviour by the fish) which gives the increase of harvest (h) with an increase of one unit of respectively fishing effort (E) or stock biomass (X). A priori, one expects the elasticities to be within the range a > 0; 0 <= b <= 1. Active gears, like bottom trawls which moves on the bottom while fishing, and long line, which attract fish by bait, tend to have a lower value of b than more passive gears have. Gill nets seems to have b-values closer to 1, which means that the probability of catch is almost proportional to the density of fish.

Due to the limited time series available it was not possible to estimate these elasticity coefficients. Therefore, we referred to the literature and in particular to the b estimator obtained by Eide et al (1998) for a particular trawl fleet fishing cod. They predicted a harvest increase of 0.424 percent when the stock biomass increased by one unit. One interpretation of this is that the density of cod at the trawling grounds may be less affected by changes in the

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total stock biomass, or the trawlers adjust trawling hours per haul, speed or other factors[1]. This implies that the density of the stock at the fishing ground does not increase proportionally when total stock biomass increases. From the same reference, we set a=1.2. An analysis performed showed that the model is highly sensitive to the actual values used as exponents for effort and total stock biomass.

Using this non-linear relationship between effort and fishing mortality we are considering the possibility of crowding. In turn, crowding makes extra trips less efficient, resulting in a flattened fishing mortality rate. Crowding is a direct interference between vessels that reduces their efficiency, e.g. when a trawler and its gear are blocking the way of another trawler

Fishers stop fishing once the marginal cost of fishing exceeds the marginal value of the catch, even if the TAC remains unfilled. The presented model does not consider the marginal costs, and therefore the catches of the modelled fleet segments can be below the quota, but only due to the mixed nature of the fishery (the max and fixed effort scenarios previously explained). The non-linear relationship between stock and catch might also be appropriate, as mobile species such as the modelled stocks can concentrate in restricted areas due to food availability or spawning events.

Using these elasticities, we estimated catchability coefficients (*q*) by fleet and species for NAFO area 3M in equation 1 (**Error! Reference source not found.**). *q* refers to the embodiment of the technology that is used to harvest fish. This estimation has been done using data of effort and catches at individual fishing vessel level for the period 2003-2007, for which the average biomass of each stock was also available. Given that the simulated period is quite long (up to 2048), we defined two scenarios for this *q*. One keeping it fixed among the simulation period and alternative one with a 1% accumulative increase per year, representing a likely technological improvement of the fishing vessels.

We used these *q* values in eq. 2 to compute the fishing days (E) required to catch the predicted (by the HCR) yield (h). We avoid subscripts s (species) and f (fleet) of eq. 2 for reading convenience, although each analysis (by fleet and by species) was made separately:

$$E=(h/qX^b)^{1/a}$$
(2)

---

[1] *Probably, there exist a combination of several of these factors.*

Table 6.4-4. Estimated catchability coefficients

Species	Fleet	q*
Cod	All	2.01767
	Spain	2.33588
	Portugal	2.00697
Redfishes	All	0.70690
	Spain	0.78255
	Portugal	0.66881
Shrimp[1]	All	0.02127
	Spain	0.00239
	Portugal	0.00017

*Pr(>|t|)<0.001.

However, given that not all the yield is captured by the EU fleet, we applied the observed catch share of the EU fleet (α) to the yield:

$$E_{EU}=(\alpha h/qX^b)^{1/a}$$

Where α was calculated using the average retained catches (i.e percentage of landings to the TAC of the years 2015-2017) in the observed data. Again, this was done for each stock and fleet.

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[1] *The shrimp fishery has been closed in recent years in the NAFO area 3M. Therefore, we used the period 2003-2010, for the estimation. Given that the time series was not complete for all the fishing nations, it was decided to simplify the estimation assuming elasticities (a, b) equal to 1.*

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Table 6.4-5. Calculated TAC share coefficients

Species	Fleet	α
Cod	Other EU	0.1757033
	Spain	0.1546321
	Portugal	0.3943741
Redfishes	Other EU	0.104712
	Spain	0.3083929
	Portugal	0.5098411
Shrimp[1]	Other EU	0.7578300
	Spain	0.0678000
	Portugal	0.0023000

As it can be seen, three different fleets were considered based on the nationality of the fleet. We had the Spanish fleet operating in the NAFO 3M area, the Portuguese fleet in the same area, and an overall EU fleet which included the Spanish, the Portuguese fleet and the rest of the EU fleets operating in this area in the period 2013-2017. The remaining non-Spanish-Portuguese fleets have been aggregated to the overall EU fleet to avoid any confidentiality problem with the data (there are less than 3 vessels per MS).

6.4.4. Results

Sub-task 4.1 – Identification and description of the existing economic data and the ecological-economic models suitable to be applied on multispecies assessment

End to end models are particularly relevant to capture ecological and technical interactions, providing a comparison of financial results of the fleets under the fishery/ecosystem of the study. ATLANTIS, being capable of giving a MSE framework (Punt et al. 2016a), is probably the first choice.

However, these are "data-hungry" models. They require a huge amount of biological and ecological processes knowledge and data that make them not easy to tackle without an important investment of resources. Models more simplistic than Atlantis, although not free of difficulties, are reviewed in (Nielsen et al. 2017). Table 6.4-6 gives an (none exhaustive) overview of the models that we think could be used for multi-species HCR evaluation.

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[1] *For Shrimp, again the period 2007-2010 was used, due to the same reason as the q estimation.*

Table 6.4-6. Type of models that could be used for assessing multispecies HCRs.

Type	Models	Pros	Cons
End to End	Atlantis (Fulton.et.al. 2005)	Is able to capture the complexities of the ecosystem relationships. It is able to handle MSEs.	Difficult to condition due to the necessity of data
	EWE (Pauly.et.al. 2000)	Is able to capture the complexities of the ecosystem relationships	It has not an internal MSE procedure. Not straightforward to simulate fisheries HCRs
Intermediate Complexity	Gadget (Begley and Howell 2004b, Salz et al. 2011)	Captures the complexity of the biological relationships. It is an assessment and can act also as a biological multi-species OM.	Not economics.
	Hydra (Gaichas et al. 2017)	Length structured multispecies, multi-fleet simulation	Limited in economics. Only revenue and it is based on fix prices
Fisheries Bio-economic models	FishRent Salz, Buisnman et al. 2011)	Fisheries simulation model. Different alternatives to simulate economic alternatives. It simulates or optimizes.	Not clearly a MSE model. Assessment is not integrated. It has not any equilibrium condition. Not multispecies interactions considered.
	FLBEIA (Garcia et al. 2017)	Fisheries simulation model. Different alternatives to simulate economic alternatives. Flexible to handle different biological OM. It handles MSE	It does not optimize. Multispecies OM not operational yet (under development). It has not any equilibrium condition.
	Macro-Fish (Da-Rocha et al. 2017)	It is defined as economic model, where, all markets (labour capital and fish) are cleared. Compatible with economic theory. Counterfactual analysis.	Not a MSE model. Assessment is not integrated. Not multispecies interactions considered.

Models of intermediate complexity are a more pragmatic way of approaching the first steps in multispecies modelling in NAFO waters. Gadget is a perfect candidate because it handles, both, single stock HCRs, or multispecies HCRs. However, there are not, currently, multispecies biological operating models that interact (with a feedback) with the economic performance on the fleet. The Institute of Marine Research Institute in Norway is currently adapting Gadget (Begley and Howell 2004b) as the biological OM of FLBEIA (Garcia et al. 2017). This integration will create a simulation model able to handle: technical interactions, biological interactions, fleet's economic performance and harvest control rules, in an integrated way, that is, with all the feedback mechanisms in place. However, this integration is not currently available as part of the FLBEIA package (it is expected to have a running version in the year 2019).

Fisheries bioeconomic models are normally fleet oriented. This implies that the fleet catch stocks to produce profits. These models are quite well stablished to perform impact assessment of fisheries plans, because they simulate the feedback between the stocks and the fleets productivity. However, they are not currently dealing with the multispecies characteristic Therefore, a model capable of introducing multispecies interaction in its biological OM is probably a good balance, between complexity and operationalization of an advice.

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Table 6.4-7. Modelling characteristics that can handled by the models selected.

Dimensions	Characteristics	Atlantis	EWE	GADGET	Hydra	FishRent	FLBEIA	Macro-Fish
Bio-Ecology	Trophic interactions	green	green	green	green	red	red	red
	Ecosystem Dynamics	green	green	red	green	red	red	red
	Assessment of Stocks	red	red	green	red	red	green	red
	Stocks Dynamics	green	green	green	green	green	green	green
	Data Poor	red	red	red	red	green	green	green
Management	Single stock HCR	green	green	green	green	green	green	green
	Multi-species HCR	green	green	green	green	red	red	red
	Effort based	red	red	red	red	red	red	green
	Spatial explicit	green	green	green	green	red	red	red
	MSE	green	red	red	red	red	green	red
(Fleet) Processes	Feedback	red	red	red	red	green	green	red
	Price Dynamics	green	red	red	red	green	green	red
	Effort Dynamics	green	red	red	red	green	green	green
	Capital dynamics	red	red	red	red	green	green	green
Fleet results	Financial results	green	red	red	yellow	green	green	red
	Economic Results	red	red	red	red	red	red	green
Resources	Complexity	red	red	yellow	red	yellow	yellow	yellow

In that sense the combination of FLBEIA and Gadget seems like a perfect candidate in where the biological operating model is able to capture multi species characteristics, and therefore HCRs dealing with this characteristic, and also to have a fleet approach. However, these models are not free of limitations, given that results cannot be interpreted using the economic theory. To do so a micro-founded model is required such as the macro-fish. Its limitation is that the integration between the ecosystem and economic dimensions is not available.

A summary of the modelling characteristics and existing models is provided in Table 6.4-7. Where a red cell implies that the model cannot handle this characteristic, a green one that it can, and a yellow one that it can but with limitations.

Given that the biological side of Gadget is currently running, including species interactions, the most data and conditioning demanding issue, will be to condition the fleet. Fishing effort and catches by fleet, species and age are required as input data. Additionally, given that vessels do operate in different areas, this information has to be given at metier level (or NAFO area). Currently the available data is provided by the NAFO secretariat and includes, by vessel and for the period 2013-2017, catches by species and days of presence for each NAFO zone (3M, N, L and O).

Market prices for fish are collected in the Annual Economic Report of the EU fishing fleet (STECF 2017) from FAO statistics, by area and species, for the period 2008-2016. In economics (financial economics) results are normally provided using Euros/ US dollars. The reason why a single currency is required is to capture the relative differences in value of the varied species caught. It is not easy to compare 1 kg of species 1 with 2 kg of species 2, given that the result is not as simple as 3 kg of fish. However, if we multiply it by their market price, and we assume that 1 €/kg is the market price of both, the result can be summarized in 3 Euros. If the market price of the second species 0.1€/kg, the results will be 1.2 Euros, which implies that is worth to capture species 1 compared with species 2, ceteris paribus. When the data is presented as monetary value instead of weight, we can assess a change on the importance of species from the fishing firm perspective.

Fish market prices are generally differentiated by species, fishing area and by fleet (or fleet segment). The price of a species can be affected by fleet nationality (production can be sold at different prices in different countries) and by the fishing gear used by the fleet (fishing gears determine differences in the quality and size of the product and hence its price). However, when differences in prices related to the fleets are negligible, the same price can be used for the total landings of a stock.

Financial indicators of the fleet are also obtained from the same source (AER), using the segment DTS >40m of the area OFR (outer fishing regions). It should be noted that this segment is completed for whole period (2008-2016), only for Spain.

Attempts (a questioner was submitted through the LDAC) have been made in this project to collect additional financial data for the EU fleets operating in the NAFO. Although the LDAC has been cooperative, they have preferred to wait until the project is explained to them to start any data collection.

Subtasks 4.2.- Trade-offs between different fleet-sectors within and among countries (special interest in the EU countries)

Description of each HCR

The financial performance projection of the fleets has been evaluated for six different HCRs:

- Single_sp: 1 combination of 3 HCRs for cod, redfishes and shrimp where the reference points have been calculated using single species criteria.
- One_stage_HCR_Disregard_shrimp: 1 combination of 3 HCRs for cod, redfishes and shrimp where the reference points have been calculated using multi-species criteria, without considering if the SSB for Shrimp is below the Blim.
- Disregard_Cod: 1 combination of 3 HCRs for cod, redfishes and shrimp where the reference points have been calculated using multi-species criteria, without considering if the SSB for Cod is below the Blim.
- Disregard_redfish: 1 combination of 3 HCRs for cod, redfishes and shrimp where the reference points have been calculated using multi-species criteria, without considering if the SSB for Redfish is below the Blim.
- Disregard_cod_and_redfish: 1 combination of 3 HCRs for cod, redfishes and shrimp where the reference points have been calculated using multi-species criteria, without considering if the SSB for Redfish and Cod are below the Blim.

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- Two_stage_HCR_Disregard_shrimp: 1 combination of 3 HCRs for cod, redfishes and shrimp where the reference points have been calculated using multi-species criteria, without considering if the SSB for Shrimp is below the Blim, where the HCR is based on a two stage hockey stick.

HCR comparisons made

Different HCRs have been tested in this report. However, we have decided to limit our results to a comparison of 6 different HCRs with the following logic (Table 6.4-8):

- Single stock-based HCR performance compared to the performance of multispecies HCRs disregarding the **prey** (Shrimp) or disregarding the **predators** (Cod and Redfishes).
- A comparisson of the multispecies HCRs disregarding each of the species included in the HCRs (Shrimp, Redfishes and Cod.
- A comparisson of the multispecies HCRs, considering two alternative HCR for the **prey** species (Shrimp): one stage vs two stage HCRs.

Table 6.4-8. HCR comparisons performed

HCR Comparison	Single	Disregard shrimp	Disregard Cod	Disregard redfish	Disregard cod & redfish	Two-stage Disregard shrimp	Logic
1	✔	✔			✔		Single vs prey vs predators
2		✔	✔	✔			Multispecies disregarding one
3		✔				✔	Two alternatives for the prey

Results are presented using the three comparisons presented above. They consider the following elements:

- Results are compared under the multispecies TAC Min and TAC Max scenarios;
- Effort evolution is presented, always compared to the effort in 2017;
- Gross revenues evolution is presented;
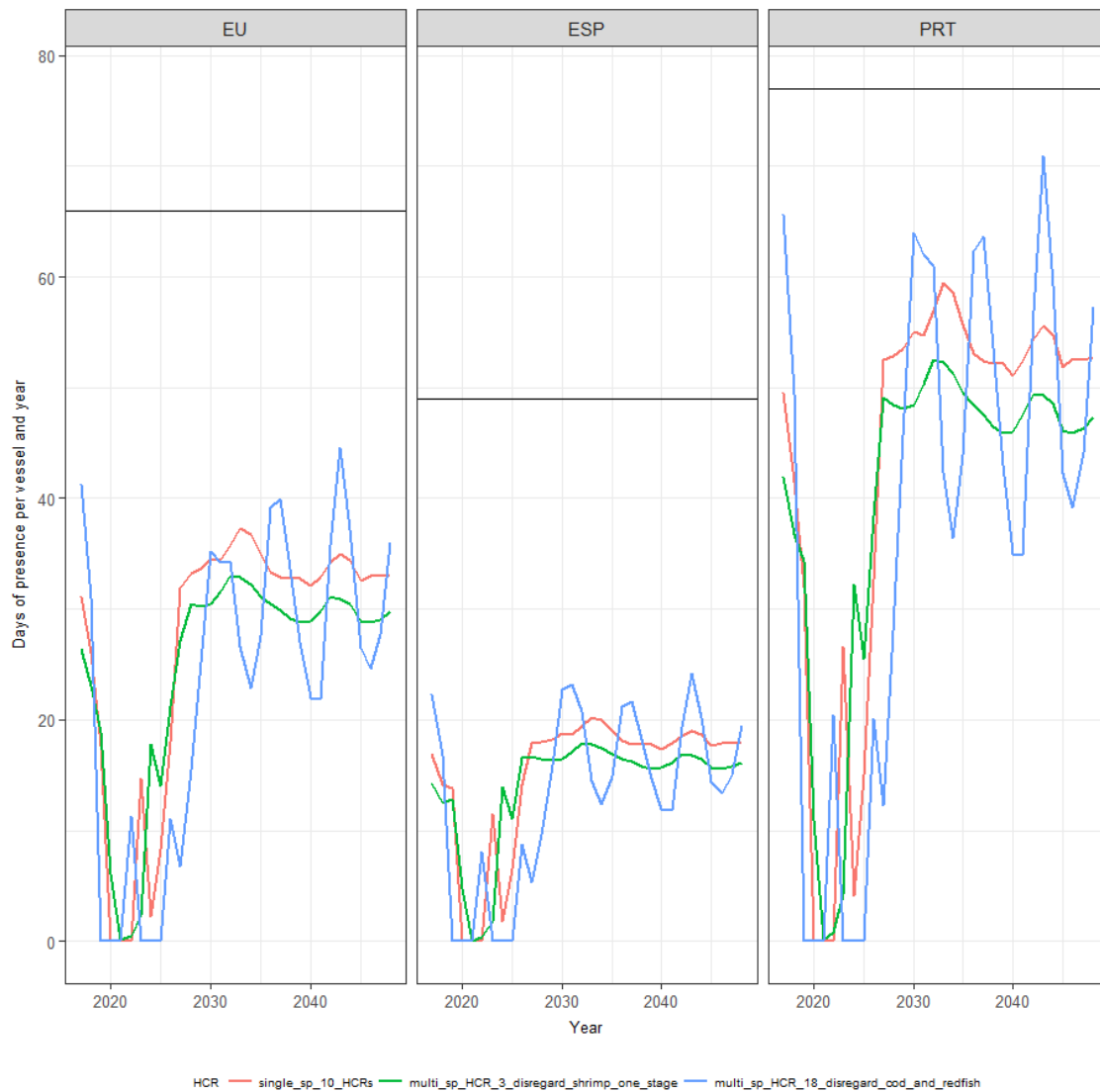
Figure 6.4-4. Simulated effort of the EU fleet in the NAFO 3M area in the period 2018-2048 under TAC min scenario.

Figure 6.4-5. Simulated effort of the EU fleet in the NAFO 3M area in the period 2018-2048 under TAC max scenario.

The two figures above present the simulated evolution of the effort under the TAC Min (the fleets stop when each first TAC quota share is exhausted -Figure 6.4-4-) and TAC Max (the fleets stop when each last TAC quota share is exhausted -Figure 6.4-5-) scenarios. Main results obtained are:

- Under the TAC min scenario, effort is always below the historical one. This implies that using the current overall selectivity levels of each fleet, discards should be allowed to mantain historical observed effort.

- For Spain and the overall EU fleet the only HCR with a higher effort level than the historical one is the multispecies HCR disregarding the two predators. For Portugal this is also true for the single stock HCR. In any case it should be noted that the

overall trend is always increasing, that is, effort tend to rise with time as a result of the HCRs.

- Even if effort is high for multispecies HCR disregarding the two predators, it should be noted that big jumps occur from year to year, which is a reflect of the un-stable HCR that is being proposed.
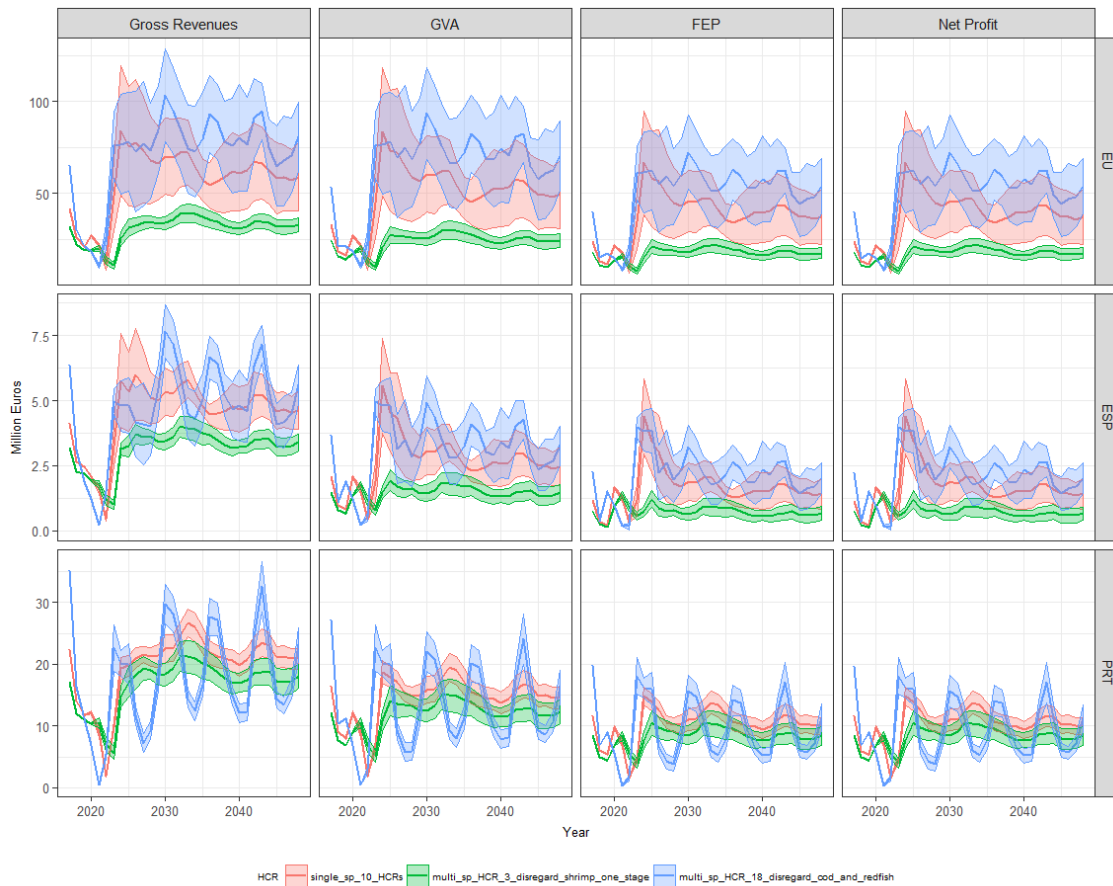
Figure 6.4-6. Simulated profit indicators of the EU fleet in the NAFO 3M area in the period 2018-2048 under TAC min scenario.

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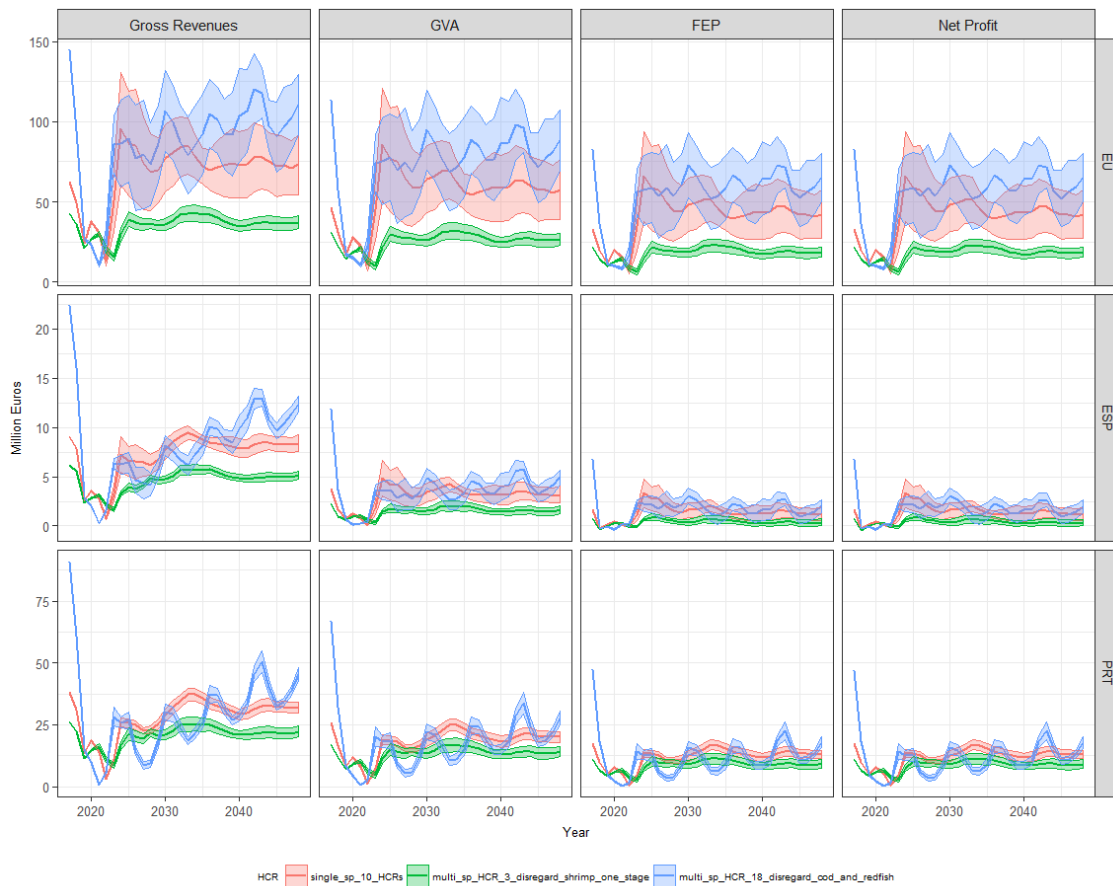
Figure 6.4-7. Simulated profit indicators of the EU fleet in the NAFO 3M area in the period 2018-2048 under TAC max scenario.

The two figures above present the simulated evolution of four financial indicators under the min (the fleets stop when each first TAC quota share is exhausted -Figure 6.4-6-) and max (the fleets stop when each last TAC quota share is exhausted -Figure 6.4-7-). Main observations from these figures are:

- In the short-term single stock HCR is providing higher economic performance than the two multistock ones. On the long run the multistock HCR diregarding the two predators provides higher economic results for the fleets.
- Disregarding shrimp always produces lower economic performance, but on the contrary, results show a much higher stability.

Figure 6.4-8. Simulated effort of the EU fleet in the NAFO 3M area in the period 2018-2048 under TAC min scenario.
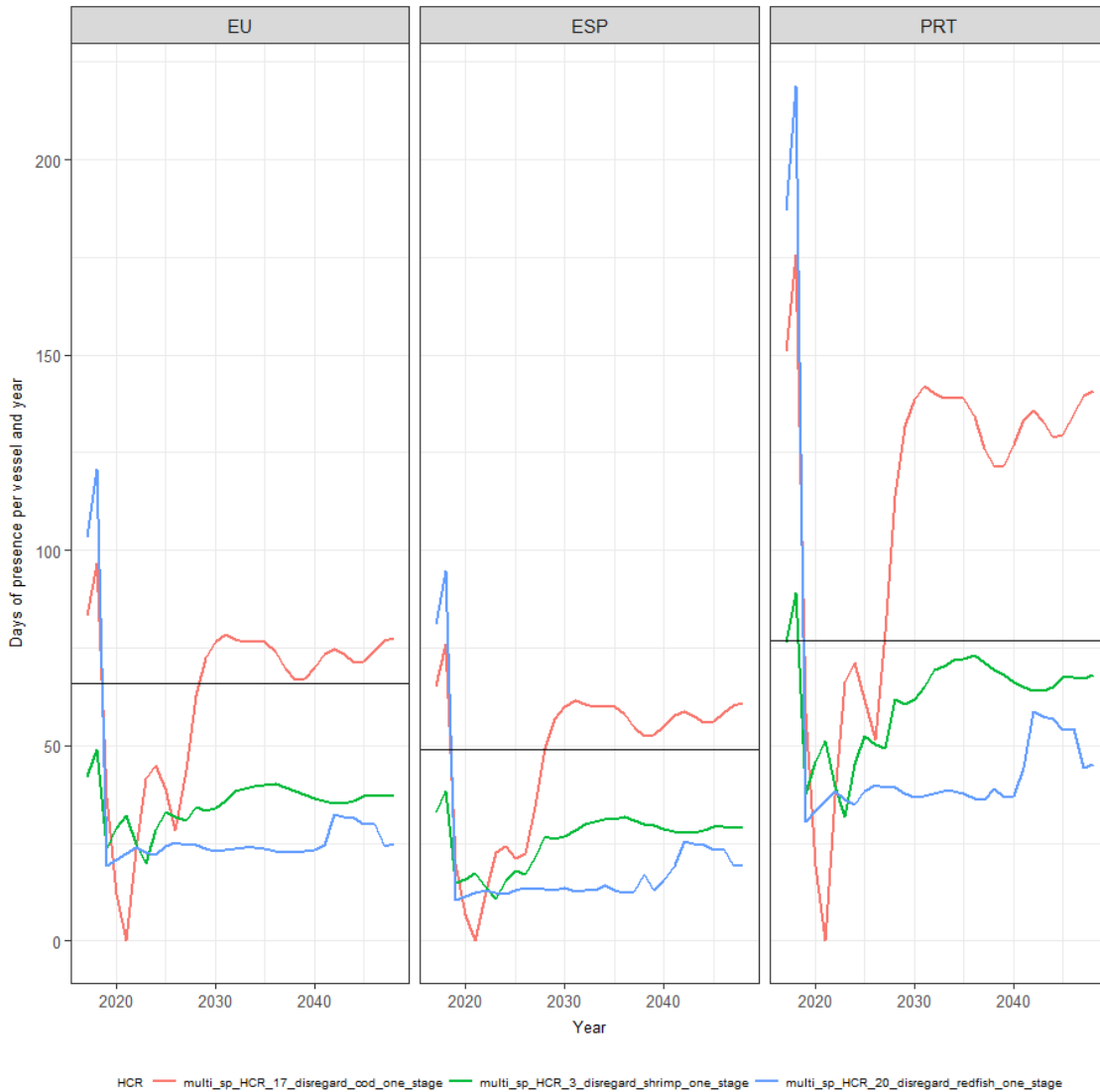
Figure 6.4-9. Simulated effort of the EU fleet in the NAFO 3M area in the period 2018-2048 under TAC max scenario.

The two figures above present the simulated evolution of the effort under the TAC min (the fleets stop when each first TAC quota share is exhausted -Figure 6.4-8-) and TAC max (the fleets stop when each last TAC quota share is exhausted -Figure 6.4-9-) scenarios. The main results obtained are:

- Under the TAC min scenario effort is always below the historical one. This implies that under the current overall selectivity levels of the fleets, discards should be allowed to mantain historical observed effort.
- Disregarding Cod is the multispecies HCR with highest effort levels for the three fleets except in the short run in where disregarding shrimp seems superior.

Figure 6.4-10. Simulated profit indicators of the EU fleet in the NAFO 3M area in the period 2018-2048 under TAC min scenario.
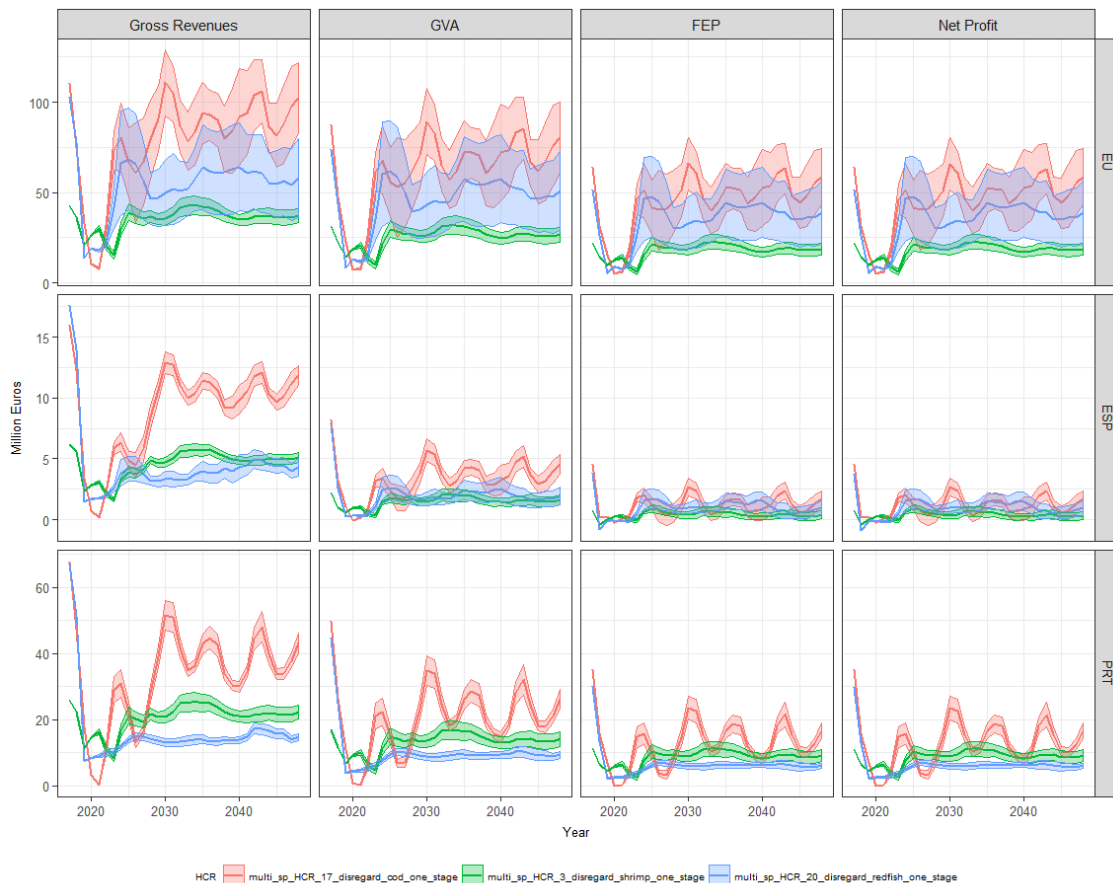
Figure 6.4-11. Simulated profit indicators of the EU fleet in the NAFO 3M area in the period 2018-2048 under TAC max scenario.

The two figures above present the simulated evolution of four financial indicators under the TAC min (the fleets stop when each first TAC quota share is exhausted -Figure 6.4-10-) and TAC max (the fleets stop when each last TAC quota share is exhausted -Figure 6.4-11-) scenarios. The main results from these figures are:

- Disregarding cod is the most profitable option in the long term for EU and Portuguese fleets, although it shows a high variability.

- For the Spanish fleet, while for the gross revenue indicator the same result as above mantains, when including all types of costs, results are not so clear. No better off HCR can be identified.
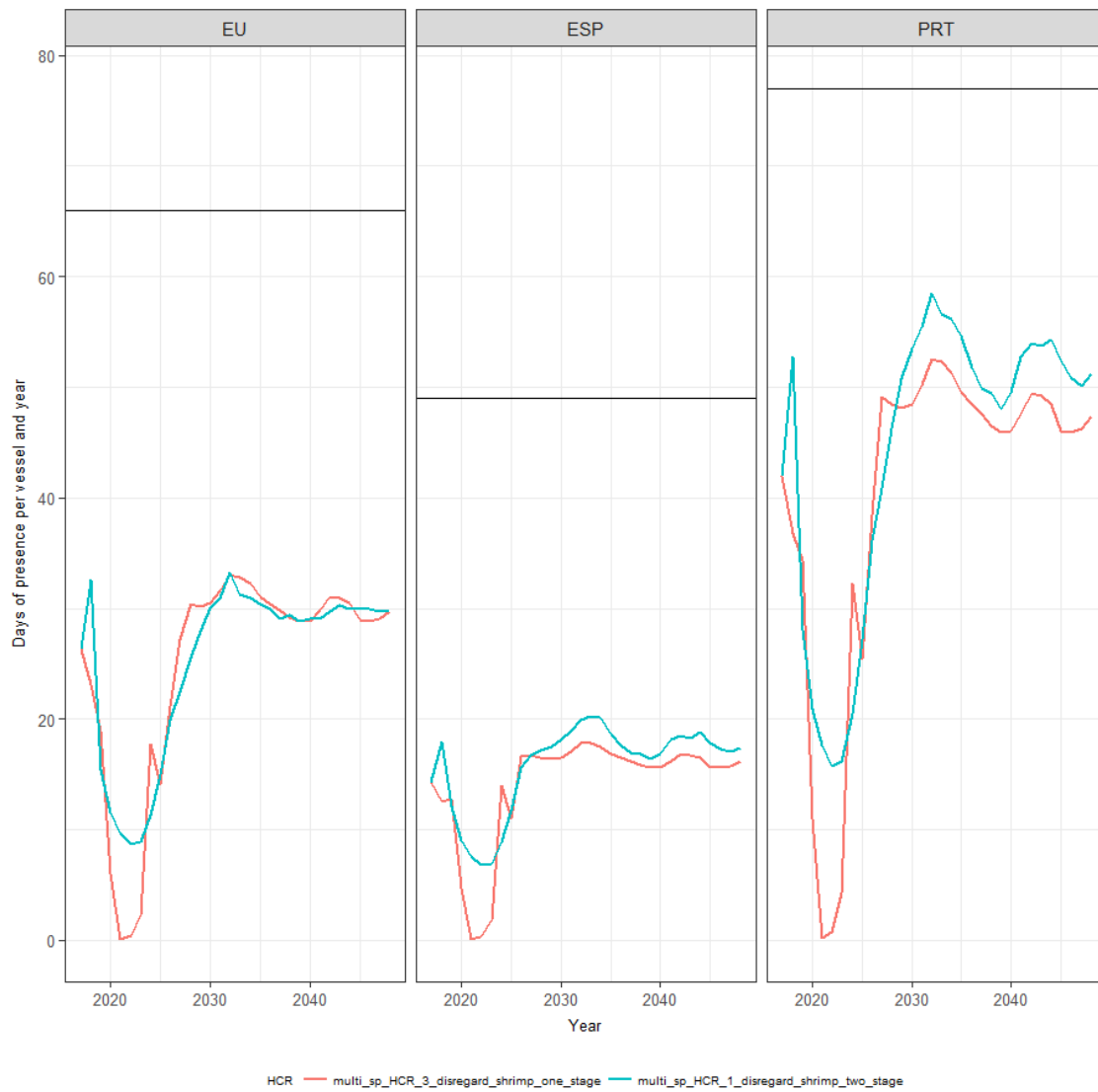
Figure 6.4-12. Simulated effort of the EU fleet in the NAFO 3M area in the period 2018-2048 under TAC min scenario.
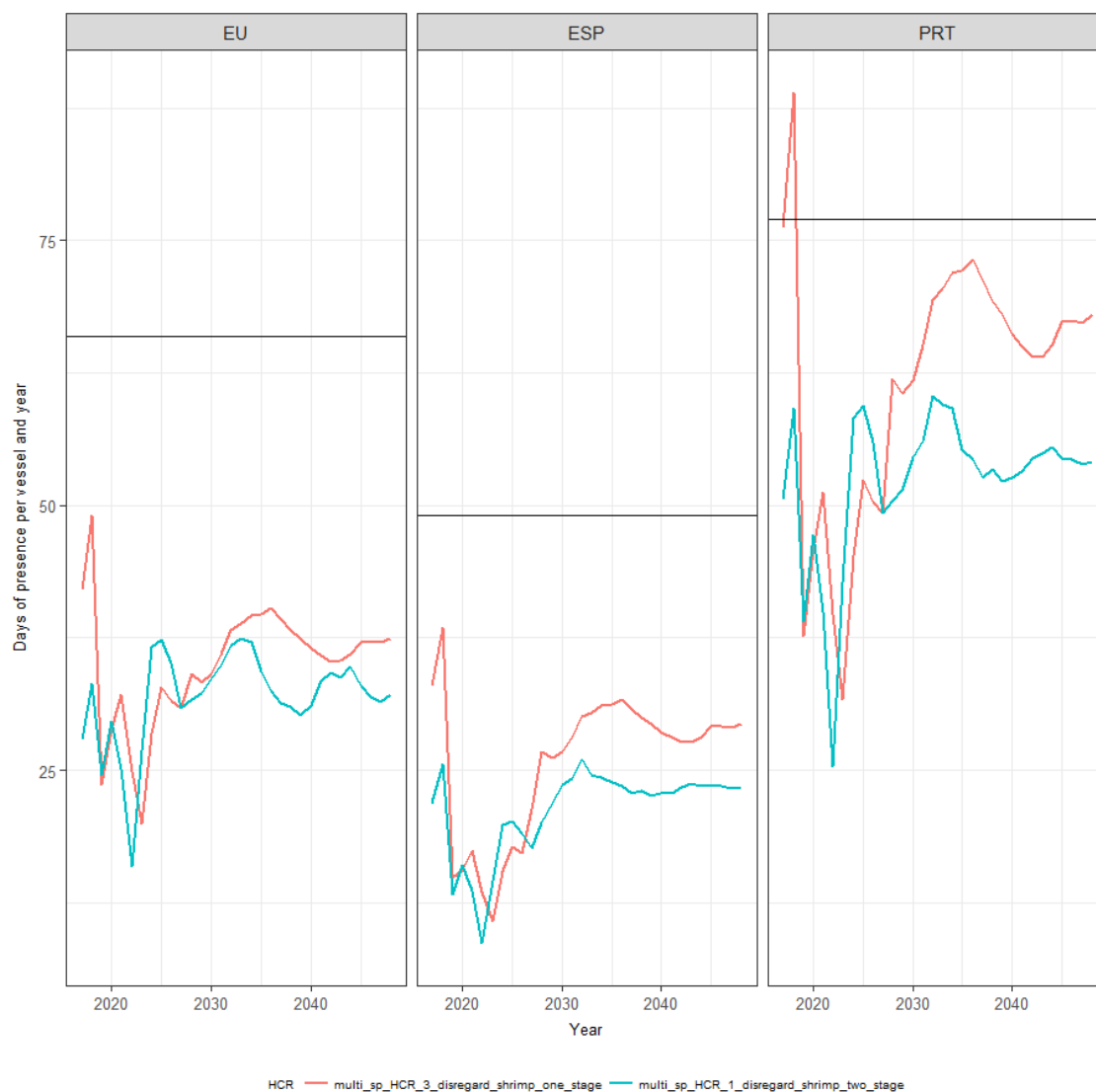
Figure 6.4-13. Simulated effort of the EU fleet in the NAFO 3M area in the period 2018-2048 under TAC max scenario.

The two figures above present the simulated evolution of the effort under the TAC min (the fleets stop when each first TAC quota share is exhausted -Figure 6.4-12-) and TAC max (the fleets stop when each last TAC quota share is exhausted -Figure 6.4-13-) scenarios. The main results obtained are:

- Even under TAC max option the effort level is always below the historical ones.
- Under TAC min the effort level is contrained by other species and not by Shrimp.
- Under TAC max (no effort contraints) one stage HCR is providing higher effort than the two stage HCR one

Figure 6.4-14. Simulated profit indicators of the EU fleet in the NAFO 3M area in the period 2018-2048 under TAC min scenario.

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Figure 6.4-15. Simulated profit indicators of the EU fleet in the NAFO 3M area in the period 2018-2048 under TAC max scenario.

The two figures above present the simulated evolution of four financial indicators under the TAC min (the fleets stop when each first TAC quota share is exhausted -Figure 6.4-14-) and TAC max (the fleets stop when each last TAC quota share is exhausted -Figure 6.4-15-) scenarios. The main results obtained are:

- In both scenarios the two stage HCR is providing higher economic results that the one stage HCR , except for Portugal in where the behaviour of the two HCR is not regular in time.
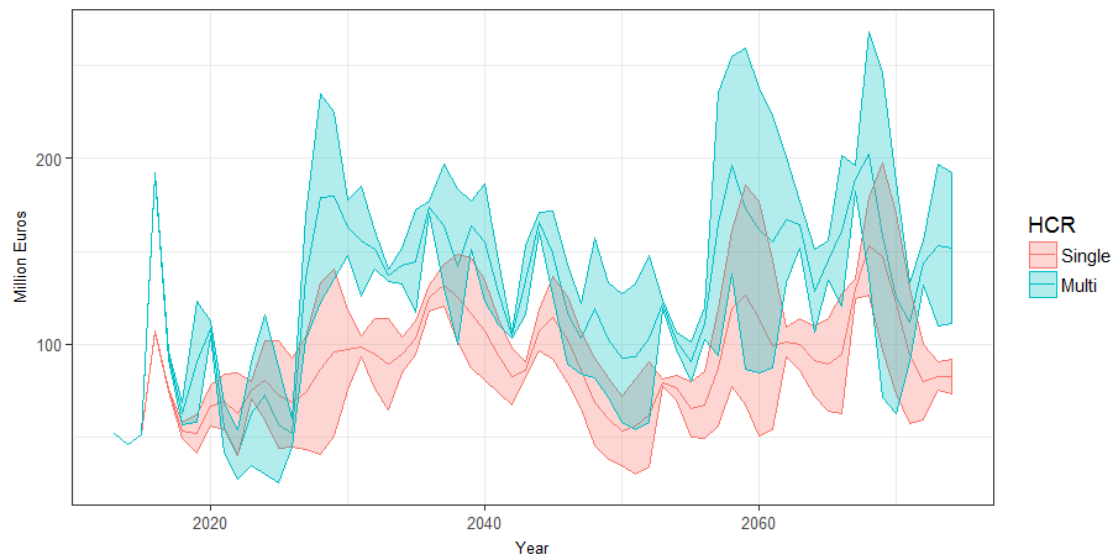
Figure 6.4-16. Value in million Euros of each HCR in along the simulation period 2019-2074.

The value of each HCR (Figure 6.4-16) was calculated multiplying the yield of each stock by a fixed price by stock. Figure 3-91 shows the mean value and the standard deviation coming from 1000 iterations in where the stock recruitment relationship was modified. When the standard deviation is considered, while the mean value of the *Multi-stock HCR* seems to be higher than the Single stock HCR, some degree of overlapping is observed. Therefore, before concluding it is necessary to understand the uncertainty.

To do so, we performed two different tests[1] to check if the two HCRs differ in their mean value. Both tests confirmed that the mean values of the two series are different.

However, this is only true in the whole simulation period. In the period 2019-2041, the uncertainty makes that the two HCRs do not statistically differ in their mean values. The result is that, from the statistical point of view, only in the period 2016-2042 (and onwards) the two HCR differ in their mean value.

The HCRs were also evaluated against the 2018 situation. To do so, the probability in each year of a TAC with a higher value in Euros than the value of the TAC set in the year 2018 is calculated. Results for Northern Prawn are not displayed given that this is always 100% (the fishery in area 3M was closed).

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[1] *A t.test log transformed and a non-parametric Wilcox test. These two tests have been run adding, iteratively, the simulation period by 1 year.*

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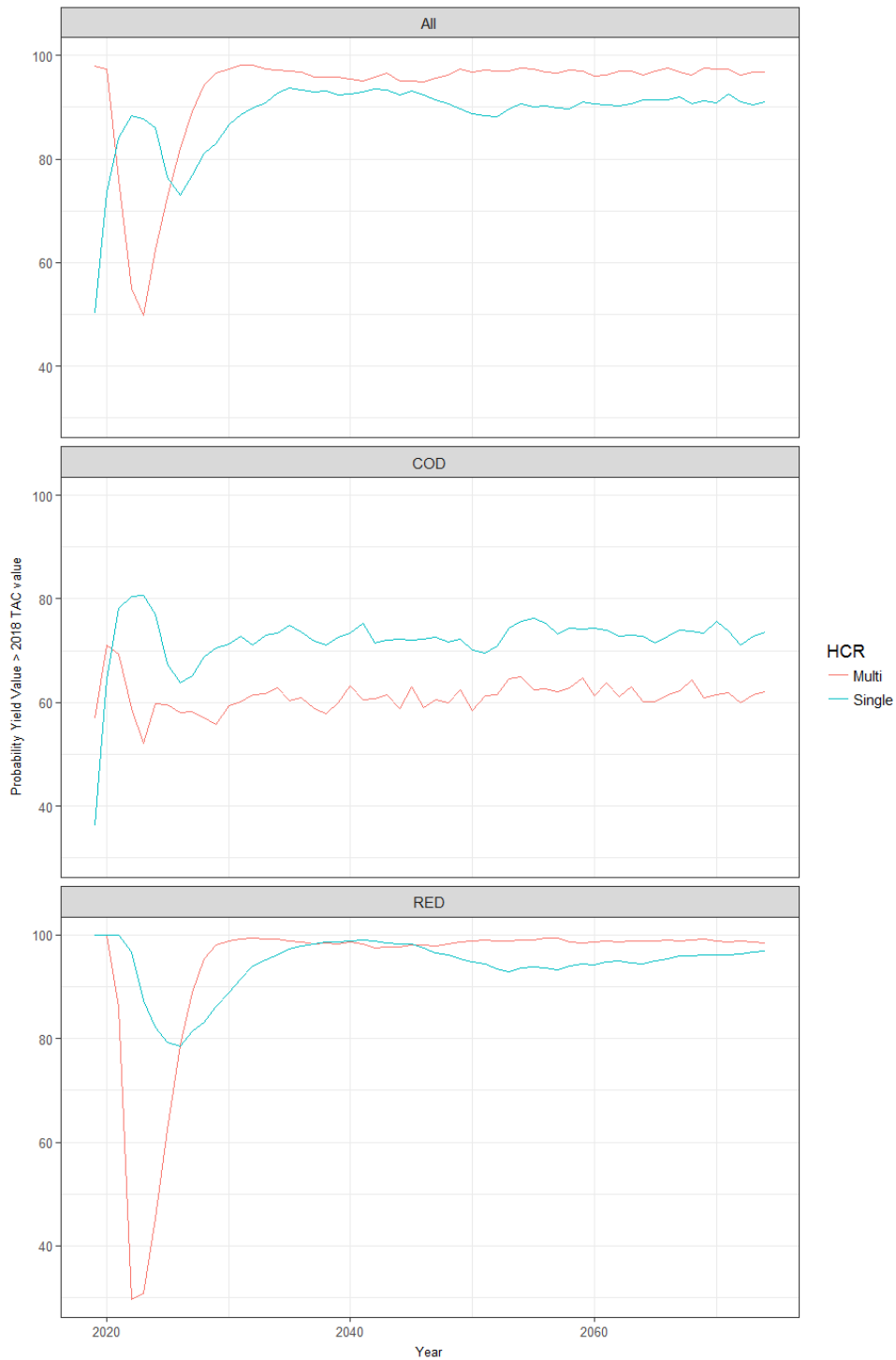
Figure 6.4-17. Probability of a value of the TAC higher than the 2018 TAC value for 2018 for the simulation period (2019-2074), by stock (Cod-COD- and Redfishes -Red-) and overall (the sum of the two stocks -ALL-) for the different HCRs disregarding the predators (Multi) and the single stock HCRs (Single).

Figure 6.4-17 shows that overall the probability of having a value higher than 2018 TAC is of 93% and 88% with a minimum value of 49.8% and 50.2% for the Multi-stock and Single-stock HCRs, respectively. It should be noted that this minimum value. These minimum

values are obtained, in both cases in the first 10 years of the simulation, for which the two HCRs have a mean value of 77.7%.

Figure 3-92 also shows how the multi stock HCR is favouring Redfishes against Cod. The Multi-stock HCR has a higher probability of obtaining a higher or equal value than the one obtained using 2018 TACs, than the Single-stock HCR.

Figure 3-93 presents the results of the net present value of the net profit indicator for all the HCRs
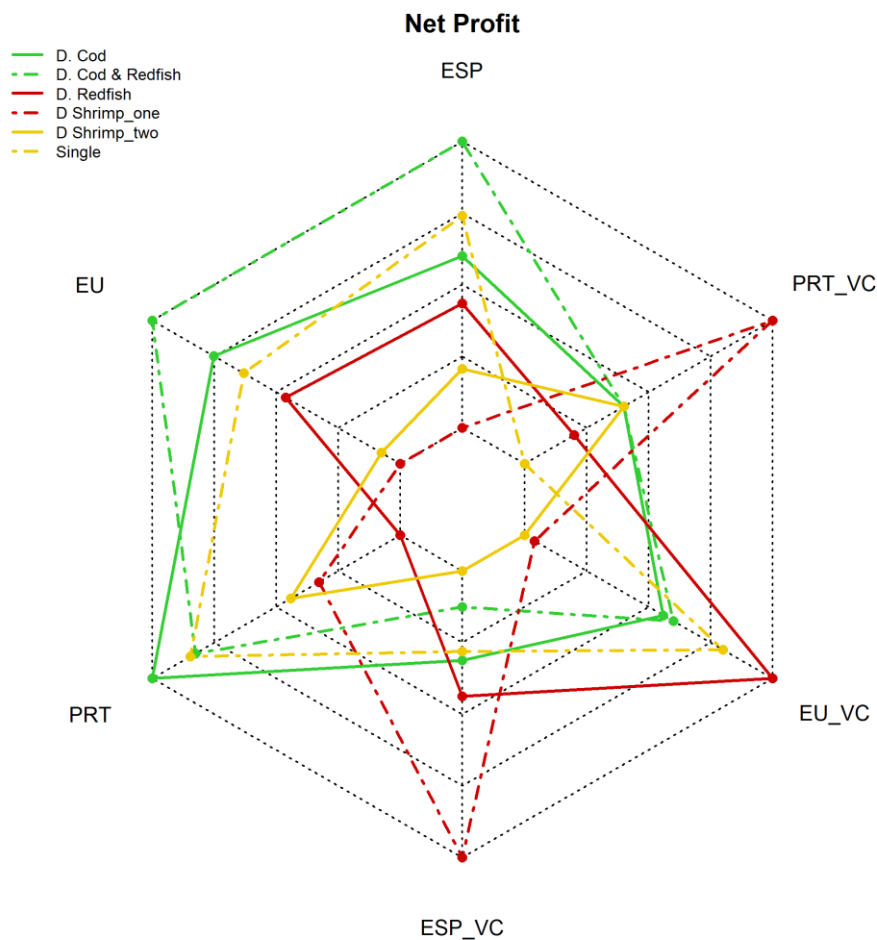
Figure 6.4-18. Trade-offs in Net profit (mean and coefficient of variation (VC) among HCRs of the EU fleets in the NAFO 3M area in the period 2018-2048 under TAC max scenario.

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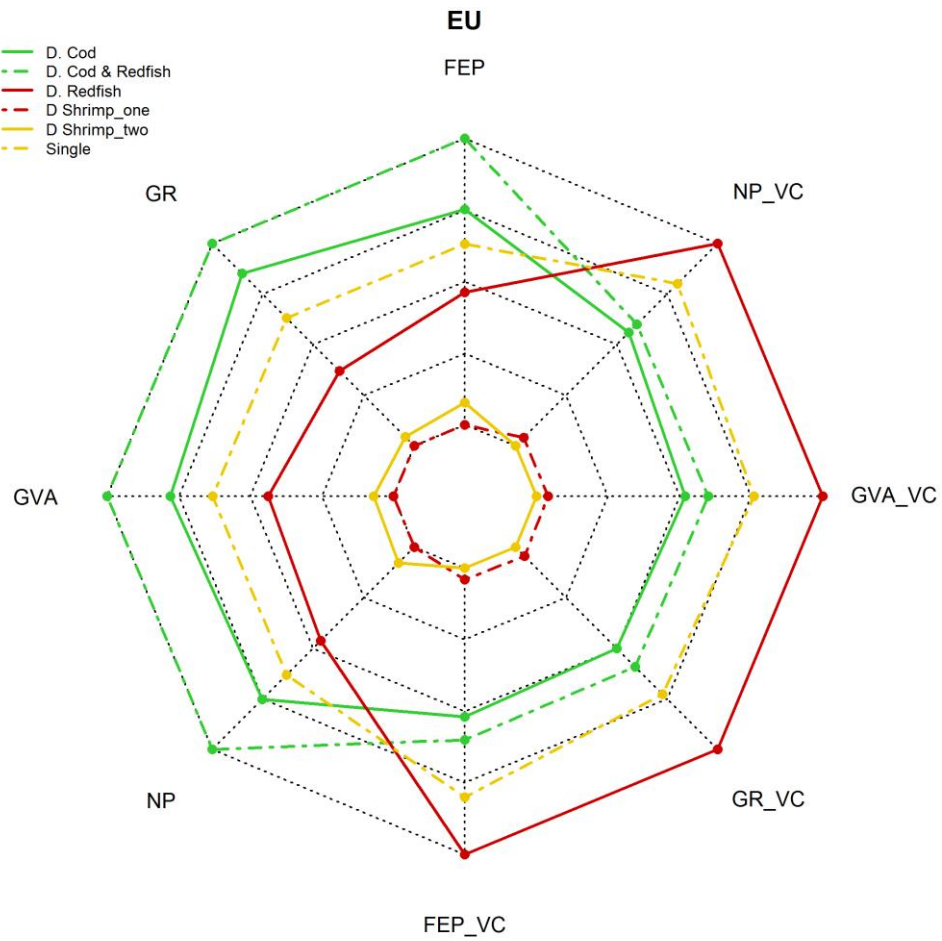
Figure 6.4-19. Trade-offs in Gross revenues (GR), Gross value Added (GVA)Net profit (NP). Mean and coefficient of variation (VC) among HCRs of the EU fleets in the NAFO 3M area in the period 2018-2048 under TAC max scenario.
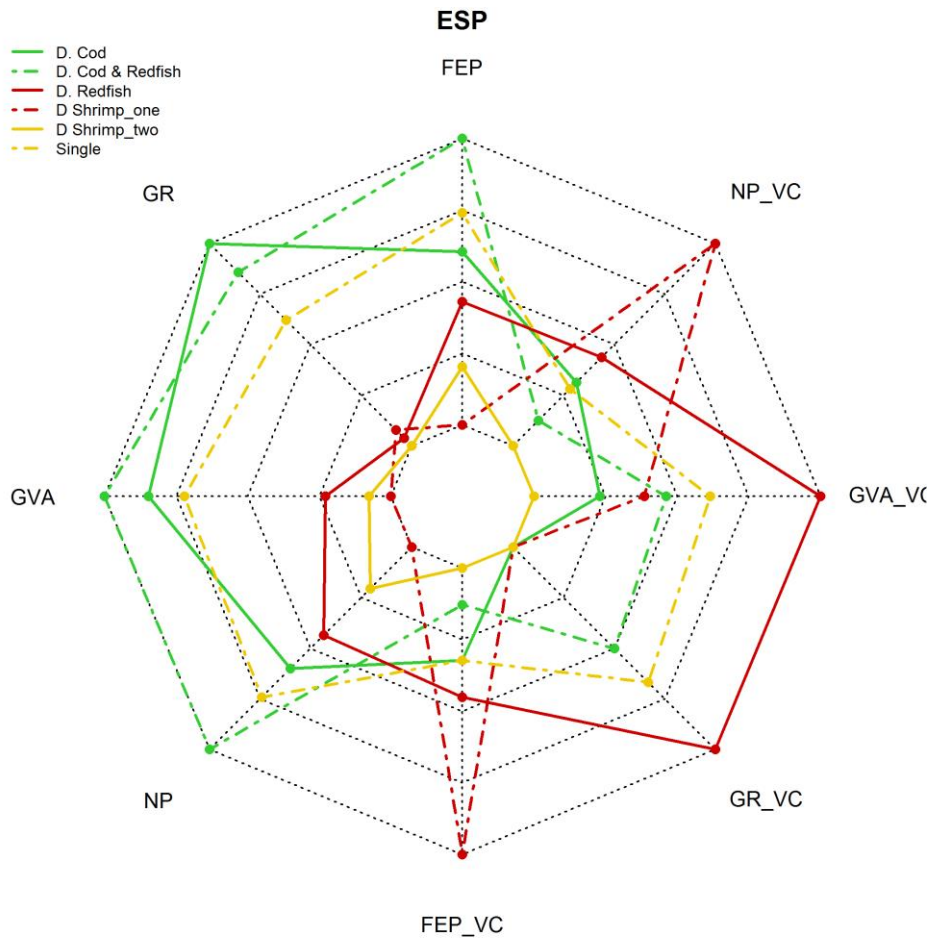
Figure 6.4-20. Trade-offs in Gross revenues (GR), Gross value Added (GVA)Net profit (NP). Mean and coefficient of variation (VC) among HCRs of the Spanish fleets in the NAFO 3M area in the period 2018-2048 under TAC max scenario.

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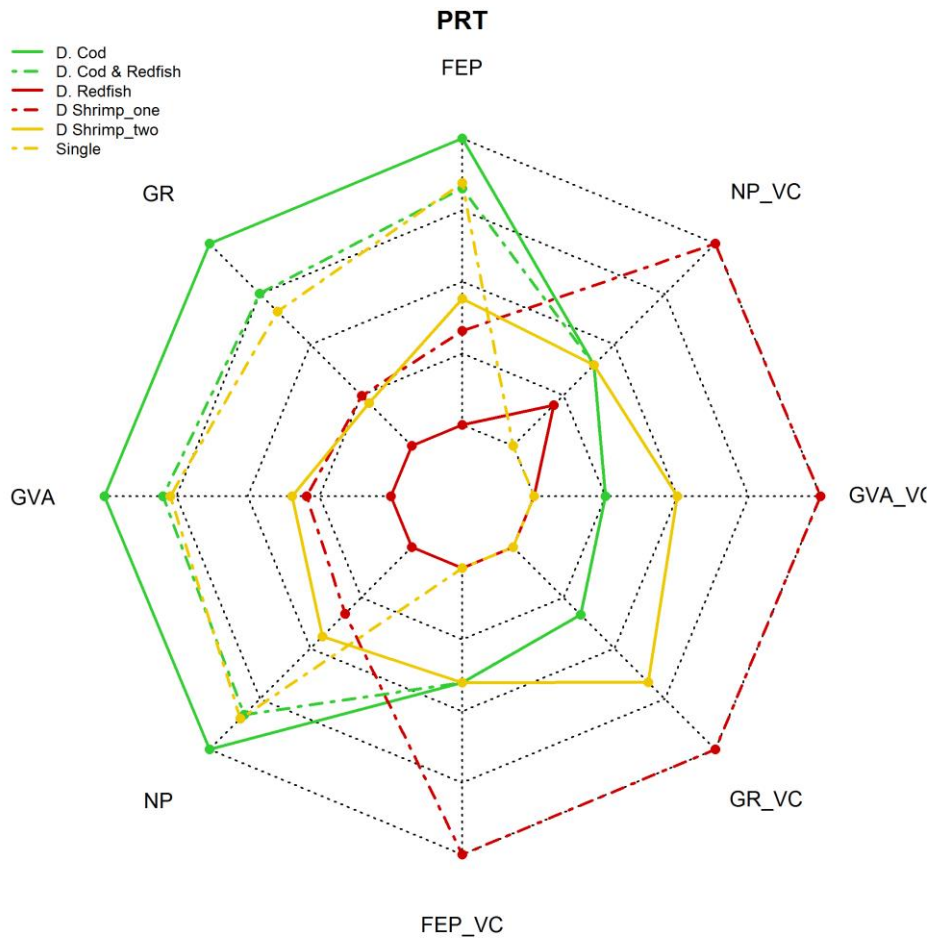
Figure 6.4-21. Trade-offs in Gross revenues (GR), Gross value Added (GVA)Net profit (NP). Mean and coefficient of variation (VC) among HCRs of the Portuguese fleets in the NAFO 3M area in the period 2018-2048 under TAC max scenario.

From Figure 6.4-18 to Figure 6.4-21 present the values in relative terms from the fleet's financial performance point of view. The overall result is that, if the maximum resource rent is considered, the multispecies HCR disregarding cod and redfish is the one providing the highest net present value for Spain and the overall EU fleets. For Portuguese fleets the single stock HCRs are the one giving the highest net present value.

On the other hand, if stability is considered (lowest variation coefficient) the two-stage disregard Shrimp multispecies HCR is giving the highest stability for EU overall and Spanish fleets, and again the single stock HCRs for the Portuguese ones.

When single vs. multispecies HCRs are compared, the multispecies HCR of disregarding the predators is the one with the highest resource rent net present value for the EU and Spain while the single HCR approach for Portugal (also in stability for this last MS). In the case of the EU overall fleet, the highest stability is obtained by disregarding Shrimp, however for Spain it is obtained disregarding the predators.

When multispecies HCR are compared, the maximum rent is always obtained (for the three fleets) disregarding Cod and the highest stability disregarding Shrimp (for EU and Spain) and disregarding redfish for Portuguese fleets.

In terms of the structure of the HCRs, the two stage HCR is always superior in both NPV and stability than the one stage one for the three fleets.

HCR also has effect in terms of the overcapacity of the fleets. When disregarding shrimp (one stage) none of the fleets generate higher resource rent by reducing the capacity. However, in the single stock HCR Spain present a likely overcapacity of 1 vessel and the overall EU fleet an under-capacity of also 1 vessel, the same as when the multispecies HCR of disregarding the two predators is simulated.

Therefore, it can be stated that there is not a clear first best HCR, and that this will depend on the fleet considered and in terms of the indicator considered. Gross revenues can be higher using one HCR, but the effort to capture the fishing possibilities allowed by it could be so high that it would be better not to catch what the HCR is allowing.

On the other hand, according to the simulations performed, there are clear benefits of a proper design of a HCR. This is shown when compared the two multispecies HCRs for Shrimp. In this comparison it is obtained how the two stage HCR for shrimp is superior in mean and stability for the three fleets considered and all the economic indicators.

It should be noted that these results have to be anlaysed simultaneously with the biological results (in terms of probability of falling below sustainability thresholds). In that sense, Figure 6.4-22 presents the trade-offs among one economic indicator (resource rent) and the probability of being above Blim for the three species considered for the different HCRs. In this figure it can be seen how, for example, while the HCR disregarding Cod and Redfish gives the highest resource rent, the probability of Cod biomass falling below Blim is of 94% (see Table 6.4-9).

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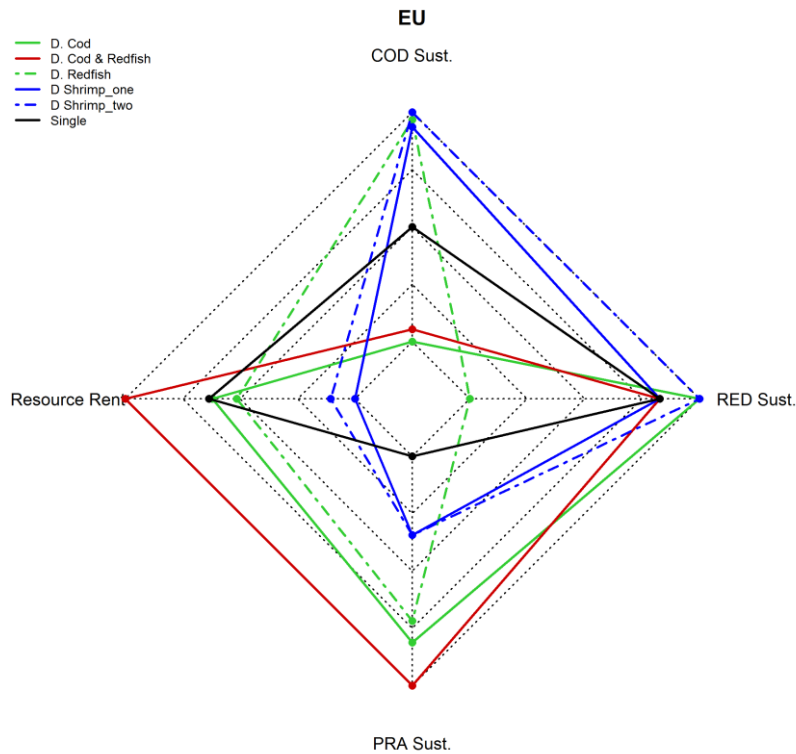
Figure 6.4-22 Trade-offs among economic and biologic indicators. Resource rent (Net Profit) discounted for different HCRs and probability of being above Blim for redfishes (RED Sust.), cod (COD Sust.) and shrimp (PRA Sust.).

Table 6.4-9 Economi indicators and biological risk for the six different HCRs

	Economic Indicator				Biologic Risk		
	Gross			Net	Pr below	Pr below	Pr below
		GVA	FEP				Blim
	Revenues			Profit	Blim COD	Blim RED	PRA
HCR	(€)	(€)	(€)	(€)	(%)	(%)	(%)
Single	2.644.008	2.294.651	1.746.370	1.745.035	52	13	99
Disregard cod and redfish	3.261.725	2.962.446	2.293.414	2.292.271	94	13	35
Disregard cod	2.558.803	2.251.580	1.722.689	1.721.516	99	0	47
Disregard redfish	2.177.232	2.003.675	1.558.551	1.557.888	8	75	53
Disregard shrimp (one stage)	1.409.902	1.087.768	787.826	786.596	11	13	77
Disregard shrimp (two stage)	1.596.352	1.269.393	931.892	930.643	5	0	77

6.4.5. *Difficulties*

Models exist, and as explained above many of them are available. Essentially the only characteristic that they share is that they are able to project stock dynamics. The rest of the characteristic differ among models, and this is precisely the reason for their existence.

The best solution in terms of balance between complexity and quality of bioeconomic assessment is the combination of two, one BOM such as GADGET and FLBEIA for the FOM.

This combination while currently under development is not still ready at least in an integrated way. A non-integrated application was presented in the precious section.

More complex end to end models are necessary only if the advice requirement is related to other uses of the sea area. Challenges remain in terms of how to parameterize the fleets and the data requirements to do so. While effort and number of vessels are well described, some data are still missing, for example:

- Data to define the size selectivity of the main target species of the EU fleet in NAFO area 3M;
- Prices by age size or commercial categories of these specific fleets.
- Redefine the financial data of the fleet. While AER is helpful, the segments selected can be too wide to capture the specifities of the EU NAFO fleet. More detailed data could be obtained in the context of a collaboration with the industry.

Conditioning a model is time demanding task that should be carefully designed and applied. When doing so an easy update concept has to be considered, that is if future assessment requirements are asked, task shouldn't be asked from scratch.

Spatial management (closure of fishing zones) are not explicitly considered, although they could be potentially required by fisheries managers. In this case a more refined spatial model will be useful (Atlantis). The combination of GADGET and FLBEIA can handle this issue only if specific metiers area defined while conditioning the fleet. Therefore, possible questions (management options) should be considered when selecting the model (s) to be used.

Market base mechanisms can be simulated, although results are unlikely to meet economic theory. Therefore, a suggestion would be to move towards a micro-economic founded model such as Macro-fish, if this (management) route is to be followed. This is also valid if effort-based management is likely to be introduced. In this case, the concept of hyperstability should be considered and simulation models are not able to endogenously consider it.

In conclusion, if multispecies HCRs are likely to be evaluated using the financial results of the individual fishing fleets as in Task 4.2 a combination of FLBEIA and GADGET seems a perfect candidate (see Table 6.4-10).

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Table 6.4-10. Characteristic that can be handled using FLBEIA as FOM with GADGET as a BOM.

Dimensions	Characteristics	GADGET +FLBEIA
Bio-Ecology	Trophic interactions	
	Ecosystem Dynamics	
	Assessment of Stocks	
	Stocks Dynamics	
	Data Poor	
Management	Single stock HCR	
	Multi-species HCR	
	Effort based	
	Spatial explicit	(*)
	MSE	
(Fleet) processes	Feedback	
	Price Dynamics	
	Effort Dynamics	
	Capital dynamics	
Fleet results	Financial results	
	Economic Results	
Resources	Complexity	

(*) while the BOM (GADGET) will be spatially explicit the FOM (FLBEIA) won't.

If other questions are to be asked:

- Ecosystem based management or spatial explicit management: Probably the best choice will be using Atlantis. The reason is that conditioning the ecosystem dynamics and interactions requires resources that can be used a end to end model able to handle other dimensions.

- Market based mechanism or effort-based management: Probably the best choice will be using Macro- Fish. This model is able to handle peculiarities like input substitutions causing effects such as hyperstability in effort-based managements.

In Task 4.2, there are several limitations and chellengges to be explored.

The period of simulation starts in 2017 and ends in 2048, which implies and strategic version of the analysis. It is assumed that the past can be considered a good "proxy" of the current and "next" future, but not, necessarily, of far-future. In that sense it is always worth to mention that:

> *"The long run is a misleading guide to current affairs. In the long run we are all dead. Economists set themselves too easy, too useless a task if in tempestuous seasons they can only tell us that when the storm is past the ocean is flat again."*

John Maynard Keynes. *The Tract on Monetary Reform*, in 1923

In other words, with the data available, it is possible to reconstruct the annual overall performance of the fleets along the simulation period, but it will give the wrong impression that we are able to infer the evolution of the fleet. Essentially this is not true if an equilibrium condition is not set (we are using identities). Therefore, results have to be interpreted as exposed, that is, as a comparison of the economic performance of different HCRs by fleet and in the NAFO area 3M, assuming that the relative productivity of the rest of the areas in which these fleets operate, does not change, or at least that the economic incentives for fishing in the fishing area 3M are not altered.

The model is not based on economic theory, but on an individual modelling of some elements of the economic dimension. The prices (ex-vessel prices, wages and interest rates) used do not necessarily clear the markets, that is, they do not necessarily reflect the equilibrium between supply and demand. Results are based on identities. That is, they are a translation of natural units (tons) into economic units (euros).

The lack of feedback mechanism between economy and biology, implies that the mixed fisheries scenarios can be misleading. When TAC max scenario is used, the over-quota catches while discarded (do not account for the revenues), imply a higher mortality than the one considered in the biological model. The TAC min scenario presents exactly the contrary behaviour of the fleet, which is there under-quota catches and the fishing possibilities not captured by the fleet(s), do not count in favor of the future abundance of the stocks. This can only be solved using a full feedback mechanism which will imply to consider a (multispecies) biological operating model embodied in the bioeconomic model itself (as explained in Task 4.1). This will also simplify reading the results, given that biological and economic results would be always compatible.

Data are not yet available to capture all the dynamics of the economic processes. One example is that no relationship between landings and prices (demand function) is considered. This, if exists, has to be contemplated using a larger time series that the one available in this work. Adittionaly, prices can also be affected by imports compiting in the same market. Adittionaly, there are other dynamics that have to be tested beyond ex vessel prices. Labor market, wages, and, specially, capital dynamics. In this last topic, it has to be tested how

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fishing firms form their expectations (rational -discounting the future- or adaptive -looking at the past-). Probably there is not a single answer, although it would be worth to use a model using this dynamic to avoid situations in where a poor economic performance of the fishing fleet is not reflected into a constrained fleet.

In general, data is always an issue. Parameters estimated seem robust (those used are statistically significant or based on published scientific literature), but some of them, especially those related to the fishing costs, could be more adapted to the specific fleets analysed. This could be done using a questioner submitted to each operator.

A final remark should be given in terms of how to incorporate the uncertainty. In this work, only the stock-recruitment relationship has been modified to account for it. Using only this source, confidence internals are high enough to make that all the results have to interpret with caution. Other sources of uncertainty, such as, fuel costs or ex-vessel prices have not incorporated, while the results will be to increase these confidence intervals.

6.5. TASK 5 – DISCUSSION AND INTERACTION BETWEEN SCIENTISTS AND OTHER STAKEHOLDERS

The objectives of this task were the dissemination of project goals and results to all the stakeholders related with NAFO (fishing industry, managers and scientific community of NAFO). To accomplish these goals, two subtasks were developed to 1) organize a workshop to present the results of the study to main stakeholders and administrations in the EU and 2) facilitating the integration of the results of this study into the NAFO scientific community and the NAFO Roadmap for the development of an ecosystem approach to fisheries management.

6.5.1. Main activities and outputs

Sub-task 5.1 – Organization of a workshop to present the results of the study to main stakeholders and administrations in the EU

A two day workshop with the main stakeholders from the fishing industry, EU administrations and science leaders of Tasks 3, 4 and 5 was celebrated at the IEO offices in Vigo (Centro Oceanográfico, Beiramar). The coordinator of Task 5 (Dr A. Kenny, CEFAS) and the project leader (Alfonso Pérez-Rodríguez, WMR), co-chaired this meeting and organized the agenda, which was agreed following participant introductions (see Table 6.5-1).

The objective of the workshop was to provide the fishing industry and other fishery related associations operating in NAFO with opportunity to find out what and how multi-species assessments are being developed and the benefits they provide in the context of implementing an ecosystem approach to fisheries management and the provision of fisheries management advice. The meeting also allowed some of the 'key' challenges associated with the operational implementation and scientific development to be identified and discussed.

The results of this workshop are reflected in the minutes that were sent to DG-MARE in due time as deliverable of this task (deliverable 5.3 in List of Deliverables table, see section 4 of this report). The contributions of the attendees to the workshop and the plenary sessions after the presentations were very productive, allowing the clarification of several questions from

the industry, as well as clear agreements about the need and the ways to increase collaboration in the future, in order to facilitate the development of the multispecies approach in NAFO. As an expression of the positive output of this workshop was the invitation that the president of the LDAC extended to the SC05 co-chairs to participate in the workshop II of the LDAC that will take place at the end of March in Brussels.

Table 6.5-1.- List of Attendees to the SC05 workshop celebrated at the facilities of the IEO in the research centre of Beiramar in Vigo.

Name	Organisation	Position
Andrew Kenny	CEFAS	WP5 Lead
Alfonso Perez	WUR	SC05 Coordinator/ WP3 Lead
Raul Prellezo	AZTI	WP4 Lead
Irene Garrido	ARVI	Arvi/IEO research scientist
Adolfo Merino	EASME	EMFF Senior Project Adviser
Ivan Lopez	LDAC	President
Edelmiro Ulloa	ARVI	Manager
Diana González	IEO	3M cod scientist assessor
Mar Sacau	IEO	NAFO EAF specialist
Mikel Casas	IEO	3M shrimp scientist assessor
Jolanta Cesiuliené	Ministry of Agriculture of the Republic of Lithuania	Chief Specialist of the Fisheries Division

Subtasks 5.2.- Integration of results on the NAFO Roadmap for the development of an ecosystem approach to fisheries management

Alfonso Pérez-Rodríguez attended the NAFO-WGESA meeting in November 2017 (minutes of the meeting provided to DG-MARE), however, due to the delay in the starting date of the SC05 project there was not significant advances in the development of tasks 1 and 2 that could be presented. For this reason the contribution to the WGESA was focused in presenting the project, the different tasks, the goals and expected results by task, as well as obtaining feedback and input from the WG. It was then agreed with EASME that two working

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documents with the results of Task 2 (update and improvement of GadCap, see the document on https://www.nafo.int/Portals/0/PDFs/sc/2018/scr18-024.pdf) and Task 3.1 (contribution to the 3M cod benchmark, see the document on https://www.nafo.int/Portals/0/PDFs/sc/2018/scr18-025.pdf) would be presented via webex to the NAFO Scientific Council (SC) in their annual June meeting in 2018.

In November 2018, Alfonso Pérez-Rodríguez attended the NAFO WGESA 2018 meeting, however, due to problems in the use of some important data sources, the results of tasks 2, 3 and 4, that were already finished, could not been presented to the WGESA members in that meeting. These three tasks are the core of the SC05 project, where the multispecies model GadCap was improved, the multispecies MSE framework and HCRs were designed, and were the ecological-economic trade-offs were quantified. This was expected to be a very important meeting in terms of interactions with the NAFO EAF roadmap. Due to this problem, the contribution to the WGESA was reduced to a presentation listing the work developed, but, without presenting any specific result (described in the minutes of the meeting provided to DG-MARE). In addition, no any working document could be presented, expected deliverable during this meeting. This restriction to the use of the data was solved after the WGESA meeting. It was then agreed with EASME and DG-MARE that a way to mitigate the negative consequences of this setback in terms of spreading results would be presenting a working document with the results of Tasks 3 and 4 via webex during the NAFO SC meeting on June 2019, despite the SC05 project will be already finished by that time.

6.5.2. *Difficulties*

The difficulties found in the development of this task are related with two main problems: the later start of the project and the ban on data use and presentation of results. These two setbacks and possible solutions for future projects are described in Task 6 section.

6.6. TASK 6 – FUTURE RESEARCH DIRECTIONS AND NEEDS

6.6.1. *Summary*

This section presents a synthesis of research needs and priorities to support the multispecies approach in the NAFO area. It starts with a summary of advances achieved in this project and knowledge on the multispecies approach gained from other parts of the world. Then, it builds on gaps and synergies identified in previous sections to provide recommendations on next steps to operationalise this approach especially in the context of the NAFO roadmap for an EAF.   Key areas of work and other actions identified include:

- Separation of redfish catch and other fishery data into individual stocks.
- Advance research on predator-prey length relationship through increased number of stomach content data, improved protocols for their analyses, and training.
- Collection of data to describe and model technical interactions between species.
- Programming work to update and expand the model to reflect new knowledge gained through data research identified in this project (some of which is covered in the previous bullet points).
- Programming work to produce a fully coupled (economic + ecological) operating model.

- Technical analysis to condition the updated operating model and run sensitivity tests.
- Establishment of resources/structures for collecting data that would allow co-operation between scientists and industry.
- Review of MS reporting obligations, guidelines, and forms to ensure they are fit for purpose.

Synergies with other areas of the EAF roadmap include:

- Single species analysis will benefit from estimates of natural mortality calculated in a multispecies assessment.
- HCR built for single-species can be assessed in a multispecies framework like the one developed in this study to test whether they are precautionary.
- Work carried out in NAFO to define Ecosystem Productivity Units (EPU) will help define the areas for which multispecies frameworks will have to be developed.
- Results of connectivity analysis under Theme 1 of the Roadmap will support incorporation of migratory fluxes between EPUs in the multispecies MSE framework.

6.6.2. Objectives

The objective of this Task was to identify key challenges in implementing the multispecies assessment in the Flemish Cap and research to progress work in this area. On the later, the aim is to identify future research activities, consider their contribution, and suggest ways in which they can be taken forward to support the implementation of a multispecies approach in the NAFO area.

6.6.3. Methodology

Sub-task 6.1 – Analyses about the progress and implementation of multispecies assessment

For the first part of this work we analysed findings and insight from previous Tasks to develop a comprehensive picture of key issues and knowledge gaps to address to make progress with implementing a multispecies assessment in NAFO. Issues considered covered both scientific and other complementary processes (e.g. stakeholder engagement). We also used experience gained from applying the multispecies framework to the Flemish Cap and from elsewhere to draw lessons and consider their transferability to future work.

Subtasks 6.2.- Research activities to strengthen the multispecies assessment implementation within the NAFO roadmap for an EAF

The second part of the work built on expert knowledge of the project team to identify research activities that can help address challenges both in terms of improving the multispecies assessment for the Flemish Cap but also more broadly, extend the approach to other NAFO areas. We also described how each of the research activities will contribute to the multispecies assessment and their importance for building a more robust assessment and used that information to highlight those activities that need to be prioritised. Finally, we discussed and documented possible next steps in the context of the NAFO Roadmap to EAF to highlight this work's contribution to the Roadmap and synergies to pursue to support the implementation of a multispecies assessment.

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6.6.4. Results

Sub-task 6.1 – Analyses about the progress and implementation of multispecies assessment

Nations and organisations around the world have tried different ways in which to incorporate a multispecies approach into fisheries management. For example, an empirical approach has been followed in the US, specifically in the Bering Sea; it introduces a cap in the total harvest for groundfish resources in addition to single-species quotas. In Australia, calculations to advice on allowable catches (using the Maximum Economic Yield concept) consider technical interactions among species, and a risk assessment of all affected species is required to ensure that they are not overfished[1]. In Europe, the MSFD is the flagship EU policy that aims to mainstream multispecies and ecosystem concepts into marine resources management. Specifically, Descriptors 1, 3 and 4 set the foundations for adopting a multispecies approach to fisheries management to safeguard food web interactions and biodiversity.

The introduction of the landing obligation by the European Union[2] has further highlighted the importance of adopting a multispecies approach to support sustainable exploitation of marine resources. This is because a great number of European fisheries are mixed fisheries so setting catch quotas for a single species without considering the productivity of and interactions with other species caught in the same fishery is inevitably going to be problematic. Therefore, this policy has given impetus to better understanding the interaction and impact of EU fisheries on all species with which they interact, not just targeted species. To support this process, the ICES Working Group on Multispecies Assessment Methods (WGSAM) has undertaken research on predator-prey interactions and multispecies modelling and its workplan for the next 3 years will cover[3]:

- Evaluation of performance of multispecies models intended for strategic or tactical management advice.
- Estimation of natural mortalities using multispecies models to inform single species assessments.
- Adaptation of existing multispecies/ecosystem models for MSE.
- Review of visualisation methods to present trade-offs and uncertainty for managers and stakeholders.

Although multispecies research and capacity building[4] have been increasing, in the majority, scientific advice for management is still developed at a single-species level (ICES, 2018, Ulrich, 2018, GADCAP 2016, MYFISH, 2016, and section 3.1 in this report). Efforts to extend the single-species approach to incorporate multispecies concepts into scientific advice have mainly focused on incorporating predation mortality into single-species stock

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[1] https://www.afma.gov.au/sustainability-environment/ecological-risk-management-strategies *Last accessed: 15 February 2019*

[2] *This refers to the obligation for fishermen to land all catches of certain species (no discards) introduced by the Common Fisheries Policy in 2014.*

[3] http://www.ices.dk/community/Documents/Science%20EG%20ToRs/HAPISG/2019/WGSAM%20MA%20ToRs%202018.pdf *Last accessed: 15 February 2019*

[4] *See, for example,* https://www.euromarinenetwork.eu/activities/2nd-advanced-school-multispecies-modelling-approaches-ecosystem-based-marine-resource *Last accessed: 15 February 2019*

assessments (ICES 2017c). However, those efforts have been taken further in areas like the Barents Sea for which HCRs that take multispecies considerations into account have been developed to provide management advice.

Development of multispecies frameworks that capture both biological and socioeconomic considerations has also progressed, but implementation of such models is still at an early stage. A recent review of modelling frameworks that combine multispecies population dynamic models with socioeconomic ones has shown that most of them have been developed in the past 5 years with only a few being more than 10 years old (Nielsen et al. 2018). They have been mainly used in research studies in Europe and their level of implementation to address specific issues or provide management advice varies; some modelling frameworks have been used in several assessments to provide advice while others have not been implemented at all (Table 6.6-1). An important element that seems to be missing from most of those models is the simulation of biological interactions among species; only two of the frameworks considered incorporated both biological and technical interactions (the latter refers to mixed fisheries, in which, in addition to the target species, some other species are fished as bycatch). The review also covered lessons-learnt from the application of such models, some of which are:

- Having advisory and management bodies and the institutional set-up to facilitate the use of ecological-economic models in cooperation with stakeholders is an important factor that can affect the level of integration of such models into management advice.

- Other factors that can be critical for successful integration of these models into co-management structures are a) model flexibility, b) transparency, c) portability, d) build-up time, e) expert knowledge of the system to be modelled, and, f) availability of model interface.

- There is a mismatch between the time required for a model to become mature (6+ years) and duration of funding for projects used to advance research in this area (3–4 years). Therefore, new funding schemes with the right timeframes are needed to support development of models that will have good documentation and user-friendly, open-source platforms. These features will enable replicability and facilitate further model development and adaptation.

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Table 6.6-1. Features of frameworks that use integrated multispecies ecological and economic models (Adapted from Nielsen et al. 2018)

Model name	Area in which it has been used	Level of use for advice	Technical /ecological interactions?	Used for EU or ICES advice?
Integration of Spatial Information for Simulation of Fisheries	Europe, Australia	Most used	Technical	Yes
Fleets and Fisheries Forecast Model	Europe	Most used	Technical	Yes
Bio-economic Impact Assessment using Fisheries Library in R	Europe	Most used	Technical	Yes
Effects of Line Fishing Simulator	Australia	Most used	Technical	No
Stochastic Age-Structure Optimization Model + ITQ Wealth Model	Europe	Most used	Technical	No
Impact Assessment Model for Fisheries Management	Europe	Average use	Technical	Yes
Mediterranean Fisheries Simulation Tool	Europe	Average use	Technical	No
New England Coupled Lobster Model	America	Average use	Technical	No
Swedish Resource Rent Model for the Commercial Fisheries	Europe	Average use	Technical	No

FISHRENT TI Thunen Institute; FISHRENT IFRO University of Copenhagen	Europe	Least used	Technical	Yes
Spatial Integrated bio-economic Model for Fisheries	Europe	Least used	Technical	Yes
Baltic Coupled Fisheries Library in R and Stochastic Multispecies Model	Europe	Least used	Both	Yes
Individual Vessel-Based Spatial Planning and Effort Displacement	Europe	Least used	Technical	Yes
Baltic Sea Ecological-Economic Optimization Model	Europe	None	Both	No
Australia Northern Prawn Fishery Tiger Prawns Bio-economic Model	Australia	None	Technical	No
Bio-Economic Module Connecting Ecology and Economy	Europe	None	Technical	No

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i)   Progress on implementing the multispecies approach in NAFO

The multispecies approach has not been implemented in NAFO yet, but it is part of the Roadmap to the Ecosystem Approach to Fisheries (See section 3.1 in this report). This project has delivered advances on both the methodologies and data side to support multispecies-based fisheries management in NAFO. Below we outline progress made in this project (described in detail in previous chapters of this report) and discuss challenges and limitations encountered and how those could be addressed in the future.

The study selected the GADGET (Globally applicable Area Disaggregated General Ecosystem Toolbox) model as the basis for developing an MSE framework for the Flemish Cap covering cod, redfish and Northern shrimp fisheries. This is a length- and age-based, multispecies model that can incorporate both technical and ecological interactions. Key technical advances achieved as part of this project are:

Improvement of inputs for the ecological model (GADGET)

- Collection of data to incorporate an additional fleet into the simulation; that is the longline fleet that operates in the Flemish Cap and which has become more important in recent years.

- Updated datasets to extend the data to 2016 which was the last year used for the assessment.

- Cross-checking of data to ensure that they were the same as those used in the single-species assessment for compatibility. This was important as some of the input data for GADGET are length-based while in the single-species assessment are age-based.

- The updated datasets were analysed to calculate new selectivity, growth, sex change and maturity curves and the consumption model and equations driving species interactions were adjusted to reflect the new information.

- Both residual and predation mortality were estimated instead of using values from the literature.

- The model has been modified to reflect the dynamics of the species. Specifically, functions of the model were updated to allow for new processes and knowledge to be incorporated in the analysis.

Reference points and MSE

- The improved multispecies model GadCap was used to develop alternative HCRs based on multispecies criteria, including one and two stage hockey stick HCRs.

- A multispecies MSE framework was created for the first time in NAFO and used to perform risk assessment for a selection of single and multispecies based HCRs.

<u>Economic component of the analysis</u>

- A review of bioeconomic frameworks for MSE highlighted that there was not a single ready-made model that could be used to run an MSE that captures both ecological and socioeconomic considerations for the fisheries covered in this study in an integrated way.

- Data needed for an economic analysis were collected and analysed. This included effort intensity and distribution, market prices of fish, and landings.

- In the absence of an appropriate integrated model, the study ran scenarios to test different dimensions of the system such as long- and short-term financial indicators of the fleet and variability of the results.

- Through this process we were able to analyse the trade-offs of different HCRs using pre-defined management objectives. The indicators used to represent the trade-offs were Gross value, Value added, Full equity profit, and Net profit.

This project also included an outreach component and the main vehicle for that was a stakeholder meeting. The aim was to provide the fishing industry and other fishery-related associations operating in the NAFO Regulatory Area with the opportunity to find out a) what and how multispecies assessments are being developed and b) the benefits they provide in the context of implementing an ecosystem approach to fisheries management and provision of fisheries management advice. The meeting helped identify and discuss some of the 'key' challenges associated with the operational implementation and scientific development of multispecies assessments and highlighted the importance of increasing the dialogue between scientists, industry and managers. On the latter, the workshop was able to identify some actions that could support the multispecies approach in NAFO. Specifically:

- Ad hoc participation at the Long Distance Advisory Council (LDAC) meeting in March 2019, especially WG2[1], was suggested as a useful forum to help facilitate a better understanding of the science being developed to support EAFM and specifically MSAs.

- Gear technology and advances in marine technology more generally (e.g. sonars, navigation and weather instrumentation) was highlighted as offering potential opportunities for collaboration with the industry in providing useful additional data to support the development of MSAs.

- Development of research and sampling programmes in direct collaboration with the LDAC.

ii) Key issues and challenges

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[1] *THE LDAC WG2 meets every year and experts are invited to the group as required to make presentations on their work. WG2 discusses issues related to North Atlantic Stocks, Fisheries Agreements and RFMOs (NAFO / NEAFC)*

In this section, different actions that may be addressed in future projects are presented. One of the elements that could be improved is provision of data of better quality in due time. Specifically, in the case of redfishes, there is paucity of detailed catch data which are needed to model this stock as beaked and golden redfish separately. Inability to develop a model that captures the dynamics of each of these two stocks separately also thwarts any work to model their trophic interactions. More broadly, information on technical interactions which is needed for a multispecies modelling exercise is missing. Data on ecological interactions also need improvement. Details about research needed to fill data gaps and facilitate further data improvement are provided in sub-task 6.2

Reporting of fisheries data will also need to be improved/modified to make it possible to get the data needed to model technical interactions between species (mixed fisheries), as well as modelling the redfish stocks separately. It is expected that additional resources will be required to collect the extra data; however, stakeholders that attended the workshop have expressed their willingness to contribute to the collection of the data. Support for the relevant research will also be necessary. Action to ensure that those resources are in place is therefore, recommended. Furthermore, a review of current reporting obligations, as well as guidelines and relevant reporting forms is recommended to ensure they are fit for purpose and can facilitate collection of such information.

Another challenge found during the development of this project was the ban on using all the survey data from 1988-2001, and all survey data related to age, maturity and growth from 2014 to 2016. This prohibition came once the project had started and Task 2 was almost accomplished. However, the ban applied not only to the use of the data, but also communication of any results. Although this problem was eventually resolved, the normal development of the project has been strongly affected. The main negative impact has been on the development of Tasks 3 and 4, and outreach activities relating to the NAFO Scientific Council (via the WGESA) and workshop with stakeholders. On the latter, the invitation letters for the stakeholders were prepared back in July 2018. However, due to the problems with data rights and communication of results, this invitation could only be sent by mid-December. The attendance of stakeholders from the fishing industry and from DG-MARE itself was limited due to the short notice. Similarly, problems with accessing data created delays and limited engagement with the NAFO Scientific Council and that hindered integration of this project's results in the lines of work of the NAFO-WGESA.

Access to economic data also posed challenges mainly due to confidentiality issues. Specifically, this study was designed on the assumption that disaggregated economic data that are submitted by EU countries every year could be made available by the EU. However, that was not the case, and this study had access to aggregated data only from the EU. At the beginning of this project a questionnaire was circulated about the economic data to overcome that issue, but that approach was not successful. This was probably because the LDAC preferred to understand the objectives of the project first before committing themselves to a data collection process.

Considering the multispecies MSE framework considered in this project, there are modelling components that can also be improved such as incorporating the sub-models for beaked and redfish as well as the technical interactions between species into the framework. For cod and shrimp, a density-dependent growth model has also been developed in this project and could be incorporated into the operating model GadCap to improve the multispecies MSE framework. Further work to improve the way in which the model captures density dependence effects in ecological processes is also needed. A very important modification that will have to be included in the future is the integration of a socio-economic model with the

ecological model GadCap. This study tried to evaluate the effects of the different HCRs in economic terms, but this was only a limited exercise. The main constraint to making progress with the economic part of the work is that multispecies biological models are not yet available as an operating model in the form of a fleet-structured bioeconomic model. Therefore, modelling technical interactions and splitting redfish species, as well as incorporating the socio-economic aspects into the MSE framework are seen as priority; subtask 6.2 provides suggestions for research and next steps to make progress on these elements of the multispecies assessment.

It was not possible for this study to do an integrated bio-economic evaluation, but it did provide an overview of why a bio-economic model is necessary. Although that question seems straightforward, it could lead to different answers depending on what is expected from the bioeconomic work. Furthermore, there are many bioeconomic models but none of them covers all the possible questions that can arise from managers. Looking at the process in detail, one of the first questions should focus on whether the economic consequences of any management actions are to be simulated, or if the system is to be optimised from the economic point of view (i.e. only identify that single management action that delivers maximum economic benefits). Note that the latter does not imply that sustainability (from the biological point of view) is not considered, on the contrary, biological sustainability is the main pillar of any economically optimised method. This question highlights an important non-research issue that needs to be addressed; that is to define the management objectives to guide scientific analysis.

One possible way forward to defining management objectives would be to ask stakeholders (including managers) which objectives they prioritise. Acknowledging that there are always trade-offs will need to be part of the process of selecting objectives. Trade-offs arise from different dimensions (economic and/or biological) but also from the time perspective (short vs long term), stability of the system vs higher revenues, or at Member State (MS)/fleet level.

Engagement with stakeholders through the workshop has also highlighted challenges that this approach poses for the industry. Developments emerging from the EAFM roadmap in NAFO have led to an increasing number of requests for different types of fisheries data (e.g. recording total catch, VME indicator species, gear dimensions etc.). The requests are made in an ad-hoc way and that is disruptive for fishing operations. Furthermore, increasing needs for data also often leads to changes to their ship-board systems (black, blue boxes, etc.) with associated costs for training staff and installing equipment. Making several modifications all in one go and identification of a minimum set of data for the industry to provide as part of a multiyear plan has been suggested as a more effective and efficient way to make the transition.

iii) Lessons learnt and recommendations for next steps

The main aim of this project was to set the foundations for implementing a multispecies approach in NAFO and did so by focusing on three interacting stocks; cod, redfishes, and shrimp. As such, it was expected that many issues and challenges would be identified. However, the process this study followed has also provided useful insight to guide future work and the application of the multispecies approach to other species and fisheries in the NAFO area and elsewhere. Section 6.2 focuses on the role of research in addressing those challenges and provides details on next steps and research priorities. Here will look at lessons learnt and actions that can complement research to facilitate implementation of a multispecies approach in NAFO.

Application of GADGET to the three stocks showed that it is not possible to maintain all three of them above B_{lim}. Economic analysis also showed that there are trade-offs in economic indicators that must be considered. These results point to some challenging decisions that need to be made when adopting management objectives for a multispecies approach. It also highlights the importance of setting management objectives early in the process. This project did not aim to provide final management strategies but that will probably be part of the next phase of implementing a multispecies approach. Therefore, stakeholder engagement will need to be part of the next phase from the very beginning with meetings to decide on management objectives and priorities, understand constraints, and agree on performance indicators and reference points.

This lesson is also reflected on experience gained from other projects such as MYFISH (Rindorf et al. 2016) which recognised that a single maximum sustainable yield solution is unlikely to exist in a multispecies context. Therefore, it called for an inclusive process from the beginning to address trade-offs in a participatory and transparent approach.

On the specifics of engaging with stakeholders, the workshop was run with representatives from the fishing industry and management, but the number of attendees was too small to ensure it was representative. Taking steps early on to secure wider representation from industry will clearly be beneficial. Allowing enough time for the industry to present their views at meetings is also a significant factor for success. Due to the limited size of the group we had for our workshop this was not a big issue and we were able to identify their concerns and opportunities through discussion. However, for a larger group in the future, planning needs to account for specific slots to provide stakeholders with a platform to present their views on key challenges and how they see the ecosystem approach developing.

Access to data also needs to be guaranteed from the very beginning; this study required a wide range of data and that helped identify issues related to data availability and accessibility. Issues that need to be addressed from the start involve data confidentiality, clarity on who will provide data and level of disaggregation, and data compatibility issues. Central bodies that hold data (such as the EU in our case) and stakeholders need to be consulted at the start of the project to secure commitment for providing the data. Agreement on the direction of data flow is also very important to ensure compatibility and avoid duplication of work. The latter is particularly important if the data required have already been submitted to a central body so unnecessary burden is not placed on stakeholders to provide data twice (i.e. to their Government/regulatory body and then to scientists).

Similarly, inclusion of all research institutes that hold relevant data/experience in the research project will be the most effective way to maximise data/knowledge use. Although this project tried to include as many of those research institutes as possible, there were still researchers that had to provide data and contribute to this work even though they were not part of it. We want to thank them for their help. This experience also highlighted how important it is to have very good overview of databases and work required to access the data and get them in the appropriate format.

Having the appropriate institutional set-up to facilitate the collection of data needed and uptake of findings of new, multispecies research is also crucial. The set up will possibly include new protocols for data collection and structures for requesting, developing, presenting, and considering scientific advice for management. The lack of appropriate data to model technical interactions for the species considered in this study is an example of gaps that will require new protocols for data collection if they are to be filled. Discussions at the workshop held under Task 5 confirmed that the industry was willing to contribute to data

collection so the right structures need to be put in place to allow co-operation between scientists and industry.

This analysis also showed that lack of a fully integrated bioeconomic model should not be an obstacle to progressing work in this area. Even though such an integrated model was not available, we were able to use results from GADGET and evaluate them in terms of the fleets' financial performance. This helped explore trade-offs and their importance in managing the three species examined. These results were also used to engage with and communicate the process to stakeholders to build capacity and trust and facilitate collaboration.

Sub-task 6.2 - Research activities to strengthen the multispecies assessment implementation within the NAFO roadmap for an EAF

The range of research activities needed to strengthen implementation of the multispecies approach reflect the multiple challenges and data gaps identified in the previous section. Below, we describe those research activities in detail looking at the contribution they can make and providing our perspective on prioritisation of the activities. Synergies and research in the context of the NAFO road map are also discussed looking at their potential contribution to the implementation of the multispecies approach. A summary of issues and gaps identified and research or other action proposed to address them is presented in **Table 6.6-2**.

   i)   Research needs

Research needed to advance the framework developed for the Flemish Cap and tested in this project is considered here looking at both data and software improvements. We also look at action needed to implement the multispecies approach in other areas/fisheries of NAFO.

Biological component of framework

One of the main challenges in developing the simulation framework further relates to lack of relevant data. That is both to support the optimisation of the parameters of different processes in the biological model or the development of additional processes to reflect the dynamics of the stocks and fisheries.

Separation of redfish catch and other fishery data into individual stocks (beaked and golden redfish stocks) is very important and therefore, is a priority for future action. At the very minimum, effort should be made to separate data for catches of beaked and golden redfish but, ideally, catches should be split into the three redfish species. This information will facilitate the modelling of the fisheries dynamics and ecological interactions for beaked and golden redfish stocks, instead of modelling everything together as at present. The data required is, by season:

   o   Catch by stock

   o   Size distribution by stock

This data can be obtained directly, (i.e. direct fishery information on the distribution of catches between the beaked and golden redfish species) or, if that's not possible, by indirect estimation using survey data (survey data are disaggregated into the different redfish species). Linked to the previous point, research to improve understanding of the prey-predator length relationship is also of priority since it will inform the interactions component of the modelling framework. This will involve stomach content data and specifically, the following actions:

- o Obtain some stomach content data at different times of the year
- o Improve the quality and quantity of information on predator size-prey size. This can be achieved by improving protocols for stomach content and using commercial vessels to collect new stomach data throughout the year not just in June-July which it is the case right now.
- o Improve the identification of fish species in predators' diet composition through education and training of scientists participating in scientific surveys.

hese data are a priority because of the extreme importance of this information in shaping the degree of interaction between stocks of different age-length ranges in the model. The configuration of the prey-predator length relationship in the model has been proven to produce very important differences in the predicted dynamic of the prey.

The other action that is of high priority is collection of data needed to model the technical interactions between species. Specifically, this will need haul disaggregated data on:

- o Date of the year
- o Location
- o Targeted species
- o Catch by species (at least target and main bycatch species), both retained and discarded
- o Size distribution by species (at least target and main bycatch species), both retained and discarded

Currently, the model we use assumes that technical interactions between the fisheries of the stocks modelled are not important. However, the few data that are available show that bycatch of cod in the redfish fishery, and vice versa, could be substantial. Hence, disregarding these technical interactions when designing a long-term management plan for a target species may produce undesirable and unforeseen effects on bycatch stocks.

Collection of information for all the different fleets fishing for each of the three stocks will also support progress with the simulation framework. For example, fishing for redfish is carried out with bottom and pelagic trawls. These two gears are expected to affect the length and age structure of the population in a different way. However, today the information that is being used comes basically from the Portuguese bottom trawl fleet, and this entails a biased modelling of the impact of the fishery on the redfish stock. Getting that data for the countries that affect redfish the most is clearly more important, but the aim should be to collect data on commercial catches from all the countries that catch any of the three redfish stocks. Specifically, data by season on:

- o Catches
- o Sample size distributions of catches obtained proportionally throughout the year
- o Age distribution
- o Maturity state

Technical component of the framework and work to advance its implementation

Collection of data will need to be accompanied by modifications in the structure of the multispecies model GadCap to simulate the processes mentioned above. Specifically, the priority will be modelling the following processes:

- o Separation of beaked and golden redfish species
- o Technical interactions
- o The prey-predator length relationship.

This will also facilitate further modifications of the MSE framework, specifically the operating model at the individual stock level, to reflect important elements of the stock dynamics in long term simulations. In terms of priorities those will be:

- o Explore how to use historical knowledge on the SSB-Recruitment relationship to reduce uncertainty in recruitment when running risk analysis. Recruitment is a fundamental process affecting model predictions on productivity of stocks and therefore, must be studied in more depth. Currently, it has been applied randomly. Future efforts need to focus on modelling time variability using an autoregressive model, but also explore other options for temporary recruitment patterns.

- o Include density-dependent processes to reflect the carrying capacity of the populations which is growth and natural mortality dependent. This is a matter of great importance and this project has opted for a pragmatic approach which is to take the historical maximum as a credible candidate for carrying capacity. However, this can be greatly improved by introducing individual-dependent growth and variation in residual natural mortality which will be a function of population density. Although the influence of density-dependent processes and water temperature on growth of cod and shrimp has been studied as part of this project (see Annex II), this has not been implemented in the operating model.

Development of a fully coupled operating model with a feedback mechanism to match the biological and economic projections is a priority with regards to making progress with the economic element of the simulation framework. This will involve incorporating a multispecies operating model driving the dynamics of the stocks within a fully integrated bio-economic model. A way forward is to integrate the GADGET model as operating model within the FLBEIA package. This is possible, because FLBEIA was designed modularly, that is, different biological operating models can be incorporated, if coded following a specific structure. Currently, IMR in Bergen is undertaking work to incorporate GADGET into FLBEIA, building on progress that this project has achieved. Therefore, using knowledge acquired in this project to integrate GADGET within the a4a-MSE framework to include GADGET as an operating model within FLBEIA is a priority. This way, the ecological and socio-economic aspects would be integrated in the same tool.

After that, another technical improvement will be to include the evaluation methods that are currently used for cod, redfish and shrimp to do the evaluation within the management procedure. Currently, the assessment method that has been used when assessing the performance of different combinations of HCRs, was the so called "shortcut" option, as indicated in the section 3.3. Including the current stock assessment methods will imply

profound modifications of the code in the GADGET-a4a-MSE framework, and hence will have to be developed in future projects. Including the current stock assessment models in the management procedure will increase realism in management strategy evaluations. In addition, it will make it possible to use the MSE framework to explore other questions about standard procedures currently followed in single species assessments.

Once the model is ready, the second priority would be to condition it. The task of conditioning a model is not an easy one, because several assumptions and data manipulations have to be applied including assumptions about the simulated species, species that are not simulated but have to be accounted for, and fleets (those that are explicitly considered and those that are none). Work described in the previous section to cover both data analysis and data collection is crucial for this part of the model application.

Understanding the dynamics of the system that the operating model represents is the next step in terms of research. This will provide an insight into sensitivity of the results to different processes within the operating model, for example stock-recruitment relationship, trophic interactions, predator-prey size relationship, prey preferences. Two possible ways to approach this are to perform a global sensitivity analysis (GSA), or to focus on exploring the dynamics of certain economic process, as follows:

Global sensitivity analysis (GSA): This is an unbiased (bio-economic) way to establish which parameters (and processes) really affect the results so priorities for data improvements can be set. This type of analysis is really resource intensive but provides a thorough mapping of sensitivities.

Selected processes analysis: If resources are not available for a GSA, work can be focused on exploring the dynamics of certain economic processes to be prioritized/selected either by the stakeholders or by the researchers themselves. We cover some of those processes below together with relevant research and data collection to support such analysis.

- o *Price formation* – This looks at how fish price is related to factors such as landings, sizes, alternative species, and imports. Research needed to inform analysis of this process includes collection and analysis of data on landings by species and sizes and market prices, but also on imports and exports of these species (i.e. final markets).

- o *Capital formation*. This explores the impact of management structure in place on the capital (i.e. number of vessels) evolution. A questioner submitted and responded by the fishing firms will support research to explore investment behaviour. Technical creep should also be explored as part of research here to understand if / how the technological evolution affects capital evolution and fishing effort efficiency.

- o *Social dynamics*. How, employment and wages will evolve, the ratio labour /capital remuneration, or if equality issues are to be considered (equality among individual vessels or vessels of different Member States. To do so, management priorities have to be set, which can be done using ad-hock workshops that will involve the industry, NGOs, scientists and managers.

Extending the framework to other NAFO areas

The framework developed in this project provides a suitable tool for assessing the performance of alternative management strategies and the trade-offs when considering all interacting species. If the multispecies approach is to be used more broadly in NAFO then the methodologies and framework developed in the Flemish Cap will need to be extended to other Ecosystem Production Units (EPU) in NAFO. Therefore, extension of the framework, including the improvements and research requirements covered above, to other areas is seen as the obvious next step. However, it is important to highlight that the choice of specific models to use as operating models (both ecological and economic) will have to be made on a case by case basis. Hence, each EPU may have a different type of model representing the dynamic of the 'real' system under management. Factors that could help decide on the appropriate model include the number of species and level of interactions including ecosystem interactions (e.g. trophic levels) that must be simulated, number of fisheries involved, degree of data sophistication, and type of management advice needed.

Despite variation in the selected models, data required for the Flemish Cap case study are expected to be needed for the other areas, too. That is length and age distribution of catches, total catches, maturity ogives, length and weight at age, stomach content data, prey-predator length relation, etc. Therefore, data to model the ecological and technical multispecies interactions will need to be collected, as well as developing the socio-ecological-economic models and MSE framework.

Table 6.6-2: Recommendations for future research and other actions to address knowledge gaps and foster implementation of the multispecies approach. Highlighted cells indicate priority activities.

Issues and gaps	Future research	Other actions
Lack of species-specific seasonal data (fishery and non-fishery related)	• Collect/analyse commercial fishery data seasonally • Collect/analyse stomach data • Analyse fishery data	• Enhance collection of fisheries data by MS and by fleet type to include seasonal data on: fleet, species-specific catches and bycatch, target species, size distribution, age distribution, maturity information.
Knowledge and data on redfish are at group level	• Separate and analyse catch and other data of redfish to individual species and different seasons	• Report fishery data for redfish at species level, or at least by stocks: beaked and golden redfish
Improve understanding of species interaction; prey-predator length relationship	Improve the quality and quantity of data on predator and prey size through: • Collection and analysis of stomach data at different times of the year for ecological interactions. • Better protocols for stomach sampling	• Improve identification of fish species in predator's stomach contents, and measurement of those fish prey through training of scientists participating in the scientific surveys

Improve understanding of species interaction; technical interaction	Analyse bycatch data linked to targeted species	• Industry/MS to provide information about targeted species on a haul-by-haul basis and collect data for targeted and bycatch species and their size distribution.
Resources required to increase quality/breadth of fishery data submitted by MS		• Put resources/structures in place to collect data and allow co-operation between scientists and industry • Review MS reporting obligations, guidelines, and reporting forms to ensure they are fit for purpose.
Accuracy in the way population dynamics are simulated in the model needs to be improved	Write new code so software functions reflect new knowledge for the following processes: • Separate beaked and redfish stocks • Refine prey-predator length relationship • Add technical interactions	
Accuracy in the way population dynamics are simulated in the model needs to be improved	• Explore ways (knowledge to use) to better describe the stock-recruitment relationship in the model • Add density dependent processes to reflect carrying capacity • Add density-dependent growth sub-models for cod and shrimp already developed in this project into the operating model	
Socio-economic aspects are not part of the MSE framework	• Integrate the GADGET model as operating model within the FLBEIA package	
Management objectives, constraints, performance measures and reference points need to be defined to guide the technical (socio-economic) analysis		• Consult with stakeholders (including managers) on objectives they would prioritise and select the alternative management strategies to be tested.
Need to understand the sensitivity of model results to	• Conduct Global sensitivity analysis *or* • Selected processes analysis	

different processes	

    ii)   Multispecies assessment in the context of the NAFO roadmap for EAF

NAFO began the implementation of an EAF in the years following the publication of the FAO Guidelines on Deep Sea Fisheries. In 2008, the NAFO Scientific Council established the Working Group on Ecosystem Science and Assessment (WGESA), with the task of developing a framework that could deliver an EAF for NAFO (the so-called roadmap for an EAF), as well as supporting the NAFO Scientific Council work on ecosystem issues. To accomplish these tasks the work within the WGESA has been developed under Terms of Reference (ToRs) grouped in four themes as shown in Table 6.6-3:

Table 6.6-3. Terms of Reference for the WGESA

Themes	Description
Theme 1: Spatial considerations	Mapping of sensitive habitats and ecosystem production units, with emphasis on connectivity, exchanges and flows among ecosystem.
Theme 2: Status, functioning and dynamics of marine ecosystems	Develop research and summarize new findings on the status, functioning and productivity of ecosystems (including modelling multispecies interactions).
Theme 3: Practical application EAFM	Long-term monitoring of status and functioning of ecosystem units and the application of ecosystem knowledge for the assessment of impacts and management.
Theme 4: Specific requests	*Specific requests from Scientific Council or Fisheries Commission*

The NAFO Roadmap was developed under Theme 3 with an aim to establish sustainable exploitation levels through a three-tiered hierarchical approach:

- The first tier defines fishery production potential at the ecosystem level
- The second tier utilizes multispecies assessments to allocate fisheries production
- The third tier involves single-species stock assessment

In 2011, through Theme 4, the NAFO FC requested the SC to provide an explanation on the possible connection between the observed dynamics on cod, redfish and shrimp in the Flemish Cap. It also requested advice on the feasibility and manner by which these three species could be maintained at levels capable of producing a combined maximum sustainable yield, in line with the objectives of the NAFO Convention. Since then, different studies were undertaken to answer these requests (Ávila de Melo et al. 2013, Pérez-Rodríguez and Saborido-Rey 2012), including the development of a multispecies model (Pérez-Rodríguez et al. 2016).

Contribution to the Roadmap

Work under this project is a continuation and extension of previous work to give answers to the FC request, specifically for the Flemish Cap. The new results, methodologies, and progress made in this project are contributing directly to ToRs of Themes 2 and 3. Another contribution of this project is that it helps connect the first and third tiers of the NAFO EAF. Here this is done specifically for the Flemish Cap, but that can also be used for other Ecosystem Production Units in the NAFO area.

The results of Task 2 (section 3.2) have provided an improved and updated multispecies model that can assess the magnitude of species interactions, as well as give answers to diverse ecological questions about the influence of changes in ecosystem components on the dynamic of the three main stocks of the Flemish Cap (Theme 2). In addition, natural mortality estimated with GadCap (residual and predation mortality) has been used during the 3M cod benchmark as an alternative source of natural mortality to be used in the stock assessment, as well as in short term forecasts to define the catch advice (Theme 3 and connection with the 3rd tier of the NAFO EAF). Work under Task 3 has resulted in an MSE framework that can assess alternative combinations of management strategies for all the stocks in an EPU (Flemish Cap as case study) defined from a multispecies perspective (input to Theme 3 and the 2nd tier of the NAFO EAF roadmap).

The framework created in Task 3 (section 3.3) can also be used to assess management plans that are defined from a single species perspective (connection of 2nd and 3rd tiers of the NAFO EAF roadmap). In addition, progress achieved in Task 4 (section 3.4) provided the tools to explore the socio-economic trade-offs of alternative management strategies (theme 3) in addition to ecological consequences.

Potential synergies with other parts of the Roadmap

Work under this project is directly linked to the 2nd tier of the Roadmap and therefore, future lines of research to develop a multispecies assessment are expected to link to other lines of work developed in NAFO.

An example of synergies with other areas of the EAF roadmap is work developed in the ecosystem tier (tier 1 in the EAF roadmap). Specifically, estimates of Fisheries Production Potential (FPP) developed under tier 1 can be used to calculate the carrying capacity of the EPU in relation to a given group of species. In the Flemish Cap case study, this group consists of cod, redfish and shrimp. In this project, a proxy for the carrying capacity of the system was used which was the maximum value observed in the historic period. This may be improved by using the maximum FPP for this group of species to estimate the necessary biomass to produce that maximum production. This can be incorporated into the multispecies model to ensure that estimated maximum productivity is in line with the FPP. The multispecies model (in addition to all the applications demonstrated in this project) can then be used as a tool to distribute that productivity (the FPP) among the stocks. The distribution of productivity and biomass would vary depending on the management strategy selected.

Synergies with work developed under the single species tier are expected to occur at different levels. As mentioned already, single species analysis will benefit from estimates of natural mortality calculated in a multispecies assessment (e.g. to be used in the stock assessment during the benchmark process). In addition, multispecies assessment work can benefit from HCRs decided at a single-species level to test the behaviour of the model. This will also

provide useful insight for the single-species assessment as the HCR can be assessed in a multispecies framework like the one developed in this study, or an updated one, which will include the improvements proposed in this section, to test whether they are precautionary.

The multispecies approach can assess the performance of different management strategies for several species at the same time and therefore, it can be used to assess trade-offs at different levels. The levels explored so far are related to the risk of population collapse and economic risks. However, other ecological risks may be considered such as the risk of negatively impacting vulnerable Marine Ecosystems (VME). The multispecies MSE framework considered here with technical interactions incorporated into the operating model can be used to assess such risks. A way to achieve that is to link risk assessment work currently being conducted within the WGESA to assess the impacts of bottom trawl fisheries with the multispecies MSE. The multispecies MSE framework could provide estimates of fishing effort by species and show how they will change depending on the management strategy used. These estimates can be combined with the work of the WGESA to calculate the area-specific impact of different management strategies for a group of interacting species.

Other work undertaken by the WGESA that links to and can benefit the multispecies approach is that of the conceptual model for 3LNO area that was considered by the WG recently (WGESA report 2018). The model combines a dual economic and ecological lens to contemplate questions such as those relating to the way in which key ecosystem parameter values (e.g. harvest levels, ecosystem pressures) concurrently impact human use and ecosystem components. The value of extending the model to include specifics of fishing activities in the NAFO regulatory area was considered at the WGESA meeting. Specifics of such extension that were covered in the discussion included unit of analysis, possible data limitations and potential solutions and initial metrics (analytical approaches) for quantifying trade-offs. The concept of commodity (fish) value chains was also explored as well as methods and sources of data for landed price (value) for NAFO fleets catches. Although this work is still at concept level, steps have been scheduled to take this work forward, for example, by using real data to condition the model. Clearly, there are synergies to explore between the 3LNO model and work on the multispecies assessment described here such as joint data analysis and evaluation of metrics and model performance. Those need to be considered at WGESA or other planning forums.

Finally, all the work carried out in NAFO to define EPU will help define the areas for which multispecies frameworks will have to be developed. In addition, the results of connectivity analysis under Theme 1 of the Roadmap will allow for incorporation of migratory fluxes between EPUs in the multispecies MSE framework. It could also facilitate modelling of some stocks that work as connecting elements between EPUs, like Greenland halibut.

6.6.5. *Difficulties*

We have not encountered any difficulties.

7. LIST OF DELIVERABLES

The following table provides a summary and the timing of the deliverables/reports to be submitted to EASME and DG-MARE during the course of this project:

Table 4.1. Summary and the timing of the deliverables/reports

Task	Nr.	Milestones	Delivering date	Status
0	1	Inception Report	September 2017	Delivered
0	2	Interim Report	May 2018	Delivered (Interim report)
0	4	Final Report with Executive Summary	March 2019	Delivered (Final report)
2	1	Updated and improved multispecies model GadCap	May 2018	Delivered (Interim report)
3	1	Estimates of natural mortality (M1+M2) for single species short term projections	April 2018	Delivered (Interim report)
3	2	List of exploratory multispecies reference points and description of potential multi-species HCR configurations	September 2018	Delivered (Final report and attached excel files)
3	3	First configuration of a multispecies MSE framework	November 2018	Delivered (Final report and attached folder with MSE tool)
4	1	Assessment report of ecological-economic models and frameworks to be applied on multispecies assessment	November 2018	Delivered (Final report)
4	2	Preliminary estimates of trade-offs between fleets/countries	January 2019	Delivered (Final report)
5	1	Research document to be presented at the NAFO Scientific Council 2018	June 2018	Delivered
5	2	Research document to be presented at the NAFO WGESA 2018	November 2018	Delivered. Agreed with DG-MARE to be presented during the NAFO SC June meeting 2019
5	3	Workshop minutes.	January 2019	Delivered

8. LIST OF MEETINGS

The following table provides a summary and the timing of the meetings to be carried out within the course of this project:

Table 5.1. Planned meetings for the project

Deliverable name	Location	Participation	Date[1]	Status
Kick off meeting	Brussels	EASME/DG MARE + AZTI + WMR	September 2017	Done
Workshop	Spain	EASME/DG MARE + Participating members	17th-18th January 2019	Done
Final meeting	Brussels	EASME/DG MARE + AZTI	March 2018	Done

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[1] *Measured in weeks or months from the date after the signature of the contract.*

9. LIST OF MILESTONES

The following table provides a list of the milestones of each specific task of the project, including the means of verification during the project:

Table 6.1. List of Milestones identified in the project.

Task	Nr.	Milestones	Delivering date	Status
0	1	Kick-off meeting and minutes	September 2017	Done
0	2	Final report	May 2018	Done
0	3	Final Report	January 2019	Done
0	4	Final meeting and minutes	March 2019	Done
1	1	Best practices and lessons from the selected regions implementing a multispecies approach.	January 2018	Done
1	2	Description of the elements of roadmap of the EAF in NAFO, those already developed and those that are pending to be addressed	February 2018	Done
2	1	Update of all required input databases for GadCap.	January 2018	Done
2	2	Improvement of relevant components of GadCap.	May 2018	Done
4	1	Modelling approach to perform the economic evaluation	January 2019	Done
5	1	Meeting of the NAFO WGESA meeting 2017	November 2017	Done
5	2	Meeting of the NAFO Scientific Council 2018	June 2018	Done
5	3	Meeting of the NAFO WGESA meeting 2018	November 2018	Done
5	4	Workshop between scientists, stakeholders and administrations in the EU	November 2018	Done
6	1	List of issues and gaps, recommendations and future research activities	November 2018	Done

10. REFERENCES

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ANNEX I: LIST OF ACRONYMS

Table I.1. List of acronyms used in the report (note that this list is preliminary and is being updated for the final report).

Acronym	Name
AZTI	AZTI-Tecnalia
CEFAS	Centre for Environment, Fisheries and Aquaculture
CESGA	Centre of Supercomputation of Galicia
CFP	Common Fisheries Policy
CPR	Continuous Plankton Recorder
CPUE	Catch Per Unit of Effort
CTD	Conductivity Temperature Depth
DFO	Department of Fisheries and Oceans
DG MARE	Directorate-General for Maritime Affairs and Fisheries
DST	Decision Support Tables
EAF	Ecosystem Approach to Fisheries management
EASME	Executive Agency for Small and Medium-sized
EBFM	Ecosystem Based Fisheries Management
EPP	Ecosystem Production Potential
EPU	Ecosystem Production Unit
EU	European Union
FAO	Food and Agriculture Organization of the United
F_{MSY}	Fishing mortality that produce an average catch at the
FPP	Fisheries Production Potential
Gadget	Globally applicable Aggregated-Dissagregated General
GSA	Global Sensitivity Analysis
GT	Gross Tonnage
HCR	Harvest Control Rule
ICES	International Council for the Exploration of the Sea
IEO	Instituto Español de Oceanografía
LDAC	Long Distance Advisory Council
M1	Residual natural mortality
M2	Predation mortality
MEY	Maximum Economic Yield
MP	Management Procedure
MRAG	MRAG
MS	Member State
MSE	Management Strategy Evaluation
MSFD	Marine Strategy Framework Directive
MSVPA	Multispecies Virtual Population Analysis
MSY	Maximum Sustainable Yield
NAFO	Northwest Atlantic Fisheries Organization
NAFO SC	NAFO Scientific Council
NOAA	National Oceanic and Atmospheric Administration
OM	Operating Model
RFMO	Regional Fisheries Management Organization
SMS	Stochastic Multi Species
VPA	Virtual Population Analysis
WCPFC	Western and Central Pacific Fisheries Commission

WGEAFM	Working Group for the Ecosystem Approach to
WGESA	Working Group on Ecosystem Studies and Assessment
WGSAM	Working Group on Multispecies Assessment Methods
WMR	Wageningen Marine Research

ANNEX II: Sub-task 1.1 – Multispecies approach in other management organizations.

1.- Europe

a) Framework for multispecies management

The European Union: Marine Strategy Framework Directive and the Common Fisheries Policy

The European Union (EU) has created marine environmental legislative instruments based on complex and ambitious objectives, with the ultimate intention of fostering the holistic protection of European seas, the Marine Strategy Framework Directive (MSFD; EU, 2008). The European Union has as a main goal the effective protection of the marine environment across Europe, and the MSFD is the element that vertebrates the whole set of actions to achieve it. The MSFD aims to achieve Good Environmental Status (GES) of the EU's marine waters by 2020 and to protect the resource base upon which marine-related economic and social activities depend. It was adopted on 17 June 2008 and came into force on 15 June 2008.

The Directive enshrines in a legislative framework the ecosystem approach to the management of human activities having an impact on the marine environment, integrating the concepts of environmental protection and sustainable use. It is the first EU legislative instrument related to the protection of marine ecosystems.

There are 11 descriptors that describe how the environment will look like when GES is achieved:

- Descriptor 1. Biodiversity is maintained
- Descriptor 2. Non-indigenous species do not adversely alter the ecosystem
- Descriptor 3. The population of commercial fish species is healthy
- Descriptor 4. Elements of food webs ensure long-term abundance and reproduction
- Descriptor 5. Eutrophication is minimised
- Descriptor 6. The sea floor integrity ensures functioning of the ecosystem
- Descriptor 7. Permanent alteration of hydrographical conditions does not adversely affect the ecosystem
- Descriptor 8. Concentrations of contaminants give no effects
- Descriptor 9. Contaminants in seafood are below safe levels
- Descriptor 10. Marine litter does not cause harm
- Descriptor 11. Introduction of energy (including underwater noise) does not adversely affect the ecosystem

Descriptors 3 and 4 relates to the sustainable exploitation of fishing resources, considering and preserving species interactions, i.e. the multispecies approach to fisheries management. Modern fisheries management recognizes that stocks are part of food webs, that species interact, co-occur in space and compete for resources. Therefore, an EAFM justifies and places as a priority to understand species distributions, their stock distribution and structure, as well as how species and stocks interact and co-occur in space in order to formulate and inform multispecies fisheries assessment and advice (Garcia et al. 2003, Rindorf et al. 2013).

The Common Fisheries Policy (CFP; EU, 2013) is a set of rules for managing European fishing fleets and conserving fish stocks, giving all European fishing fleets equal access to EU waters and fishing grounds and allowing fishermen to compete fairly. The CFP aims to ensure that fishing and

aquaculture are environmentally, economically and socially sustainable and that they provide a source of healthy food for EU citizens. Although maximization of catches is a main goal within the CFP, there is a priority to ensure that fishing practices do not harm the ability of fish populations to reproduce. The EU CFP advocates, among other goals, of a progression towards Ecosystem- Based Fisheries Management (EBFM), as opposed to the current single-species paradigm widely applied in the management of commercial fish stocks. The goal is the management of all the stocks in EU waters at the Maximum Sustainable Yield (MSY) level by 2020. However, as will be discussed later in the MYFISH project section (see MYFISH project section below), the ecological interactions between species and the mixed nature of the fisheries (technical interactions) in most of the European fishing grounds makes this goal difficult to achieve and will require specific approaches.

Accodingly, the EU has a regulatory framework, both in the CFP and the MSFD, that align well with the tenets of EBFM and a multispecies approach to minimise the negative impacts that fishery exploitation might have on marine ecosystems.

The International Council for the Exploration of the Sea (ICES) and the Working Group on Multispecies Assessment Methods (WGSAM)

The International Council for the Exploration of the Sea (ICES[1]) is an intergovernmental body founded in 1902 to conduct and coordinate research into the marine ecosystems of the North Atlantic. The main objective of ICES is increasing the scientific knowledge of the marine environment and its living resources and to use this knowledge to provide unbiased, non-political advice to competent authorities. ICES provides scientific advice for the management of fisheries resources to a number of governments and regional fisheries management organisations, and the EU is one of the main clients.

ICES has almost 150 expert groups and workshops that address the many diverse issues of the marine ecosystem. The core of ICES work is accomplished through those expert groups and workshops, which tackle a broad spectrum of marine science topics. One of this topics deals with the multispecies approach to fisheries management, addressed by the Working Group on Multispecies Assessment Methods (WGSAM). The Terms of Reference of WGSAM aims at enabling research on predator-prey interactions for developing advice on the EAF (ICES 2016c). WGSAM, which cover both model development and integration into practical management advice, is formed by scientific experts who contribute to defining standards for models needed to advise on the management implications of multispecies interaction identifying and promoting the research needed to establish a good understanding of how food web and fishery interactions influence one another. This work is developed in connection with the Working Group on Mixed Fisheries (WGMIXFISH), providing a scientific forum for establishing best practice in multispecies assessment methods considering technical and ecological interactions.

b) Developments of research in multispecies and ecosystem modelling

Multispecies assessment models in European waters:

Different multispecies models have been developed in the European waters since the 1970s. The Multispecies Virtual Population Analysis (MSVPA) has its origins in the North Sea model of Andersen and Ursin (1977). Initially this model was criticized for containing too many inestimable parameters to be useful in fisheries management and it was therefore considered relevant to develop

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[1] http://www.ices.dk

a simpler model more in line with the single species models used by the ICES Stock Assessment Working Groups. Focussing on the predatory interactions between the commercially exploited fish stocks for which catch-at-age data it was possible to construct a multispecies model, the MSVPA (Gislason and Helgason 1985), with only three equations: catch and stock number equations of the single species Virtual Population Analysis (VPA) plus an equation describing how predation mortality (M2) depends on the biomass of the prey and the total food intake of the predator. Multispecies analyses using MSVPA have been carried out by ICES for commercially important stocks in the North Sea and the Baltic Sea since the 1980s.

In contrast to these deterministic models a stochastic model, Bormicon (BOReal MIgration and CONsumption model) was developed in 1997[1]. This model and its successor Gadget (Begley and Howell 2004a) are designed to include processes like recruitment, natural mortality, migration, growth, consumption and maturity. Furthermore, Gadget is length-structured, and age-data can supplementary be used. This models have been applied in Icelandic and Barents Seas, as well as in some other areas in Europe and North America.

In 2004 a new model, successor of MSVPA, was developed: the Stochastic Multi Species model (SMS) (Lewy and Vinther 2004), modelling a lower number of processes than Bormicon or Gadget. Only recruitment, fishing mortality and predation were included while migration, growth and maturity were left out. SMS uses the same data sources as MSVPA, however the food selection model is parameterised, and in contrast to the fully age-structured MSVPA, in SMS the stomach content and the food selection model are length based. This allows a more realistic food selection model and the use of the originally sample stomach data for the North Sea. SMS has been used to provide multispecies advice in the North Sea and the Baltic Sea (see North Sea and Baltic Sea sections below).

MYFISH project: Maximising Yield Of Fisheries While Balancing Ecosystem, Economic And Social Concerns (Rindorf et al. 2016)

As introduced in previous section, under the CFP the EU aims at managing all the stocks with the MSY approach by 2020. However, the strong ecological interactions between species in several of the European marine ecosystems, and the mixed nature of the fisheries in most of the European fishing grounds makes this goal difficult to achieve. Reaching MSY for one stock may affect the achievement of MSY for other stocks and compromise ecological, environmental, economic, or social aims (Rindorf et al. 2017b, Rindorf et al. 2017c). With the goal of looking for alternatives to face these difficulties, between years 2012 and 2016, the EU funded the project MYFISH[2].

The project MYFISH defined limits to sustainability and listed relevant measures of yield to be maximised (ecological, social, economic measures). The effects of aiming for these yield measures while respecting sustainability was assessed and an operational framework for their implementation was provided. These tasks were approached through case studies (described below) addressing multispecies fisheries across Europe. The relevance of the recommendations made was ensured by the active involvement of stakeholders throughout the project.

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[1] http://agris.fao.org/agris-search/search.do?recordID=XF2015019010

[2] www.myfishproject.eu

- *Participation of stakeholders:*

Stakeholders, scientists and managers met across case studies in a series of workshops during the development of MYFISH. This led to a co-creation process between scientists and stakeholders primarily using Regional Advisory Councils (RACs) as forum. In the early stages, the workshops focused on identifying and ranking objectives for the management of a given fishery (Kempf et al. 2016, Rindorf et al. 2017c). By having an inclusive process from the beginning, the objectives and underlying hypotheses for management could be identified, debated and agreed. This facilitated a process where less relevant choices could be excluded, returning an operational set-up for evaluation of management measures. There was broad agreement among stakeholders that trade-offs are more appropriately addressed in a participatory approach. For all the different case studies, the approach facilitated identification of conflicts between user group's objectives, which is expected will enhance the fishery management compliance. Even when the results of e.g. a Management Strategy Evaluation (MSE) were not as expected, the transparency and understanding of the process was a clear benefit.

- *Understanding MSY*

The MSY concept has been used in fisheries management for more than 50 years (Larkin 1977). During this time, we have acquired knowledge about how the MSY principle applies to stocks and how MSY objectives relate to other objectives. So far only single species related MSY reference points are used in European management although it is well known that species interact with each other. The main argument often used is that multispecies approaches are too complicated and uncertain. However, estimates of MSY and the average biomass (B_{MSY}) achieved when fishing at a fishing mortality providing MSY (F_{MSY}) are highly sensitive to assumptions on the future productivity of stocks and whether predator-prey relationships are taken into account or not. Changes in productivity are related not only to the level of spawning stock biomass (SSB) but often to changes in e.g. temperature and associated changes in the food web. When taking single species F_{MSY} values and making a long-term simulation with a multispecies model, the yield and the SBB that can be reached are considerably lower compared to what is predicted in standard single species models because fish eat each other and any recovery of a predator stock has its cost on the prey (Table 6.6-1).

- *Multispecies pretty good yield (Rindorf et al. 2017b):*

Since 1982, when the Maximum Sustainable Yield (MSY) concept was incorporated in the United Nations Convention of the Law of the Sea, this approach became an standard for managing fisheries worldwide. The MSY principles reflect a focus on obtaining continued high catches by controlling fishing mortality to benefit the productivity of fish stocks. However, while maximizing sustainable yield and maintaining healthy stocks addresses stock-specific aspects of sustainability, it does not address the issue that the maximum ecological, economic, or social benefit may not occur at F_{MSY}.

Table 6.6-1.- MSY, BMSY and FMSY derived from different modelling approaches

Type of MSY	Single Species MSY						Multi Species MSY					
Explanation	Full Productivity			Reduced Productivity: Stock recruitment relationship based on currently observed lower recruitment levels			Maximising total yield in tonnes from the main target species in the North Sea. Full productivity.			Testing single species F_{MSY} values in the multi species model SMS. Full productivity.		
	MSY^1	$B_{MSY}{}^1$	$F_{MSY}{}^1$	MSY^1	$B_{MSY}{}^1$	$F_{MSY}{}^1$	MSY^2	$B_{MSY}{}^2$	$F_{MSY}{}^2$	MSY^3	$B_{MSY}{}^3$	$F_{MSY}{}^3$
Cod	102903	466778	0.33	52765	232811	0.33	49000	172000	0.34	42239	154880	0.33
Saithe	128899	259062	0.32	71305	160000	0.29	128000	200000	0.38	127809	261076	0.32
Haddock	114190	329127	0.37	not tested	not tested	not tested	67000	125000	0.6	49912	142961	0.37
Herring	611000	1639000	0.33	349000	1272000	0.35	523000	1274000	0.35	431414	1202390	0.33

[1] *Values come from the MYFISH-ICES WKMSYREF III report for herring, haddock and saithe. For cod the values come from ICES WGNSSK 2015. All values were derived with the model Eqsim and no harvest control rule with $B_{MSYtrigger}$ was used for the estimation of F_{MSY}. High recruitment events for haddock are highly sporadic and do occur suddenly. Reduced recruitment levels were therefore not tested during WKMSYREF III.*

[2] *Optimisation based on the ICES WGSAM keyrun 2014. The maximum total yield in tonnes was estimated with a penalty for solutions where stocks are predicted to fall below the precautionary reference point for SSB (Bpa).*

[3] *Long-term simulation until 2050 based on the ICES WGSAM keyrun 2014.*

The concept of "pretty good yield" (PGY) was introduced in recognition that there exist a range of harvest policies than can provide a yield very close to MSY while also producing other desired outputs, be they biological or economic. Hilborn (2010) showed that in a single-stock context yield varies comparatively little with fishing mortality near the equilibrium MSY for many stocks. Selecting a target fishing mortality rate within the range of PGY adheres to the principle of maximization of sustainable yield while allowing consideration of other aspects to be included in decision-making. In 2015 such single-species ranges were explored by the European Commission and ICES for potential implementation in long-term management plans (ICES 2015a). The fraction of MSY used to define PGY describes the degree to which it is possible to trade-off one objective (the maximization of yield) to achieve other objectives. The flatness of many yield curves provide a very large space within which to operate. ICES opted for 95% of MSY (Figure 6.6-1), lower percentages are unlikely to be precautionary (indeed, the 95% upper range is often not; Rindorf et al. (2017a)). A solution to this may be to use asymmetrical percentages setting the "lower FMSY" at, for example, that corresponding to 95% of MSY and the "upper FMSY" corresponding to 98% of MSY or more.
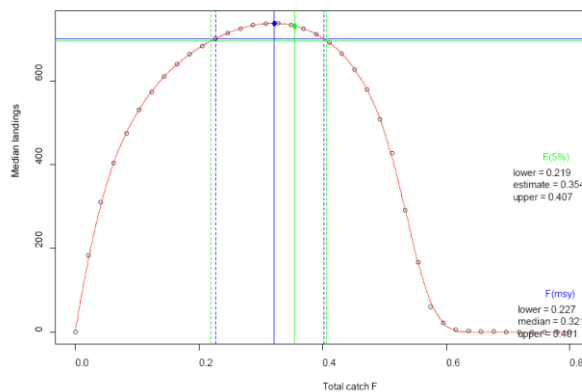
Figure 6.6-1.- 95% range of MSY for Sole stock in the ICES area IIIa with fixed F exploitation from F = 0 to 0.8. Median landings yield curve with estimated reference points. Blue lines: F_{MSY} estimate (solid) and range at 95% of maximum yield (dotted). Green lines: F(5%) estimate (solid) and range at 95% of yield implied by F(5%) (dotted). Modified from ICES (2015c).

In a system of interacting species (both biological and technically) MSY cannot be obtained for all or even most species at a time. In mixed fisheries there is a dilemma between maximizing profits or ensuring the sustainability of less-productive stocks (so-called choke species). The principle of halting all fishing when the catch of the least-productive stock reaches its F_{MSY}-based TAC leads to a low impact on the least productive species, but may also lead to substantial economic and social losses. In addition, in case of important ecological interactions between exploited stocks, the level of fishing that leads to MSY for one species depends on the level of fishing imposed on prey, predators, and competitors. Therefore, the "ecosystem sustainable harvest rate" for a given species depends on that exerted on other species.

As part of the tasks for MYFISH project, Rindorf et al. (2017b) investigated how the principles of a PGY range of fishing mortalities in a single-species context can be expanded to a PGY space to accommodate a multispecies situation (Pretty Good Multispecies Yield, PGMY), where the yield from one stock affects the yield from, or sustainability of, other parts of the ecosystem. Rindorf et al (2017b) describe the way to estimate the PGMY with socio-economic consideration in 5 steps (see Figure 6.6-2):

1. <u>Define the combined Pretty Good Yield (PGY) space</u>: As a starting point it can be assumed that species are fished without technical nor biological interactions, i.e., a purely traditional single species approach. The PGY space would be define by all the possible combinations of Fs that provide yields above the 95% MSY for all individual stocks.

2. <u>Define the Technical Interactions space:</u> Many species experience fishing mortality by the same fleet at the same time, and hence in a second step the technical interactions space has to be defined. This space contains the combinations of Fs that are possible given the different productivity capacity of the stocks, the different catchability, and the fact that they are caught together in the same fishery. Since single species F_{MSY} differs between species and these differences are rarely matched exactly by the differences in catchability in a given fleet, when combining this technical interaction space with the above PGY space, fishing mortality will be placed at the high end of the PGY F-range for some species and at the low end of the PGY F-range for others.

3. <u>Define the Pretty Good Ecosystem Yield (PGEY):</u> Combinations of low fishing mortality on a predator may result in higher natural mortality on prey stocks, which are not compatible with high fishing mortality on that prey stock. For this reason, as a third step, multispecies models accounting for the ecological interactions will allow determining the combinations Fs that are sustainable from the ecological perspective, defining the PGEY. Adding this layer to the previous two will reduce the range of Fs that are sustainable.

These three steps provides the basis to define the Pretty Good Multispecies Yield PGMY (Figure 6.6-2). However, the socio-economic component can also be added by accounting for economic considerations in PGMY as the combinations of fishing mortality rates where the total profit of the fishery exceeds a minimum specific proportion of Maximum Economic Yield (Pretty Good Economic Yield PGMEY). The Pretty Good Social Yield can be defined by the combinations of yield that produces higher benefits at the social level.
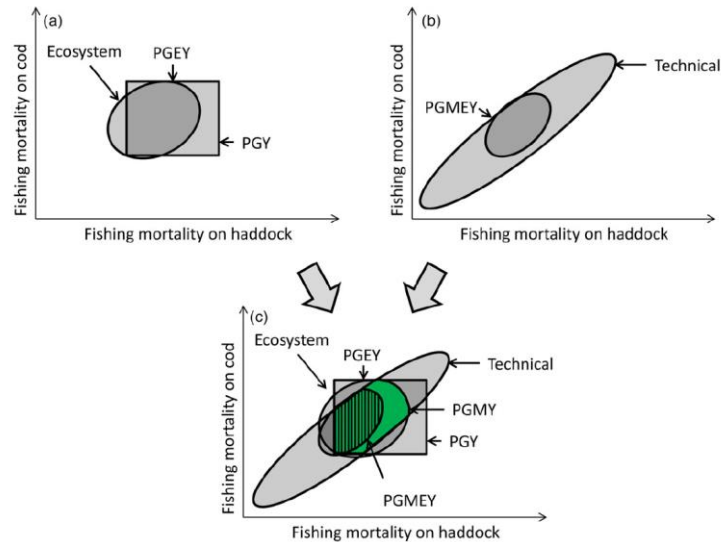
Figure 6.6-2.- Hypothetical PGMY and PGMEY space for two groundfish species caught in a mixed fishery, loosely based on the relationships between cod and haddock in the greater North Sea. The two species are interlinked biologically and technically as cod is a predator on juvenile haddock and mixed-trawl fisheries target both species. Combinations of fishing mortality leading to PGMY (the space consistent with PGY and ecosystem considerations in (a) and technical interactions for the two species in (b) are indicated. The combinations of fishing mortality rates where the total profit of the fishery exceeds a minimum specific proportion of MEY (PGMEY, striped) is shown in figure c. Shaded forms indicate the areas of desirable multispecies or ecosystem combinations, technical interactions, and the single-species PGY that is compatible with maintaining stocks above biomass limits. Similar figures can be plotted giving isopleths rather than single shapes for each consideration as done here. Modified from Rindorf et al. (2017b)

The addition of further objectives may narrow the sustainable space to the point where no set of fishing mortalities exists that satisfies all objectives. For example, while the options that meet social objectives, such as maximizing employment at the same time as ensuring all participants can make an adequate living, may be a desirable objective, it may not be compatible with other ecological or economic objectives.

- *Showing the results of evaluations: MYFISH Decision Support Tables (DSTs)*

One of the main outputs of MYFISH project were the Decision Support Tables (DSTs). DSTs are graphical tables reflecting the effects and trade-offs of implementing different MSY options on ecosystem, economic and social constraints with a particular focus on the risk of exceeding acceptable levels for constraints. The goal of the DSTs was to convey a large amount of information on alternative management scenarios in an accessible manner, making it more understandable to fisheries stakeholders.

The MYFISH DSTs integrate a number of graphical devices (see Table 6.6-2): (1) icon arrays which also incorporate 'fading out' to represent uncertainty; (2) icons that closely resemble the actual species concerned; (3) different types of icons to represent different quantities, fish stock or profit; (4) colour to show regions of particular concern and (5) embedded pie-charts to show progression or difference. As an example, in these DSTs, the number of cod icons would refer to the mass of cod, the number of Euro signs to profit, the colour red to problems, and fading to uncertainty. The goal is to convey information in a manner which makes comparison across several criteria of the merits of

alternative management scenarios more accessible to stakeholders than would be achieved with a table of numbers.

- *Case studies:*

From all the 5 cases studied as part of MYFISH project, the Baltic Sea and the North Sea has been selected for this subtask 1.1 report since they are more useful for the multispecies approach.

1. *Baltic Sea case study*

The Baltic Sea case study focused on studying the trade-offs between having a large stock and large catch of valuable cod, which consume herring and sprat, or a smaller stock of cod together with a higher stock of sprat and herring, as a smaller percentage of these fish are then eaten by cod. To describe this trade-off in detail, a coupled ecological-economic optimization model was developed for the three main species in the Baltic Sea: cod, herring, and sprat (Voss et al. 2014). Results showed that management strategies based on profit maximization would rebuild the cod stock to high levels but may cause the risk of stock collapse for forage species with low market value, such as Baltic sprat. Unless compensation is paid, this would challenge equity between fishing sectors. It was concluded that optimizing equity while respecting sprat biomass precautionary levels would reduce potential profits of the overall Baltic fishery, but may offer an acceptable balance between overall profits, species conservation and social equity.

These results were discussed in detail at a joint meeting of the Baltic Sea Advisory Council (BSAC[1]) and MYFISH participants, and a specific DST was used in this workshop as a conveyance tool (Table 6.6-2).

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[1] http://www.bsac.dk/

Table 6.6-2.- DST and key for the central Baltic Sea showing three potential management options and their respective outcome for cod, herring and sprat in terms of spawning stock biomass (SSB, thousand tonnes), catch (thousand tonnes), total profits (million €), distribution of profits to the fisheries, as well as fishing mortality.
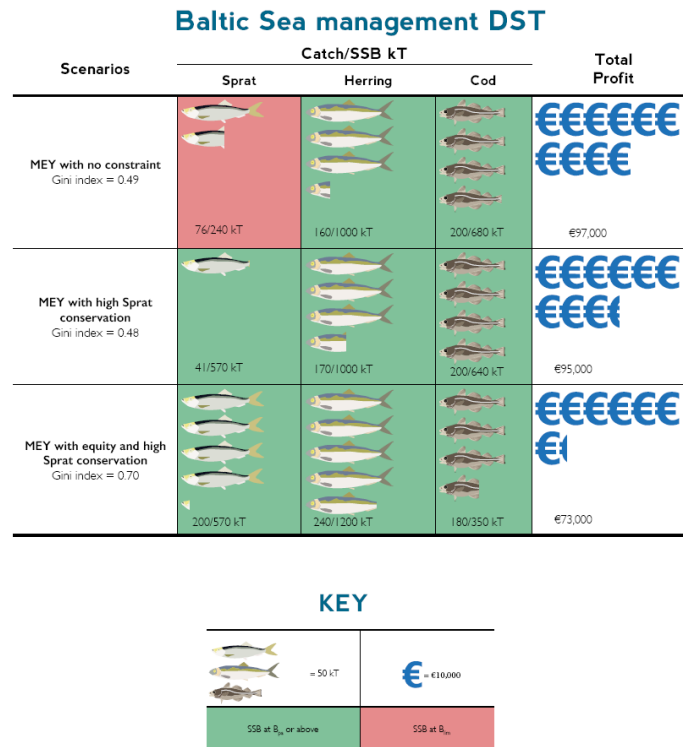
2. North Sea case study

Fisheries management based on the MSY concept is a complex task in the North Sea. Multispecies simulations performed during MYFISH project showed that the abundance of top predators like cod and saithe determine to a large extent the yield that can be taken from other species, leading to the need of trading the yield of one country or one fishery against that of another, which was identified during workshops with stakeholders as a high potential conflict area. In addition to ecological interactions, technical species interactions further complicate the situation in the North Sea, where mixed fisheries are the rule. Under the landing obligation, the maximum sustainable yield that can be achieved in mixed fisheries is constrained by the so-called "choke species" because fisheries have to stop when the quota of these species is exhausted. In addition to ecological and technical interactions, trade-offs between economic optimisation and social benefits, such as employment, have to be taken into account when defining objectives for fisheries management in the North Sea. The effect of species interaction in the North Sea on long term yield and sustainability was assessed with the stochastic multispecies model (SMS) (Lewy and Vinther 2004).

Three management scenarios were agreed with stakeholders for further examination:

- Maximising the total landings in tonnes
- Maximising the value of total landings
- An iterative process where it is attempted to get a yield in tonnes close to the maximum of each species while assuring that no species are exploited unsustainably (pretty good yield concept (Rindorf et al. 2017b)).

Landings were maximized when a higher fishing mortality than that leading to single species MSY of cod and saithe was explored. A higher fishing mortality would require a higher fishing effort and would lead to a cod stock below precautionary limits (see the Decision Support Table for the North Sea (Table 6.6-3)).

Table 6.6-3.- DST and key for the North Sea showing three potential management options and their respective outcome for cod, herring and sprat in terms of spawning stock biomass (SSB, thousand tonnes), catch (thousand tonnes), total profits (million €), distribution of profits to the fisheries, as well as fishing mortality.
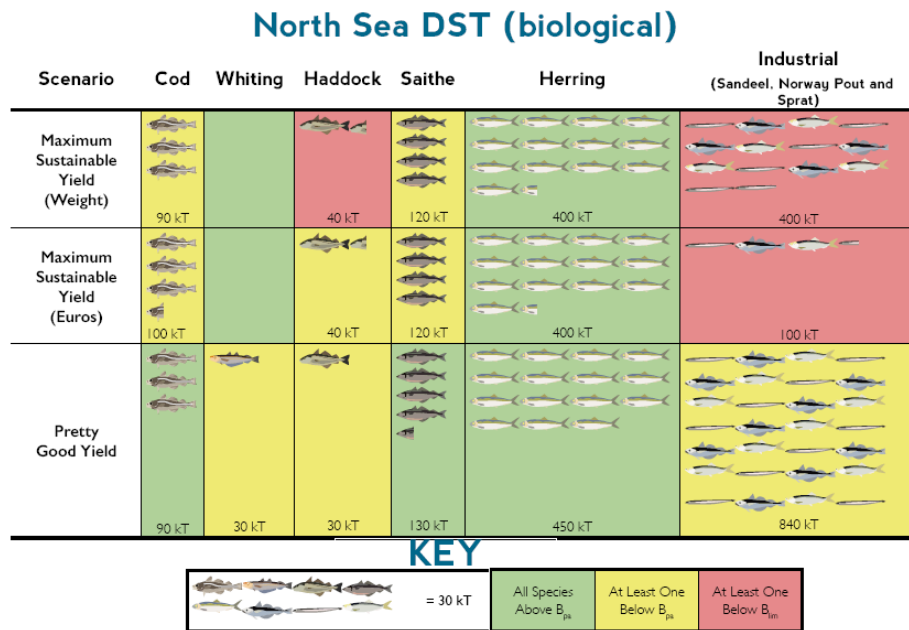
REDUS project: Reduced Uncertainty in Stock Assessments[1]

REDUS is a five year (2016-2020) strategic project at the Institute of Marine Research in Norway that aims at quantifying and reducing the uncertainty in stock assessment and advice for the most important fish stocks in Norwegian waters. The goals of REDUS project are linking models and data to understand and evaluate how uncertainty affects stock assessment and hence quota advice, and complementary how much catches can increase if we reduce this uncertainty. The REDUS framework will allow to estimate uncertainty at each level of the assessment and advice process, and aggregate the uncertainty between levels. (Figure 6.6-3).

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[1] http://redus.no/en/projects/redus/
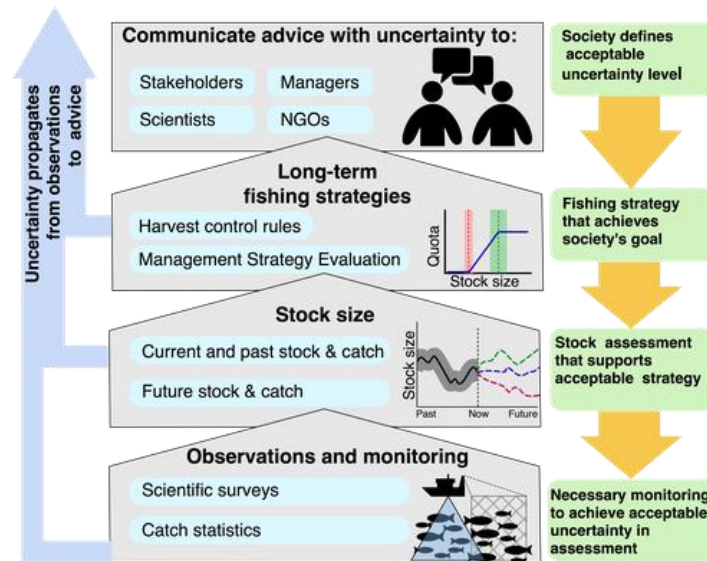
Figure 6.6-3.- Eschematic representation of the different steps where Redus will develop methodologies and protocols to assess and communicate uncertainty.

REDUS will provide a generic framework for uncertainty estimation and analysis that will allow for more optimal fisheries management and better prioritisation of fisheries monitoring and research in order to achieve the stock-specific uncertainty thresholds set by society. By coupling measures of survey and observational uncertainty with stock assessment models that account for uncertainty this provides the basis for harvest control rules and management strategy evaluation leading to providing statistically robust measures of uncertainty for quota advice and long-term harvest strategies alike.

One of the elements of uncertainty that will be assessed within REDUS is related with the process error, with the uncertainty in relation to ecological processes, and specifically to multispecies interactions. One of the main outputs expected for REDUS will be an MSE framework where multispecies and end-to-end ecosystem models will be used as operating models. This MSE framework will allow testing the performance of different HCRs for groups of exploited species at once. This HCRs may or not have implicitly considered the interaction between the species, i.e. single and multispecies based HCRs. This MSE framework will allow testing the performance of these HCRs in relation to precautionary and MSY principles when species interactions are considered, as well as evaluating the economic consequences of different joint management strategies for all species at once.

c) Use of multispecies approach for stock assessment and/or scientific advice

Over the last decades different multispecies models have been developed in the European waters (see previous sections). In addition to multispecies models new methodologies and procedures are being developed with the aim of implementing a multispecies approach in the management process within European waters, both in relation to biological and technical interactions (see the description of projects MYFISH and REDUS projects). Using some of these models/frameworks the multispecies assessment/advice is already being implemented in European waters for a number of stocks. In this section, some of the approaches already in place nowadays in some European seas are briefly described.

North Sea

In the Greater North Sea ecoregion (North Sea, English Channel, Skagerrak, and Kattegat), pelagic species (primarily herring and mackerel) account for a significant portion of the total commercial fish landings in the region, but landings of benthic and demersal finfish species (primarily haddock, sandeel, flatfish, and cod) are also significant (ICES 2017a).0

In recent years predation mortality is playing a more relevant role in the dynamic of a number of stocks in the North Sea because fishing mortality has been markedly reduced on predators (ICES 2016c). Stomach content data have shown that in the North sea predation of fish prey is produced by different fish, seabirds, and marine mammal species (Figure 6.6-4). Consumption of fish by these predators has been estimated with SMS model (ICES 2016c, Lewy and Vinther 2004). For several North Sea stocks (cod, haddock, whiting, sprat, sandeel, and herring), predation mortality estimated with SMS is now directly used in their stock assessments (ICES 2017c). This ensures that temporal changes in natural mortality are explicitly accounted for in their assessments, as well as in the catch advice and when defining reference points. Estimates of natural mortality, derived from SMS model (Lewy and Vinther 2004), are updated by ICES-WGSAM every three years (ICES 2018).
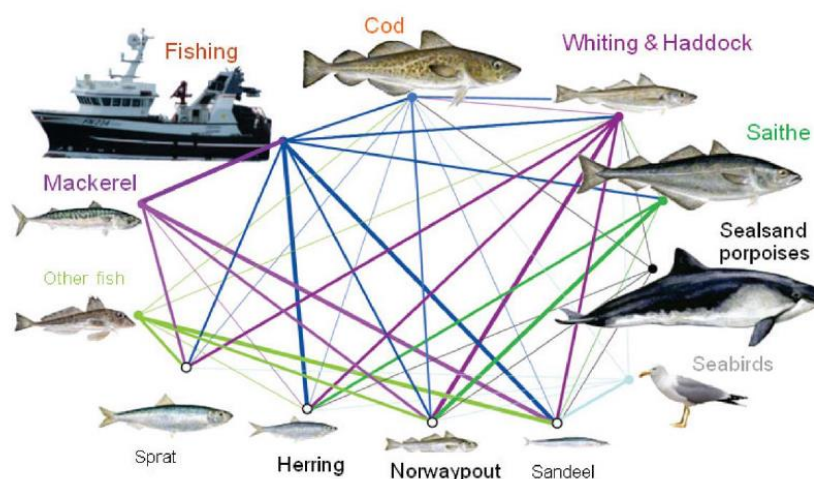
Figure 6.6-4.- Overview of the important predators and prey in the North Sea SMS model foodweb (Lewy and Vinther 2004).

The implementation of a multispecies approach for the North Sea cod and haddock consist in using in the single species stock assessment model the predation mortality values at age and year estimated by the SMS model. Once incorporated these values of natural mortality the single species stock assessment model is re-optimized. When providing the catch advice, short term forward projections are performed, fixing as natural mortality at age and year the average $M=M1+M2$ values estimated by the SMS model in the last three years of the assessment. Alternatively, if there is a strong trend during the most recent years, M at age can be set equal to the estimated values in the terminal year (ICES 2017c).

Baltic Sea

The commercial fisheries in the Baltic Sea targets only a few stocks: the mid-trawl pelagic fisheries targeting for sprat and for herring, and the bottom-trawl fisheries for cod and flatfish. Commercial fishing effort has declined in recent years. Most of the Baltic Sea fish stocks with reference points are fished at or below F_{MSY}. Eastern Baltic cod is a predator on herring, sprat, and juvenile cod

(Figure 6.6-5). As it was described in the MYFISH project section, multispecies analyses indicate that trade-offs exist between fishing on cod or herring and sprat.

Several different multispecies models have been developed and tested for the fisheries system herring-cod-sprat, like the Kiel Model, BALMAR, stock production models and Stochastic Multispecies Model (SMS) (ICES 2013). Of all these models, the SMS model was finally selected for multispecies advice. A key-run for this multispecies model was developed during the WGSAM in 2012 (ICES-WGSAM 2012), and have been used as the basis to provide estimates of natural mortality for single species stock assessment of herring, sprat and cod in the Baltic Sea, taking into account the degree of spatial overlap (ICES 2017b). As described in the previous section for the North Sea, the estimates of natural mortality from the SMS Baltic Sea multispecies model are used in the single species stock assessment models, both during the ptimization of the assessment model and the short term forecast to provide a catch advice.
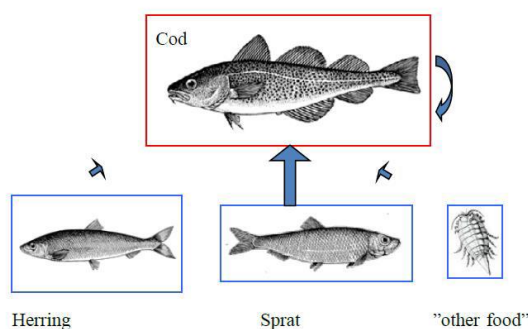
Figure 6.6-5.- The main Baltic Sea foodweb.

In addition, in the Baltic Sea, exploratory analysis to find potential candidates for MSY multispecies reference points have been conducted. SMS forecasts scenarios were made using an array of target Fs for the three species, cod, herring and sprat, and all the possible combinations of Fs. The resulting F_{msy} values (Figure 6.6-6) should be considered as preliminary, since the spatial considerations in the prey-predator overlap, as well as the recruitment relationships have to be further explored. Despite the limitations, this exercise was an outstanding step for the use of a multispecies approach to estimate reference points and Harvest Control Rules more ecologically sounded.

Barents Sea

The Barents Sea is one of the most productive fishing grounds in the world, with few but very strong interactions among its dwelling species (Figure 6.6-7), affected by important migrations within and outside the Barents Sea. Strong top-down, bottom-up and competition interactions determine the status of this ecosystem, strongly affected in the last decades by changes in water temperature (Howell and Filin 2014). Cod is the most important predator in the Barents Sea (4.2 million tons in 1946; Yagarina et al. (2011)) consuming about as much food annually as harp seals and minke whales combined. Juvenile cod are mainly a plankton predator (hiperiids, eufausiids), although capelin become a very important prey soon (Dalpadado and Bogstad, 2004). Adult cod is mostly piscivorous, with capelin as the main prey. During years of low capelin abundance, there is a remarked increase of cannibalism (Yagarina et al, 2011). Capelin is the most important fish prey species in the Barents Sea (8,5 million tons in 1975; Gjøsæter et al. (2011)). Young herring graze on capelin larvae in the Barents Sea in summer and autumn (Hallfredsson 2006), which is thought to be

one of the major mechanisms causing the recruitment failures. The harp seal is the dominant top marine mammal predator in the Barents Sea, preying on gadoids such as polar cod, small haddock and cod, but also capelin and herring. Minke whale, the most abundant baleen whale in the Barents Sea, select for capelin, herring and krill as prey. With the exception of harp seals, all these species are of very high commercial importance.
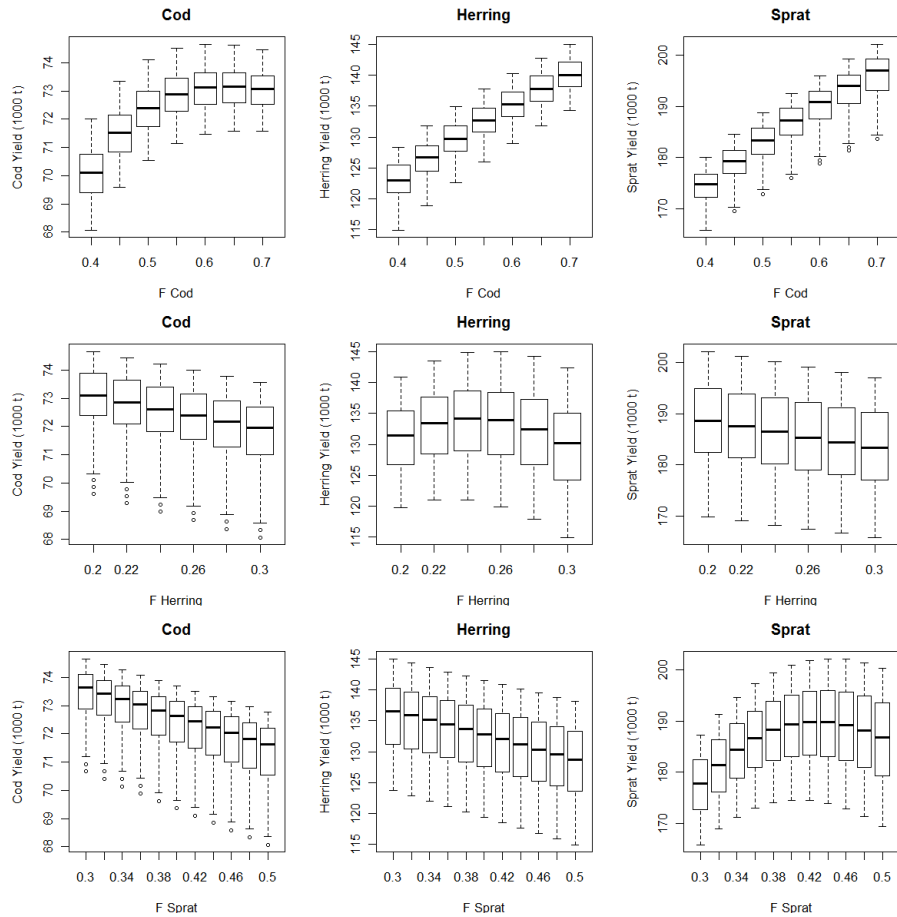
Figure 6.6-6.- Box plots of scenario results (Yield at equilibrium) for combinations of F on the three species, considering stochastic recruitment.

The Barents Sea, main species:
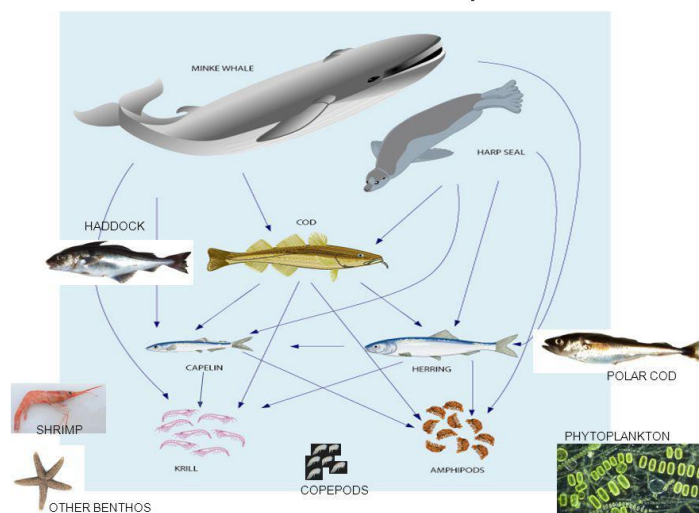
Figure 6.6-7.- Diagram with the main species and trophic groups inhabiting the Barents Sea, as well as the qualitative fluxes of connection between them.

Development of multispecies models designed to improve fisheries management in the Barents Sea started in the mid-1980s. The first models developed were MULTSPEC, AGGMULT, SYSTMOD and MSVPA (Bogstad and Filin 2011). These models were predecessors of more advanced models, such as Bifrost, Gadget and STOCOBAR that are presently used to provide fisheries advice from a multispecies perspective, including:

- Improved estimates of natural mortality (predation and residual mortality) and recruitment.
- Better understanding of stock-recruit relationships.
- Better understanding in growth and maturation rates.
- Testing of alternative harvesting strategies.

Bifrost (Boreal integrated fish resource optimization and simulation tool) is a multispecies model for the Barents Sea (Tjelmeland and Lindstrøm 2005) with main emphasis on the cod-capelin dynamics. The prey items for cod are younger cod, capelin and other food. The capelin availability partly shields the cod juveniles from cannibalism, and by including this effect, the recruitment relation for cod is significantly improved. In prognostic mode, Bifrost is coupled to the assessment model for herring and the negative effect of herring juveniles on capelin recruitment is modelled through the recruitment function for capelin. Bifrost is also used to evaluate cod-capelin-herring multispecies harvest control rules.

A GADGET (Globally applicable Aggregated-Dissagregated General Ecosystem Toolbox) age-length structured model was developed to assess the interactions between cod, herring, capelin and minke whale in the Barents Sea as part of the EU projects BECAUSE, UNCOVER, DEFINEIT and FACTS. This is a multi-area, multispecies model, focusing on predation interactions within the Barents Sea. Although very rudimentary, an FLR routine was developed to run Gadget as an Operating Model and allowing testing the performance of various assessment programs under a range of scenarios with multispecies considerations (Howell and Bogstad 2010). This work is being extended in the ongoing project REDUS (presented in previous section).

The multispecies approach in operationalized in the management of the Barents Sea fisheries in different ways. Predation on cod and haddock by cod has since 1995 been included in the assessment of these two species in a pragmatic approach. Cod natural mortality caused by cannibalism is based on data of the cod proportion in the cod diet (ICES 2016a). These data are used for estimation of cod and haddock consumed by cod and further for estimation of its natural mortality within the XSA (Extended Survivor Assessment model). The average natural mortality for the last years is used as predicted M for the coming years for cod and haddock projections to provide catch advice.

Cod consumption was used in capelin assessment for the first time in 1990, to account for natural mortality due to cod predation on mature capelin in the period January–March. The assessment of the Barents Sea capelin is based on the use of two different models: 1)CapTool, an Excel spreadsheet from which the catch quota corresponding to the harvest control rule is calculated using stochastic prognostic simulation from the time of measurement (October 1) to the time of spawning (April 1 the following year); 2)Bifrost, multispecies model used to estimate parameters in the two main biological processes behind the simulations: maturation and predation by cod. CapTool is hence used to implement the output from Bifrost in the short-term (half-year) prognosis used for determining the quota.

However, the operationalization of the multispecies approach in the Barents Sea has gone beyond the use of the multispecies model based natural mortality and prey consumption estimates; HCRs with multiespecies considerations have been designed and are currently used for scientific catch advice. During the Workshop on Management Plan Evaluation on Northeast Arctic cod and haddock and Barents Sea capelin (WKNEAMP; ICES (2015b, 2016b)) several HCR were tested. It was finally decided to adopt for the NOrth East Atlantic cod one of the two step hockey stick HCRs that were assessed. These type of HCRs use more than one F value depending on the level of SSB in relation to more than one reference point, and calls for higher fishing pressure at high stock sizes (see Figure 6.6-8). This HCR is implicitly multispecies, as it aims to avoid stock sizes high enough to cause reduced productivity due to increased natural mortality via cannibalism, but also implicitly accounting for density-dependent effects on growth.
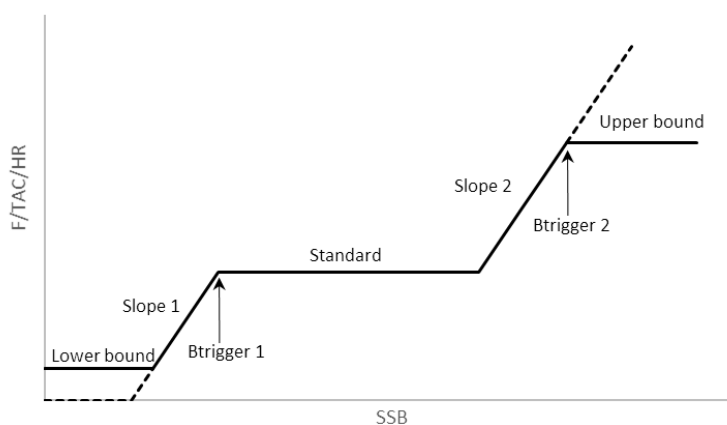
Figure 6.6-8.- General outline of the new harvest rule examined (two steps HCR), with different parameteres indicated.

Other "two steps" HCRs tested during the WKNEAMP, in addition to cod SSB being higher than $2 \times$ Bpa, required also a low capelin stock for F to be increased above 0.4. In this HCR, the trophic interactions are further considered, the indirect effect of capelin abundance on cod cannibalism is considered. However this HCR was finally not adopted.

2.- <u>US West coast with focus on the Alaska region</u>

Here, we examine the framework within which the multispecies approach is used in the management of fisheries resources in the US. The reference area is the US West coast with focus on the Alaska region.

a) Framework for multispecies management

The Magnuson Stevens Act is the main regulation for managing resources in the US and it sets 10 national standards for fishery conservation and management. The concept of multispecies management (in biological and technical terms) is introduced in those standards and specifically in the following 3 (text underlined by us):

- To the extent practicable, an individual stock of fish shall be managed as a unit throughout its range, and <u>interrelated stocks of fish shall be managed as a unit or in close coordination</u>.
- Conservation and management measures shall take into account and allow for variations among, and contingencies in, fisheries, fishery resources, and catches.
- Conservation and management measures shall, to the extent practicable, A) minimize bycatch and B) to the extent bycatch cannot be avoided, minimize the mortality of such bycatch.

The Act authorises the regional Fisheries Councils to produce Fisheries Management Plans (FMPs) for fisheries under their authority. The FMP sets the framework for applying the multispecies approach in developing management recommendations to the Secretary of Commerce. Using the North Pacific Fishery Management Council (NPFMC)[1] as an example, one can see that its policy that guides the development of FMPs specifically recognises the need to move to an ecosystem-based approach:

"the Council intends to consider and adopt, as appropriate, measures that accelerate the Council's precautionary, adaptive management approach through community-based or rights-based management, ecosystem-based management principles that protect managed species from overfishing […]"

This is also reflected on the reference points used to develop management advice; although stock assessments do calculate the Maximum Sustainable Yield (MSY), an alternative productivity reference level, the Optimum Yield, is also calculated. The latter is the amount of fish which will provide the greatest overall benefit to the Nation, particularly with respect to food production and recreational opportunities, and taking into account the protection of marine ecosystems, including species interactions.

A step that the NPFMC has taken to capture multispecies considerations into quota decisions in an empirical way is to introduce a cap in the total harvest for groundfish resources in the Bering Sea[2]. Although it is not clear exactly how the extraction of each individual species might affect the food web structure, this approach looks into the total amount of biomass that can be extracted by the

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[1] *It is responsible for the management of marine resources in the Bering Sea*

[2] *This refers to the groundfish complex that comprises of a predefined set of species*

system and sets a limit for it. This is a first step into defining a multispecies-based reference point. The limit is currently set at 1.4 to 2 million tonnes (this is called the Optimum Yield, OY) and is part of regulation that governs fisheries management in the area[1]. Historical estimates of groundfish catches from the period 1968-1977 were used to set the overall MSY for the groundfish complex and the OY is set to 85% of that MSY estimate. Both average and maximum annual catches were used to define the range for the cap[2]. The period used for these calculations (1968-77) covers the time before the implementation of the OY (early 80s) during which the fishery is considered to have operated profitably.

In addition to the overall cap, the Bering Sea FMP provides a general set of rules that set the Optimum Yield (OY) within the overall cap and also adjust the total allowable catches (TAC) for individual species or group of species:

- For the groundfish complex the overall OY is set at 1.4 to 2.0 million mt which represents 85% of the historical estimate of MSY (the sum of historical MSYs for target species, as explained above). This is in response to recommendations of the Environmental impact assessment for a 15 percent reduction from MSY to maintain a healthy ecosystem[3].
- The Total allowable catches for a species or group of species are set based on current estimates of MSY (where possible) but they could be lower than those estimates to account for bycatch considerations, management uncertainty, or socioeconomic considerations
- All the TACs for target species will be summed up to ensure that the total is below the OY
- Furthermore, 15% of each stock's or stock complex's TAC is held aside as reserve which, among others, is used to adjust species TAC for conservation.

On the protection of marine ecosystems, the Bering Sea FMP lists several ecological factors that may be considered in determining the reduction in MSY needed to get to the Optimum Yield. Interactions among species was one of the components of the ecosystem that the FMP is covering. Specifically, it refers to multispecies predator-prey modelling that has been used to assess the current status of the species complex and explore the effects of different harvesting regimes. The analysis they used comes from the early 2000's and although it does highlight some challenges that are still relevant, such as difficulties in decoupling variability in recruitment that is due to predation from variability that is due to climate change, it does not reflect advances in this field that have taken place in the past few years. Below we cover some of the most recent work that focuses on multispecies modelling and developing ecosystem models more broadly.

b) Developments of research in multispecies and ecosystem

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[1] https://www.npfmc.org/wp-content/PDFdocuments/fmp/BSAI/BSAIfmp.pdf *last accessed: May 2017*

[2] *However, the Council does recognise that the sum of single-species MSYs might provide a poor estimate of MSY for the groundfish complex as a whole.*

[3] *The EIA stated that a 15% reduction was "intended both to assure the continued health of the target species themselves and to mitigate the impact of commercial groundfish operations on other elements of the natural environment."*

Multispecies modelling has been used for research in the US West Coast for several years and many studies have been published on multispecies and ecosystem based modelling and fisheries management. For example, Van Kirk et al. (2010) used a multispecies age-structured assessment model to estimate mortality for three species in the Gulf of Alaska simultaneously, while Kaplan et al. (2018) compared three ecosystem modelling approaches (Ecopath, MICE (Models of Intermediate Complexity for Ecosystem assessment), and Atlantis) applied in the California current to provide an insight into differences in their results that could affect management decisions.

Extended research covering a wide range of models such as simple age-aggregated multispecies models that account for trophic interactions (Uchiyama et al. 2016) and age-structured multispecies statistical models (Jurado-Molina et al. 2005) have also been undertaken for the Bering Sea area in the Alaska region. The Bering Sea Project is a recent example of such research which, however, aimed to develop models that approach fishing not only from a multispecies perspective but an ecosystem perspective taking into account multispecies interactions and climate effects (Punt et al 2016). The Project developed a Field-Integrated End-To-End modelling program (FETE) to implement fisheries management in the ecosystem context and help select among different management strategies. The programme brought together research on climate, ocean physics, trophic-level interactions, and key species groups such as seabirds and marine mammals. This was the culmination of more than 5 years of previous work on plans for interdisciplinary research focusing on Bering Sea and was supported by the establishment of an Ecosystem Modelling Committee.

This initiative is much broader than a multispecies modelling exercise and therefore, it is covered only partly here. However, it provides useful insight into challenges and steps to take to maximise the value of multi-disciplinary efforts, as described below:

- Reach an agreement on research and management questions early on: This will reduce the risk of developing a model and then try to retrofit it to address questions of scientific and management relevance.
- Fieldwork and modelling work to be designed together from the start using common end-goals and interaction between researchers to be maintained throughout the program.
- Specify the accuracy in model results that would be needed to make those results useful for management: The project highlighted that setting the accuracy before the modelling work starts was one of the greatest challenges. The expectation was that the desired quality (or accuracy) of predictions would be evaluated at the beginning of the process but that was proven difficult and the process was time-consuming. Therefore, an iterative process might be a more pragmatic way to address the issue of accuracy.
- An Ecosystem Modelling Committee consisting of independent experts in modelling and environmental science as well as conceptual thinkers was established to guide selection and development of models through transparent criteria for model selection and evaluation. They also acted as the intermediary between scientists, funding bodies and other resources providers offering guidance and feedback when needed.

Research in this field has also focused on how ecosystem/multispecies models could be operationalised to be part of marine management decisions. Uncertainty in the predictions of such models coupled with limited exposure of managers and others to such models can act as a barrier for their use. Kaplan and Marshall (2016) used the Atlantis model as a reference and considered options

to strengthen the robustness of those models and increase their use and creditability. His work was also the result of recognising the importance of engaging with decision makers but also peer-reviewing such tools. They held multi-day review panels involving international experts to challenge the model and the data used and have provided insight into the credibility and quality control standards that they deem appropriate for such models and could be of help in designing other multispecies models.

In particular, they have identified 4 standards about the dynamics of the stock which cover natural mortality, productivity, size/age structure, and diet. (Table 6.6-4). Although they might not be the usual outputs of a model to present for management advice they can be used to test model reliability using information that might be available from empirical studies or stock assessments.

Table 6.6-4 Standards about system dynamics that could be used to test the reliability of a multispecies model as derived from a review of end-to-end models (Kaplan and Marshall,2016)

Component of system dynamics	Standard
Productivity	Species representing the majority of functional groups and comprising 80% of the total biomass (for species with stock assessment or survey data) should have productivity trends that qualitative match expected productivity from stock assessment or survey data.
Natural mortality	Natural mortality including predation should be plotted as a function of age over time. It should decrease with age for the majority of species or groups and should be consistent with expectations from life history theory or literature parameters.
Age and length structure	Predicted age and length structure from the model should qualitatively match expected age and length structure, for the majority of species or groups.
Diets	Diet predictions from the model should qualitatively match diet data from empirical studies, for the majority of species or groups. Predicted diets should fall within the range of empirical diet compositions, acknowledging high empirical diet variability (and uncertainty) across space, season, and year.

The work by Holsman et al. (2016a) also looked at fisheries management from a multispecies perspective by accounting for trophic interactions and temperature-specific growth and predation. They used a multispecies statistical catch at age model to calculate multispecies biological reference points (MBRP) for fisheries management and applied the model to a 3-species complex in the Bering Sea (Walleye pollock, Pacific cod, and arrowtooth flounder). They used a species aggregated female spawning biomass and the combined mortality that will lead to a set proportion of it (i.e 40%) to

define reference points. This process meant that species could be fished below the target if the aggregate biomass remained above the target.

The results showed that multispecies models produced higher estimates of combined yield for aggregate maximum sustainable yield (MSY) targets than single species models, but that changed when individual MSY targets were used. They also found that high predation rates and trophic- and management-driven effects led to the most significant changes for prey species.

This analysis showed that multispecies models are not necessarily more conservative than single species models; that depends on the assumption and restrictions that underpin any reference points calculated by the multispecies models. They also concluded that such models could be a useful tool for deriving MBRPs using harvest scenarios that combine a minimum biomass threshold with yield targets to meet biodiversity and yield objectives

A spatially- and age-structured multispecies model, MICE, was also developed for the California Current Ecosystem (CCE) and was combined with MSE to assess the ecosystem and fishery-related performance of the HCR for the northern subpopulation of Pacific sardine (Punt et al. 2016b). The model simulated the dynamic of forage species (sardine, northern anchovy, and 'other forage') and two predators (brown pelicans and California sea lions in the Southern California Bight) and evaluated the impacts of variable availability of forage species on those predators. Scenarios on how bottom-up forcing impacts forage species were also developed using information on variation in the prey biomass from scale deposition data; those scenarios were used for hypothesis tests.

To assess the performance of the HCRs in relation to predators the model reported performance metrics for each predator species showing the following:

- the mean number of mature animals relative to carrying capacity,
- the probability that the number of mature animals drops below half of carrying capacity, and
- the probability that the number of mature animals drops below one-tenth of carrying capacity.

The model used sensitivity tests as a way to address shortcoming stemming from the fact that there were substantially fewer data for the predators and therefore, key parameters such as those related to productivity could not be estimated.

Through sensitivity analysis, the model identified predators that were more vulnerable to the availability of forage fish modelled and defined the conditions (e.g. forage species declines) that could put them at risk; e.g. lead to significant declines in reproductive success. This can provide useful thresholds for when fisheries managers decide on catch quotas for those forage species.

The results also highlighted key factors influencing the predators' status such as

- The way in which prey populations impact predator numbers (reproduction and/or survival)
- The extent to which prey populations are driven by environmental factors.

To better understand those factors the authors highlighted the importance of monitoring predators' diets and their survival rates; such data will help reduce uncertainty in the findings of this kind of models.

c) <u>Use of multispecies model for stock assessment and fisheries management advice -application</u>

Hollowed et al. (2000) used a catch-age stock assessment model that accommodated predation mortality to assess the status of the Gulf of Alaska walleye pollock. The model simulated predation from 3 species on pollock as an additional fishing mortality to explore the effect of assumptions about functional feeding responses and uncertainty in predator biomass on stock assessment results. The addition of predation mortality is an important component as studies highlight predation as the main source of mortality for pollock in the Gulf of Alaska. This addition of a mortality component led to higher estimates of total mortality, which varied depending on the age, than those found with conventional single-species stock assessment models.

Similarly, Van Kirk et al. (2012) added predation in a multispecies age-structured assessment model used to assess the status of arrowtooth flounder, Pacific cod, and walleye pollock in the Gulf of Alaska by adding two more species that prey on the original 3 species (expanded model). That created a model that explicitly accounted for species interactions affecting the abundance of the assessed species (founder, cod, and pollock). In addition to the standard catch and abundance indices the model was also fit to stomach content data to inform model estimates of predators' consumption of the 3 species. The analysis highlighted the correlation between survey catchability and residual mortality[1] (M1) which created problems with model convergence and presented a possible way to address that challenge. Their results showed that incorporation of predation led to changes in the trophic structures and predation linkages that the model without predation predicted. The expanded model captured the effects of cohort-specific predation in the structure of the populations but also showed that there were limitations in how well the model fit the data; i.e. improved catch and survey fits were achieved at the expense of the quality of the model fit to predation mortality data.

The results from both models were used in the 2017 stock assessment of walleye pollock in the Gulf of Alaska to calculate natural mortality including predation mortality at different ages. These mortality estimates were then used as input to a single-species stock assessment model[2].

A three-species stock assessment for walleye pollock, Pacific cod and arrowtooth flounder was also used for the Eastern Bering Sea (EBS), Alaska recently to provide estimates of current status of the stocks (Holsman et al. 2016b). The results of the analysis built on previous work (Holsman et al, 2015; described in the previous section) were also compared to those found with models that did not include trophic interactions (single species models). The analysis used a multispecies statistical catch-at-age model that combined catch-at-age assessment modelling with multispecies virtual population analysis. The model (CEATTLE, for Climate-Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics) included temperature-dependent von Bertalanffy weight-at-age functions and temperature-specific, bioenergetics-based predation interactions. To find biological reference points of relevance to management, a proxy for *B40%* was estimated. This was done by projecting the model under no fishing (simultaneously for all three species), and then projecting it under fishing to iteratively solve for the harvest rate that results in an average of 40% of unfished biomass in the last 5 years of the projection. Some of the key points from this work are:

- The multispecies model compensated for elevated predation mortality on younger age classes by increasing estimates of recruitment. Thus, the multispecies model is

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[1] *This analysis separates natural mortality into a variable predation mortality and a residual natural mortality term.*

[2] https://www.afsc.noaa.gov/REFM/Docs/2017/GOApollock.pdf

- expected to lead to higher recruitment estimates than those from the single-species model, and that difference is more profound for species with high predation rates.
- MSCAA models may be most useful for species that exhibit strong trophic interactions (predator and prey species) or contrasting management or biological constraints that require simultaneous evaluation
- The model estimates TAC but in a multispecies context so, its results provide reference points that are in line with information needed for decision making.
- The results could also be used in single species stock assessments, for example, the estimated natural mortality from the multispecies model which includes predation mortality could be used as input to single species models.

d) How multispecies considerations are captured in Fisheries management and quota setting

A primary route currently used to feed multispecies model outputs into fisheries management is through the Fishery Ecosystem Plans that many of the Fisheries Management Councils have being preparing.

In areas such as Alaska, multispecies models also help define parameters that are used in stock assessments such as predation mortality[1] and answer questions related to multispecies interactions. The assessment of walleye pollock in the Bering Sea is an example of presenting results from multispecies models in the stock assessment report that supports management decisions[2]. The report presents estimates of reference points (MSY-related) from both single species and multispecies models and there is a full description of the multispecies assessment in a supplement that is part of the report[3]. The multispecies assessment includes 3 species, walleye pollock, Pacific cod, and arrowtooth flounder and calculates the harvest rate that leads to 40% of unfished biomass with the constraint that spawning is always greater than 35% of unfished biomass[4]. Its results highlighted that the level depletion for the calculated harvest rate will be different for each of the 3 species and it will also differ depending whether a single species or multispecies model is used to calculate the depletion.

Similarly, the stock assessment report for walleye pollock in the Gulf of Alaska presented to the FMC includes results from an ECOPATH model to examine how natural mortality will be affected by different components of the ecosystem and the role of fishing mortality[5]. Through this work food web links have been highlighted; for example, it was shown that declines in its population will lead to declines in halibut and sea lions. Effects of predation were also examined with key predators

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[1]*Bering Sea fishery Ecosystem plan 2018.* https://www.npfmc.org/wp-content/PDFdocuments/membership/EcosystemCommittee/Meetings2018/DRAFT_BSFEP.pdf

[2] https://www.afsc.noaa.gov/REFM/Docs/2017/EBSpollock.pdf

[3] https://www.afsc.noaa.gov/refm/stocks/plan_team/2017/EBSmultispp.pdf

[4] *This model is very similar to the Holsman et al 2016 which was described in the previous section and therefore, it is not covered in detail here.*

[5] *This material is part of the stock assessment and fishery evaluation (SAFE) report prepared for the FMC. https://www.npfmc.org/safe-stock-assessment-and-fishery-evaluation-reports/*

being identified while fishing mortality was presented in relation to predation mortality to provide context[1].

As mentioned already, for areas such as the Bering Sea, these ecosystem considerations will be in addition to a broader/empirical approach that is in place already and sets a cap in the total catches of the species complex that can be taken each year.

Multispecies modelling is also used to develop management testing scenarios for the Integrated Ecosystem Assessment (IEA) Report which is produced as part of the NOAA IEA programme[2] and is also made available to the FMC. These documents are part of input to management discussions but there is not an agreed/quantitative way in which the findings of such research are used to adjust quotas or the overall management of a fishery. Instead, such information is considered in the process of adopting TACs through informal steps. For example, in the Alaska region, those steps involve interdisciplinary experts serving on the Council's FMP teams and Scientific and Statistical Committee (SSC) and consider ecosystem factors in the recommendation of the annual ABCs. Furthermore, an Ecosystem Considerations report is presented annually to the SSC and the Council before setting quotas on groundfish. Presenting contextual ecosystem information just before the review of species-specific harvest recommendations is seen as best practice as it facilitates discussion on ecosystem status and observations that might not be captured in the single-species stock assessment and allows for rapid incorporation of such information into the decision making[3]. Such observations could relate to temperature (e.g. patterns outside previously observed values) or unusual trends in species that are somehow connected to the assessed ones.

Another use of multispecies and ecosystem modelling is to support Environmental Impact Assessments that need to accompany fishery management measures proposed by the FMCs. For example, the Atlantis California Current Ecosystem Model was used to simulate the ecosystem effects of the range of harvest policies that were part of the Pacific FMC's 2015-2016 Harvest Specifications and Management Measures (NMFS 2015). The Atlantis model calculated the values of 10 metrics (e.g. ratio of target species biomass to catch, total system biomass, and mean trophic level of biomass) for each of the management alternatives. The value of each of those metrics was also presented relative to its value in a benchmark management scenario to provide standardised results.

3.- Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR)

a) Framework for multispecies management

The Convention that underpins CCAMLR explicitly accounts for multispecies interactions and advocates for an ecosystem approach. In particular, the convention requires that any harvesting and associated activities be conducted in accordance with the following principles[4]:

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[1] https://www.afsc.noaa.gov/REFM/Docs/2017/GOApollock.pdf

[2] https://www.integratedecosystemassessment.noaa.gov/index.html

[3] https://www.npfmc.org/wpcontent/PDFdocuments/membership/EcosystemCommittee/Meetings2018/DRAFT_BSFEP.pdf

[4] https://www.ccamlr.org/en/organisation/camlr-convention-text#II

- Maintenance of the ecological relationships between harvested, dependent and related populations of Antarctic marine living resources and the restoration of depleted populations.
- Prevention of changes or minimisation of the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades.

Further, the Convention highlights the type of work that is needed to support a multispecies approach; specifically, it directs the Commission to facilitate research in Antarctic marine living resources and Antarctic marine ecosystem and to compile data on status and factors that affect both harvested and dependent or related species.

CCAMLR has established multiple scientific groups to support an ecosystem and multispecies focused approach; those groups cover Incidental mortality, assess trends in predator populations, and develop management advice on status of Antarctic marine ecosystems[1]. CCAMLR has also been running an Ecosystem Monitoring Program for almost 30 years (set up in 1989) that is collecting data about key life-history parameters of selected dependent species. The collection of the data is done following agreed Ecosystem Monitoring Standard Methods that specify how data should be collected and formatted for submission to the CCAMLR Secretariat and the procedures to use for data analysis[2].

Predators is a species group for which CCAMLR has adopted a multispecies approach to ensure that human activity does not compromise their status. This is because krill, the main target of fisheries operating in the CCAMLR region is a major food source for many predators in the area. The measures were put in place in early 1990s and consisted of setting a minimum krill biomass that needs to be maintained to ensure that there is sufficient food for predators. This restriction is part of decision rules for setting catch quotas for krill (and subsequently, other species) and represented an ad-hoc approach which recognises the importance of krill as prey and therefore sets biomass limits that are well above the 40-50% of unfished biomass that is often used in single species stock assessment. This interim strategy was needed given paucity of multispecies modelling work and data to support a more sophisticated process (Constable et al. 2000).

b) <u>Developments of research in multispecies and ecosystem modelling and use of multispecies approach for stock assessment and/or scientific advice</u>

Multispecies modelling to support scientific research and management in the CCAMLR region started in the 1990's but gathered momentum after 2000 with a number of scientific studies exploring possible multispecies models. To facilitate progress in this area a workshop on plausible ecosystem models for testing approaches to krill management was held in 2004 with the aim to review the approaches used to model marine ecosystems and explore plausible operating models for the Antarctic marine ecosystem[3]. The workshop brought together expertise from the CCAMLR community but also included external experts that were brought in to advise on important areas in which sufficient expertise was not available. The workshop helped spearhead ecosystem modelling for the CCAMLR area since existing model was used to identify the most appropriate modelling

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[1]*https://www.ccamlr.org/en/science/working-group-ecosystem-monitoring-and-management-wg-emm*

[2] *https://www.ccamlr.org/en/science/ccamlr-ecosystem-monitoring-program-cemp*

[3] *https://www.ccamlr.org/en/system/files/e-sc-xxiii-a4-appD.pdf*

approaches but also develop the blueprint that programmers could use to produce a framework within which plausible models of the Antarctic marine ecosystem could be simulated. The latter process produced several insights/recommendations and here, we list those that focuses on modelling multispecies interactions[1]:

- Important to consider both predator–prey as well as competitive interactions in multispecies models. Modelling competition will help understand whether prey surpluses caused by the removal of one predator can result in the expansion of another predator population
- Defining a wide range of possible predator–prey interaction is a good starting point but it may not be necessary to model all the interactions to provide a representative picture of how most energy flows through the food web.
- Care needs to be taken that the dynamics of any taxonomic group are not necessarily dominated by weak predator– prey links.
- If depth structuring is an important aspect of the trophic links simulated the sensitivity of ecological, environmental, or fisheries scenarios to the resolution in the trophic structure at different depths will need to be checked.
- Individual-based foraging models provide a more realistic approach but it is likely to be less efficient in a modelling context than functional response curves. Therefore, it is worth exploring whether, and under what conditions, the latter can be a satisfactory approximation of the former.

Since then models employed to study multispecies interactions have ranged from age aggregated or disaggregated prey-predator models[2,3] (Mori and Butterworth 2004) to elaborate trophic models such as the one presented by Pinkerton et al (2010)[4] and which included 38 trophic groups. Overall, the models developed aim to capture the interaction between prey and predators but also reflect a transition to a more spatially refined management approach and adoption of ecosystem-based concepts such as bioregions[5]. The multispecies analysis has been supported by research that is undertaken in parallel to improve the quality of concepts and parameters used in multispecies and ecosystem modelling (e.g. prey consumption, testing accuracy of surveys, movement assumptions, functional relationships)[6] (Hinke et al. 2017)

Prey-predator models are the models used more often in research focusing on marine resources in the CCAMLR area. Plaganyi and Butterworth[7] used a Spatial Multispecies Operating Model (SMOM) to explore possible subdivisions of catch limits for krill among small-scale management units (SSMU) in the Scotia Sea. The model used a modified surplus production model that accounts for

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[1] https://www.ccamlr.org/en/system/files/e-sc-xxiii-a4-appD.pdf

[2] https://www.ccamlr.org/en/wg-emm-14/51

[3] https://www.niwa.co.nz/sites/niwa.co.nz/files/emm-14-51.pdf

[4] https://www.ccamlr.org/en/system/files/science_journal_papers/01pinkerton-et-al.pdf

[5] https://www.ccamlr.org/en/wg-emm-06/37

[6] https://www.ccamlr.org/en/system/files/e-wg-emm-16-v2.pdf

[7] https://open.uct.ac.za/bitstream/item/21235/Plag%C3%A1nyi_A_spatial_multi_species_2007.pdf?sequence=1

consumption by predators to simulate the dynamics of krill and semi-annual time steps to update growth and transfer of krill between SSMUs. Four predator groups were also included in the model and their dynamics was described using a delay-difference model. The model was used in a Management Procedure (MP) approach to simulate the true dynamics of the system to test different options for subdividing quota under different assumptions about the dynamics of the populations. The analysis was able to show how improvements in data could lead to narrower probability envelopes associated with key process but also highlighted the number of assumptions that are needed to run the model.

A similar model (FOOSA) that accounted for fish movement and predation was also employed by Watters et al. (2013) to provide management advice and by Hill and Matthews (2013) to test the sensitivity of such models. The model was spatially disaggregated and used delay difference equations with an additional component for the interactions among prey, predators, and fishery to describe ecosystem dynamics and advise on spatial allocation of the Antarctic krill catch limit for the Scotia Sea. The model has a 3-month time step to represent seasons within years and the function used to describe time-specific per-capita potential consumption of prey can model both Holling Type II and Type III functional responses. The model includes stochasticity to capture uncertainty in key processes and expresses reference points for predators in terms of comparable no-fishing trials. This way, the results show the impacts of fishing without the confounding effects of other drivers such as climate of past harvesting. The software used for this analysis is freely available as an R package[1]. Relevant findings and approaches they followed that might be of use in our study are as follows:

- They addressed uncertainty by simulating extreme scenarios that aimed to define plausible limits on key processes.
- Their work highlights the importance of research being supported by a community of experts and stakeholders that can define key processes and plausible limits to capture in the model and help develop an approach to communicating uncertainty.
- To make communication with decision-makers easier, they used objectives based on reference points that represented targets (e.g. full utilisation of quota) or undesirable conditions (min depletion of 75%). This way, policy makers were presented with scenario-averaged risks of failing to meet these objectives.
- This simple representation of the performance of different management measures highlights trade-offs that might be needed to achieve an acceptable level of risk. Furthermore, average-based estimated risks should be relatively insensitive to occasional predictions of extreme outcomes.
- In engaging with stakeholders, it might be necessary to present a range of contrasting risk metrics and their influence on the results to elicit their opinions
- The study also identifies unclear management objective as an important source of uncertainty affecting the use of ecosystem models.

In addition to the insight from Watters et al (2013), the study by Hill and Matthews (2013) highlighted the following:

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[1] *The model is referred to as KPFM or FOOSA and the code is available on-line: https://swfsc.noaa.gov/aerd-kpfm/*

- The use of the model to evaluate catch allocation options illustrated tensions between the ideal of well-constrained models and the reality of ecosystem-based management which is characterised by sparse data, complex structures, and high uncertainty.
- The increased complexity that characterises multispecies model leads to accumulation, and possible multiplication, of uncertainties and increased difficulty in interpreting results
- More clarity about management objectives should provide better guidance about appropriate output statistics to use to assess performance. The right choice of statistics will also help with providing an objective assessment of whether sensitivity significantly influences critical outputs.

d) How multispecies considerations are captured in Fisheries management and quota setting

The CCAMLR Convention had an ecosystem focus from the very beginning and that facilitates and requires the incorporation of multispecies considerations into decision making. To reinforce that focus, the Scientific Committee in CCAMLR has taken steps early on to ensure that it works closely with decision makers to maintain effective communication and strengthen the uptake of scientific advice into management[1]. Information from multi species and ecosystem modelling is presented to the Commission every year in the annual scientific report. The report provides responses to specific management-related questions as well as latest developments in research and trends such as latest environmental trends from the ecosystem monitoring programme. Even when there are gaps in scientific knowledge, CCAMLR applies a precautionary approach to ensure that catches will not have adverse ecosystem effects. The requirement for maintaining krill biomass at 75% of its unexploited size is an example of precautionary action to account for multispecies interactions that was taken even though robust models were not available at that time to underpin the decision.

The model FOOSA, described in the previous section, is as an example of how the outcomes of multispecies modelling have been captured and influenced management decisions[2]. In 2009, WG-EMM used the FOOSA ecosystem model to assess the impacts of different harvest levels on krill, krill predators and the krill fishery. The WG agreed that the results showed the specification of a trigger level of 620 000 tonnes for the krill fishery was not as cautious as might have been thought at the time this specification was agreed. The WG recommended that the Scientific Committee review the trigger level and its application. Following this recommendation, the Scientific Committee agreed that the results consistently indicated that if the trigger level catch was concentrated on a small part of the overall fishing area, this would increase the risk of significant adverse impacts on dependent predators[3]. It also noted that distributing the catch according to the historical fishing pattern poses higher risks than other methods to distribute catch.

Based on the advice of the Scientific Committee the Commission agreed on the need to spatially distribute the krill fishing effort into smaller areas (Subareas) to avoid large catches being taken from

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[1] *http://archive.ccamlr.org/pu/E/e_pubs/am/text.pdf*

[2] *This part of the text is based on material provided by CCAMLR (Keith Reid, pers. comms.)*

[3] https://www.ccamlr.org/en/system/files/e-sc-xxviii.pdf *Annex 4, paragraphs 3.122 and 3.126*

localised areas before the trigger level is reached. That led to the adoption of a new conservation measure to distribute the trigger level in the krill fishery amongst Subareas. The measure was initially agreed for a period of 2 years and has been reviewed and re-adopted twice since its original adoption.

ANNEX III: DIAGNOSTICS OF THE SELECTED VERSION OF GADCAP AFTER UPDATES AND IMPROVEMENTS.

Model results and diagnostics

- 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 6.6-1*). The similarity obtained for the estimated and observed commercial catches (*Figure 6.6-2*) was due to the high weight assigned to these likelihood components.
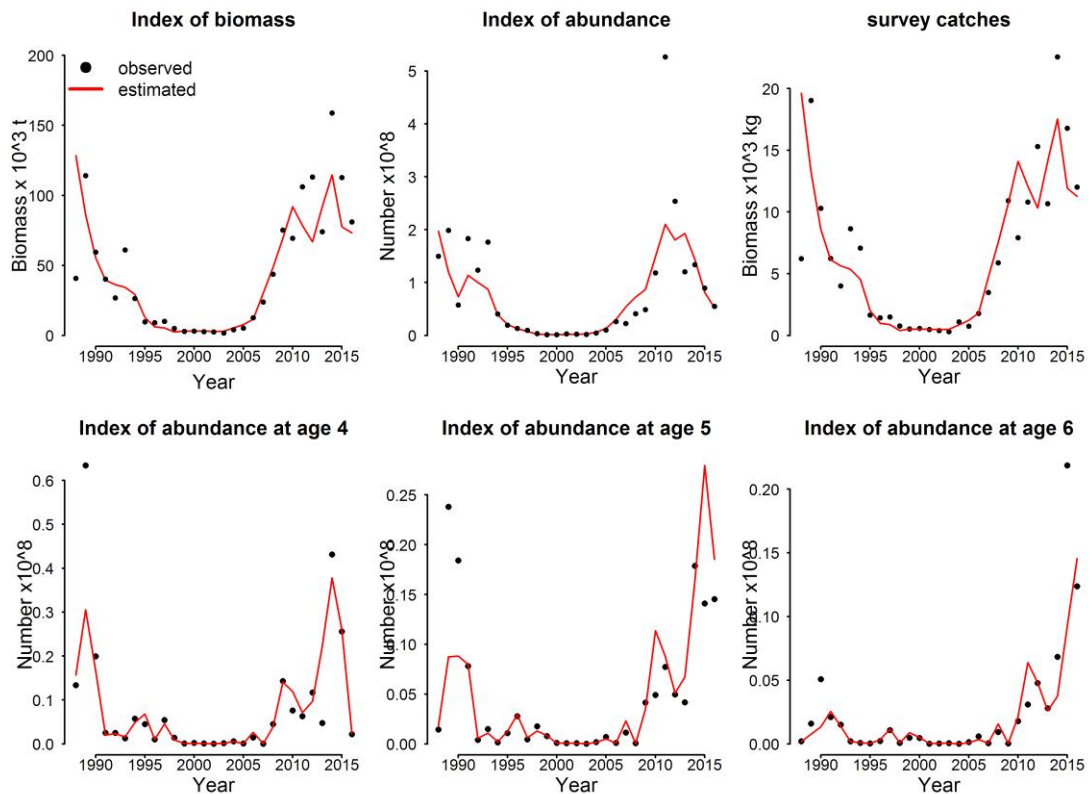
Figure 6.6-1.- Cod survey indexes of biomass, abundance and abundance of individuals at ages 4, 5 and 6. Total cod catches in tones during the EU Flemish Cap survey are also shown. Red lines are the estimated values with GADGET versus black points which represent the observed data.
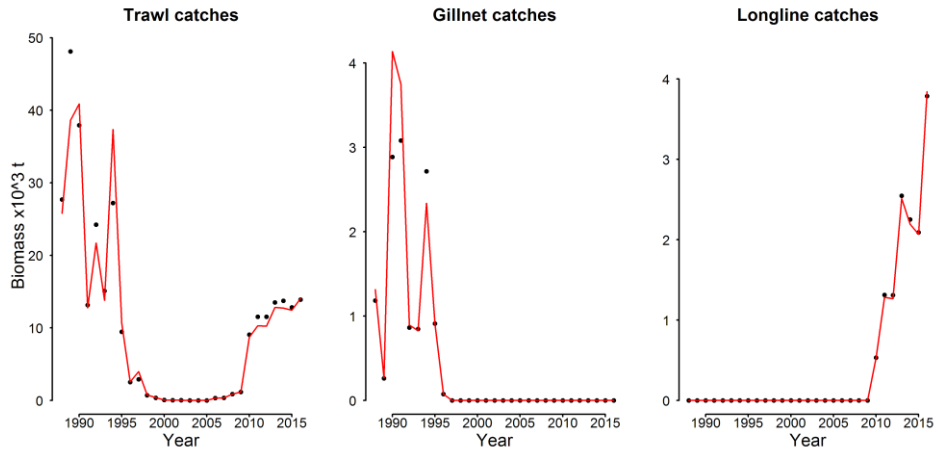
Figure 6.6-2.- Total cod catches in tones by the international trawl, longline and gillnet fleets. Red lines are the estimated values with GADGET versus black points which represent the observed data.

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 3.2-15, 3.2-16, 3.2-17, 3.2-18 and 3.2-19 respectively).
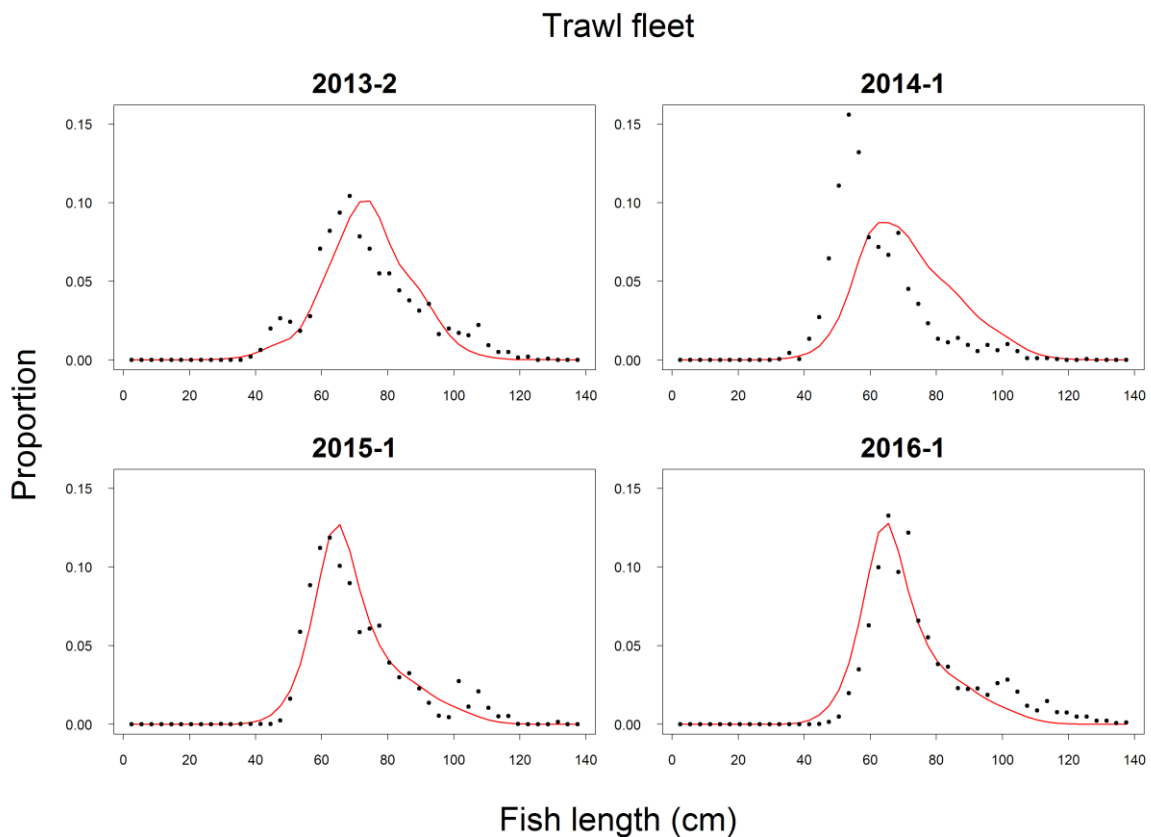
Figure 6.6-3.- Size distribution (in proportion relative to 1) of cod catches by the longline fleet. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 refers to winter of 1988). Red lines are the estimated values versus black points which represent the observed data.
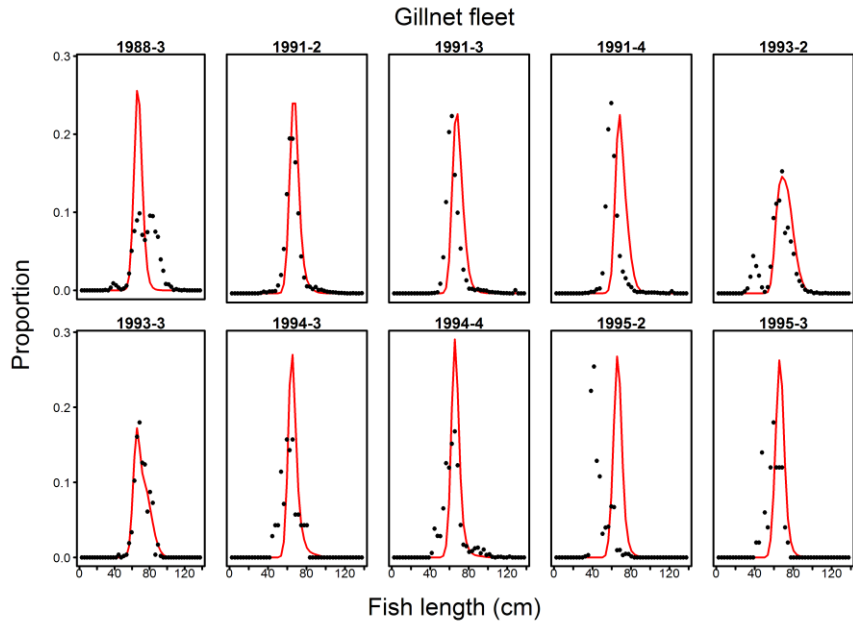
Figure 6.6-4.- Size distribution (in proportion relative to 1) of cod catches by the gillnet fleet. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 refers to winter of 1988). Red lines are the estimated values versus black points which represent the observed data.
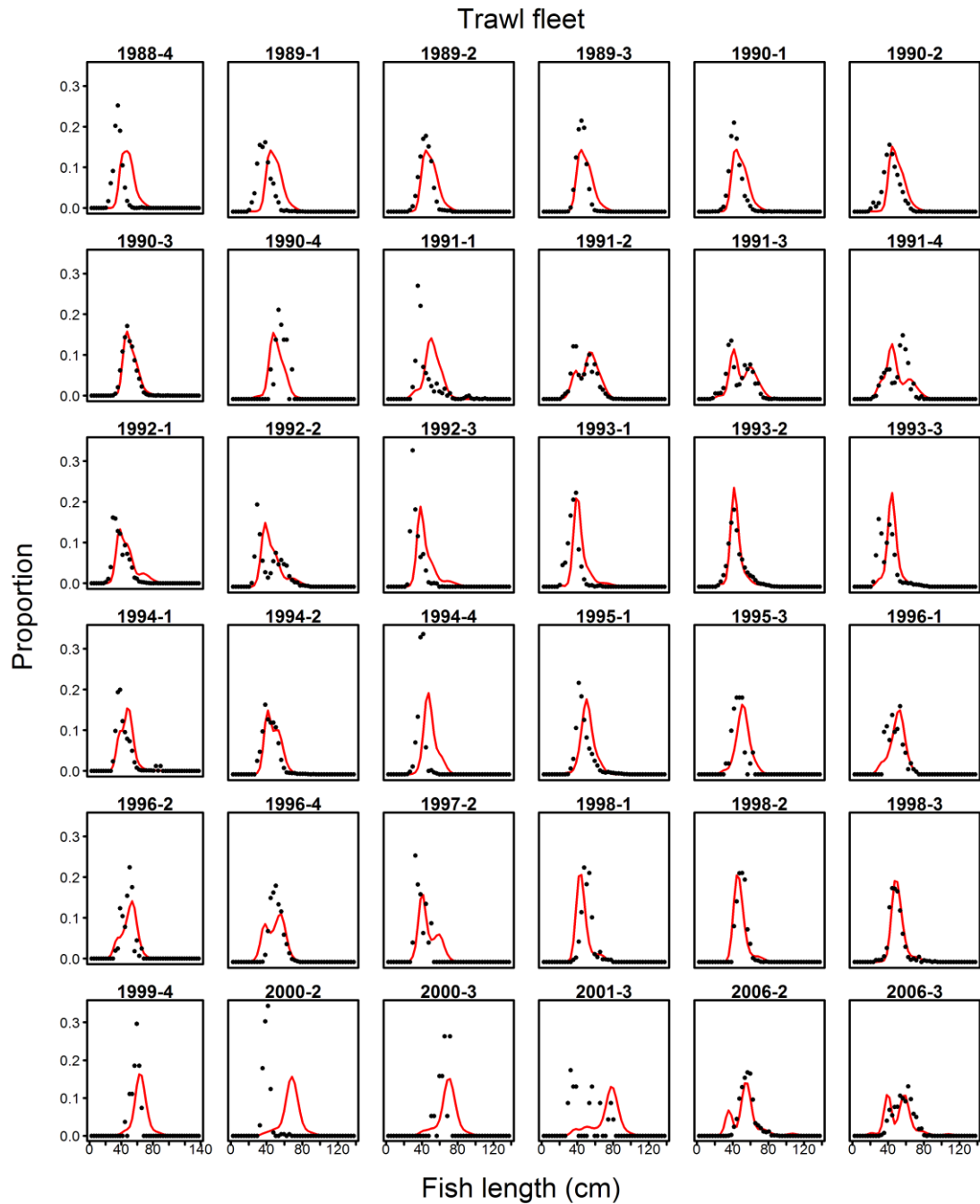
Figure 6.6-5.- Size distribution (in proportion relative to 1) of cod catches by the commercial trawl fleet over the years 1988-2006. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 refers to winter of 1988). Red lines are the estimated values versus black points which represent the observed data.
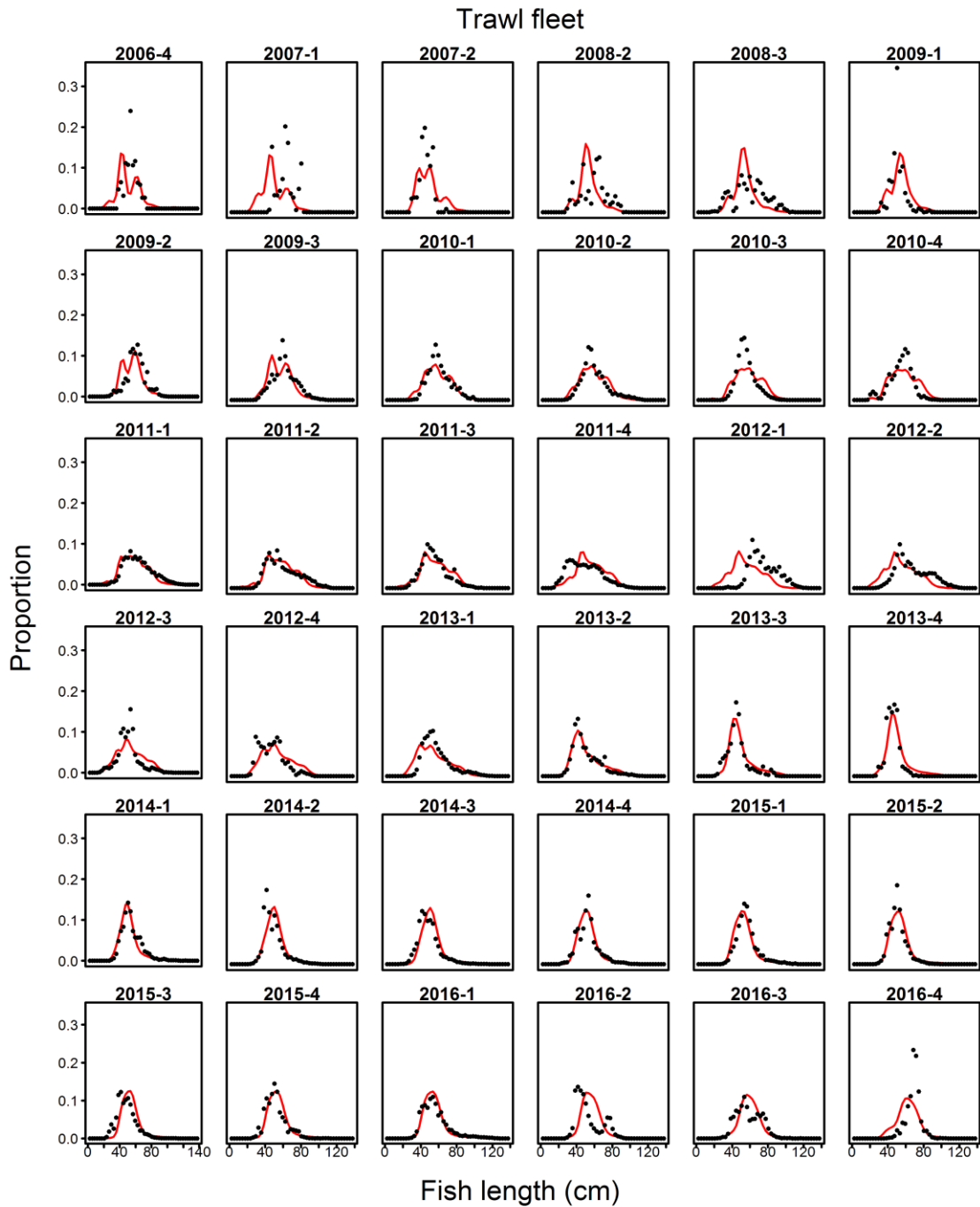
Figure 6.6-6.- Size distribution (in proportion relative to 1) of cod catches by the commercial trawl fleet over the years 2006-2016. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 refers to winter of 1988). Red lines are the estimated values versus black points which represent the observed data.

The survey length distribution estimated by the model captured properly the observed size distribution, specially in those years of high abundance of recruits, like 1991, 2005-2006 and 2010-2016.
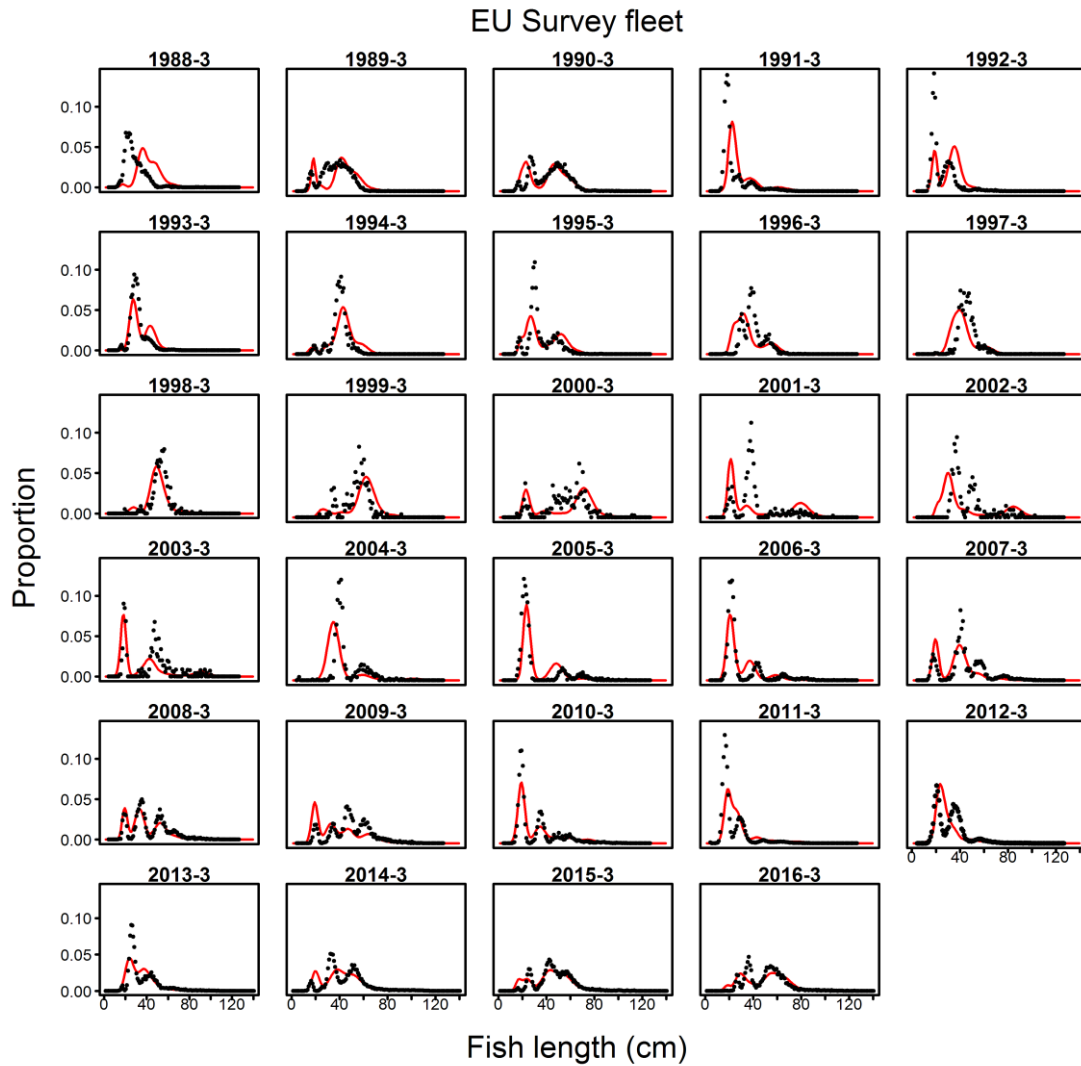
Figure 6.6-7.- Size distribution (in proportion relative to 1) of cod catches by the EU survey fleet. The label in each subpanel represents the year (Years: 1988 to 2016). For this fleet the season is always 3 (summer), when the survey takes place. Red lines are the estimated values versus black points which represent the observed data.

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 (Figure 6.6-8), with the exception of year 1994.
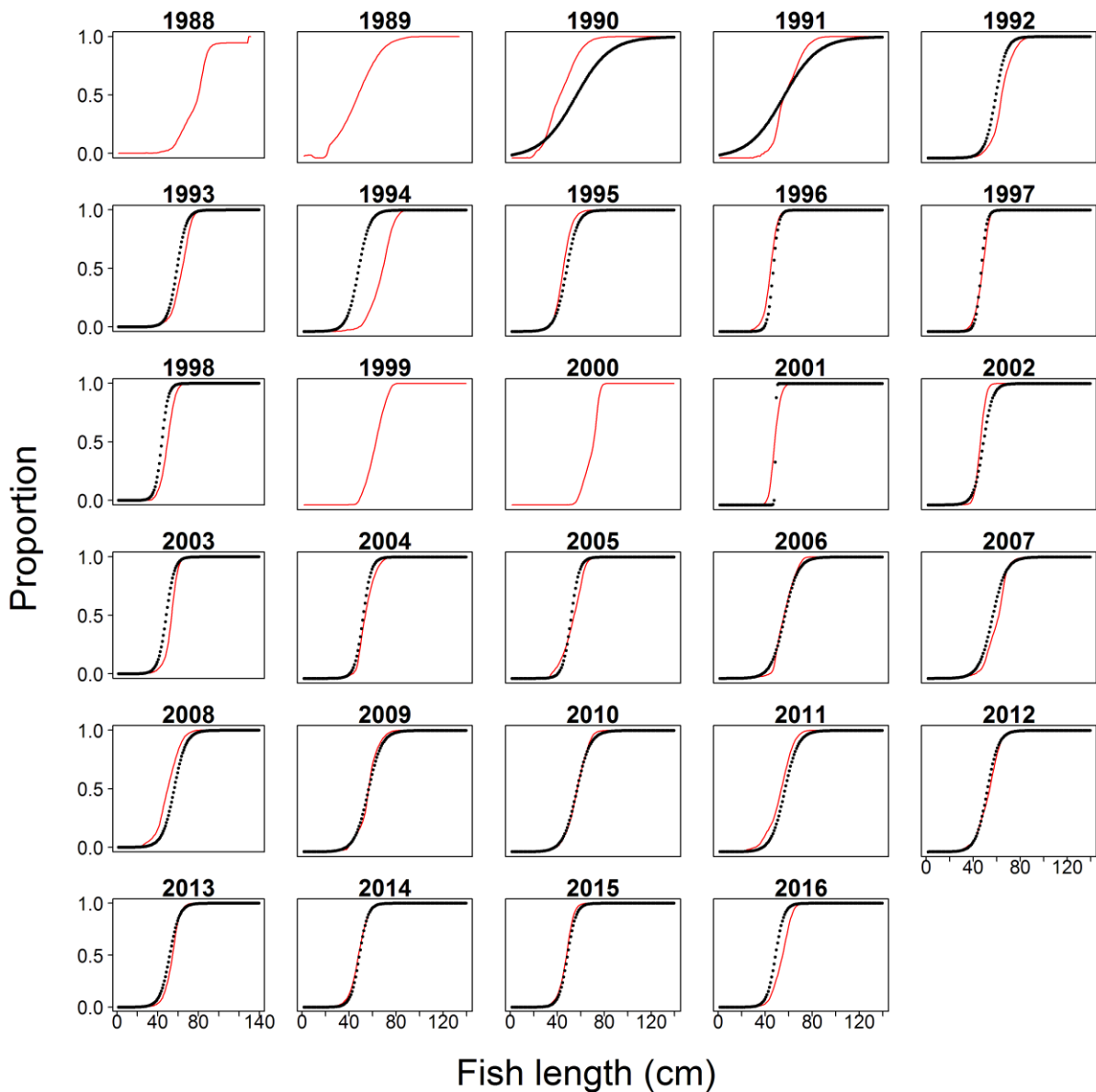
Figure 6.6-8.- Cod maturity ogives as probability, relative to 1, of being mature as a function of fish length. Estimated probabilities by the fit model in red color lines; Observed proportions in black color points.

- 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 6.6-9). However, in this stock there was a higher deviation from the observed biomass and abundance indices in some years between 2005 and 2011.
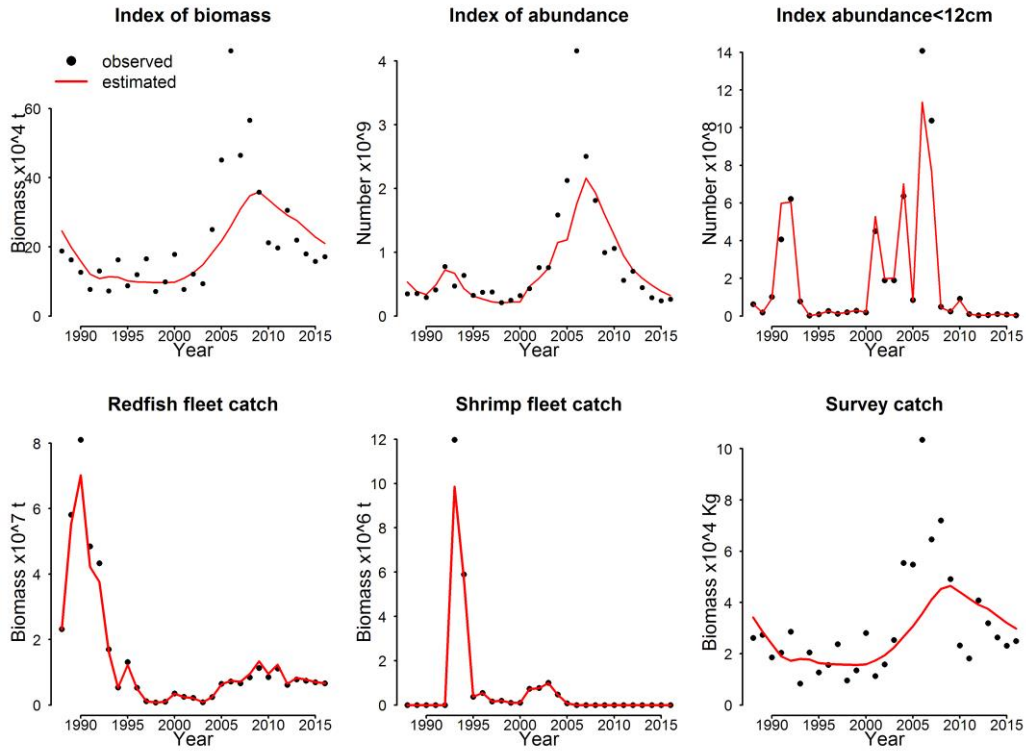
Figure 6.6-9.- Redfish survey indexes of biomass, abundance and abundance of individuals smaller than 12 cm (from left to right in the first row). Total redfish catches in tones by the international redfish trawl, shrimp trawl (as by-catch) fleets.
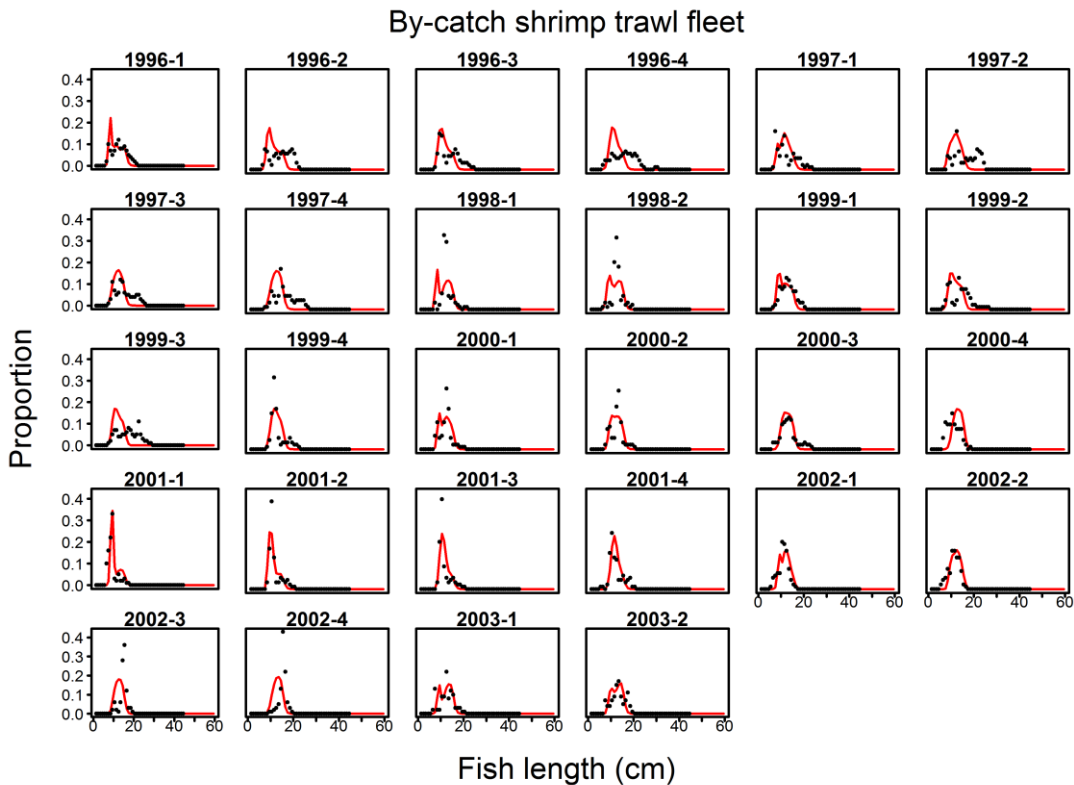
Figure 6.6-10.- Size distribution (in proportion relative to 1) of redfish by-catches in the shrimp trawl fleet. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 is winter of 1988). Red lines are the estimated values versus black points which represent the observed data.

The size distribution of the redfish by-catch from the shrimp trawl fishery was well fitted by the model (Figure 6.6-10). 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 3.2-23 and 3.2-24), like the EU survey fleet size distribution (Figure 6.6-13).
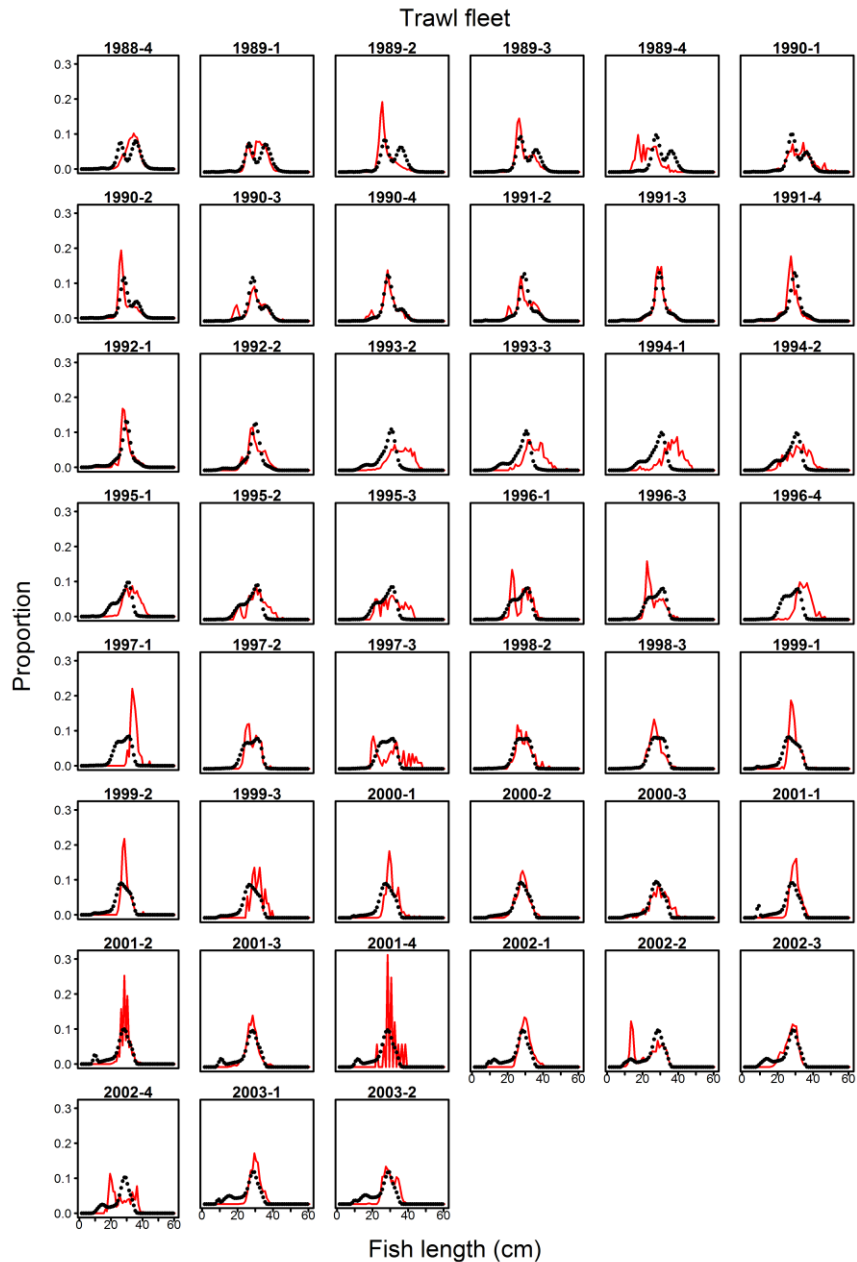
Figure 6.6-11.- Size distribution (in proportion relative to 1) of redfish catches in the redfish trawl fleet over the years 1988-2003. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 is winter of 1988). Red lines are the estimated values versus black points which represent the observed data.
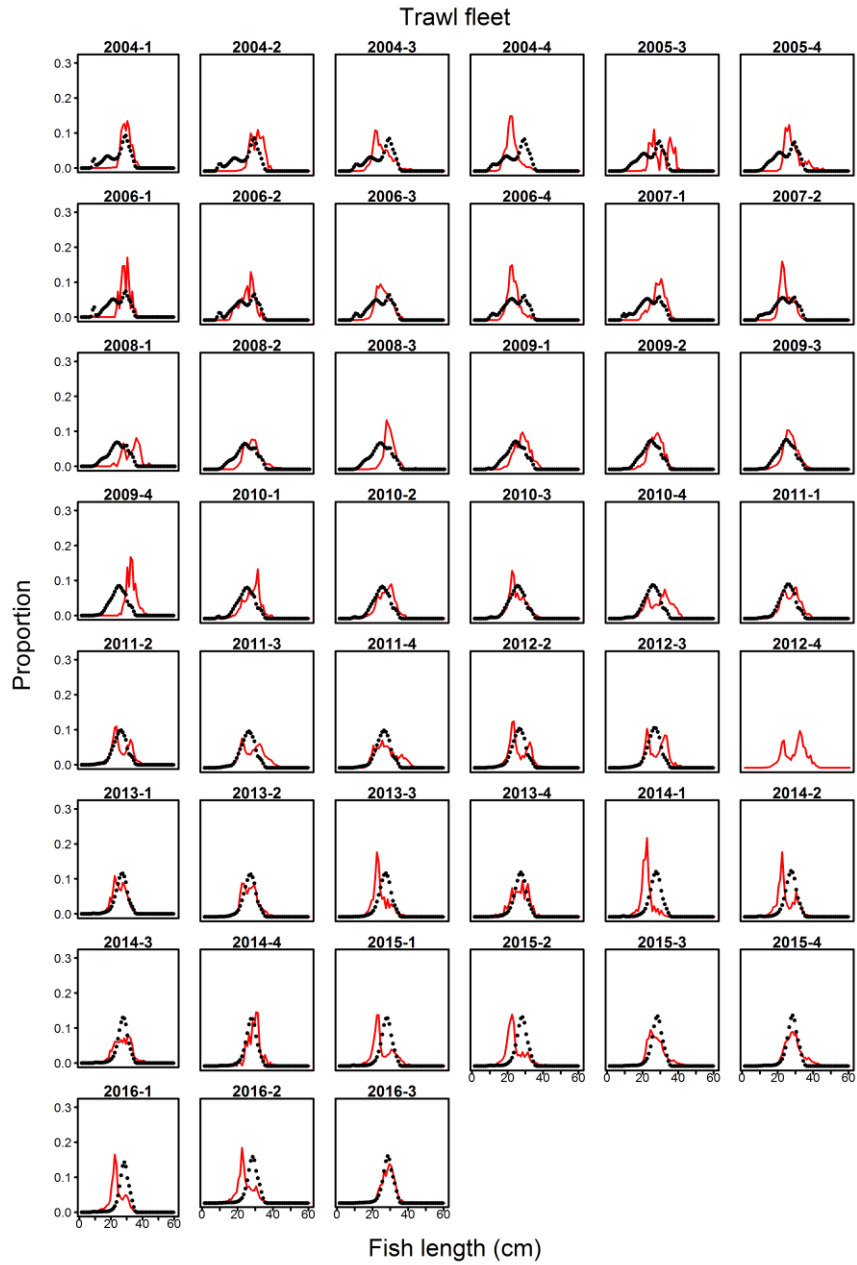
Figure 6.6-12.- Size distribution (in proportion relative to 1) of redfish catches in the redfish trawl fleet over the years 2003-2016. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 is winter of 1988). Red lines are the estimated values versus black points which represent the observed data.
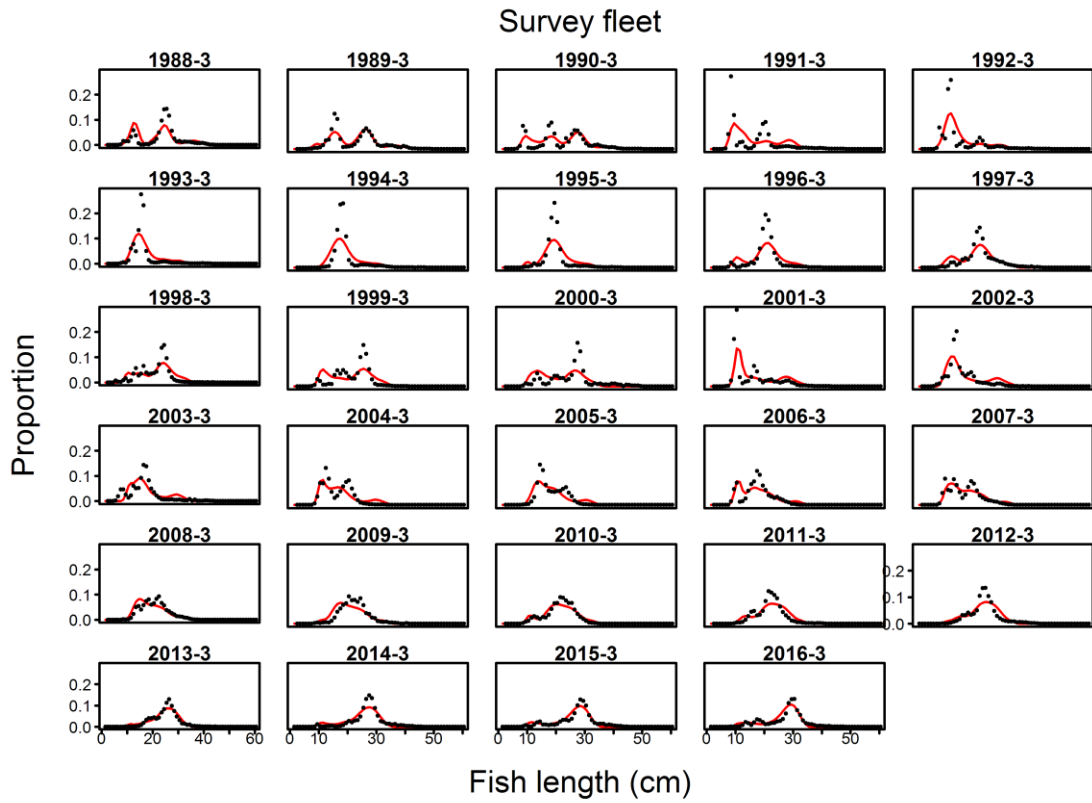
Survey fleet

Figure 6.6-13.- 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.

As shown in figure 3-40 the observed proportion of mature individuals was well fit by the model.
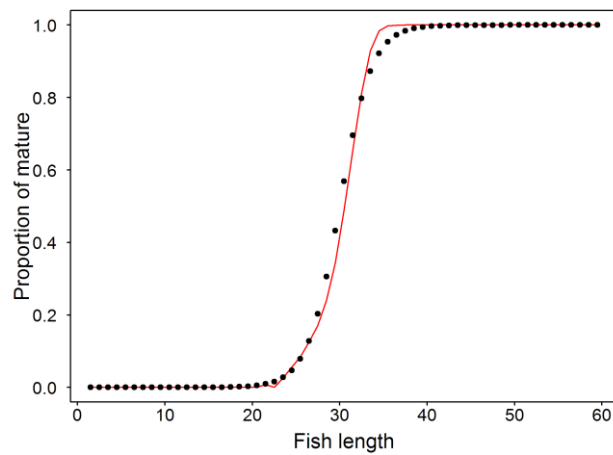
Figure 6.6-14.- Estimated (red line) and observed (black points) proportion by length of mature female individuals in the redfish stock.

- 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 3.2-26). 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.
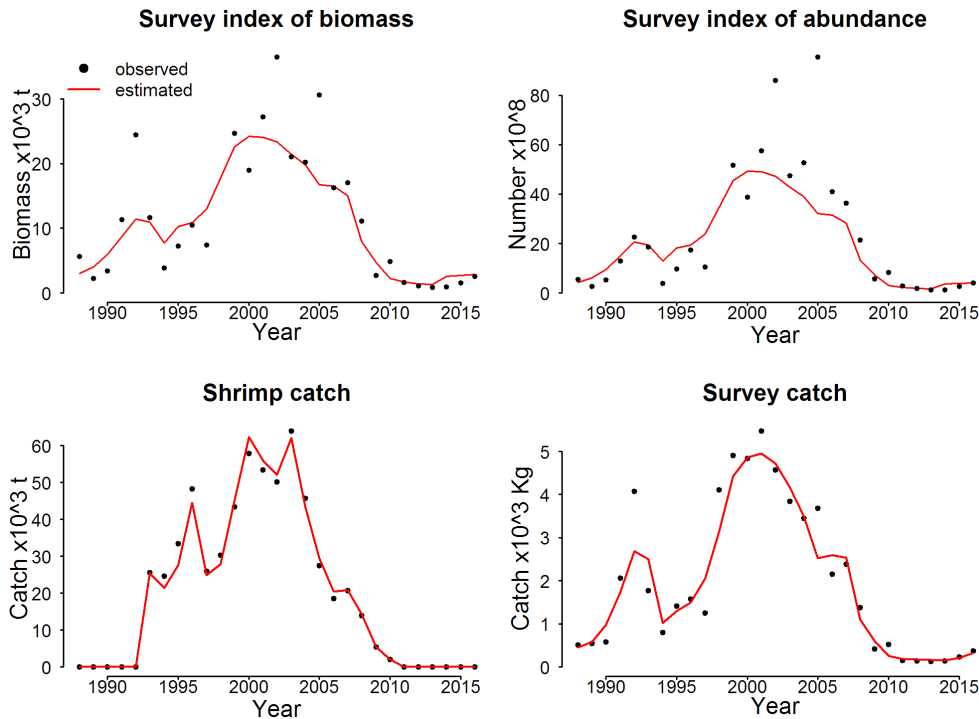
Figure 6.6-15.- Shrimp survey indexes (swept area method) of biomass (upper-left panel) and abundance (upper-right), and catch in tones by the international trawl fleet (bottom-left), and in kg for the EU survey fleet (bottom right).

The size distribution of the survey fleet (Figure 3.2-27) despite was globally well fitted, showed some deviations from the observed values in years 1988-1989 and 2011-2015. The observed size distribution for the commercial trawl fleet was in general well fit by the model (Figure 3.2-28). 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.
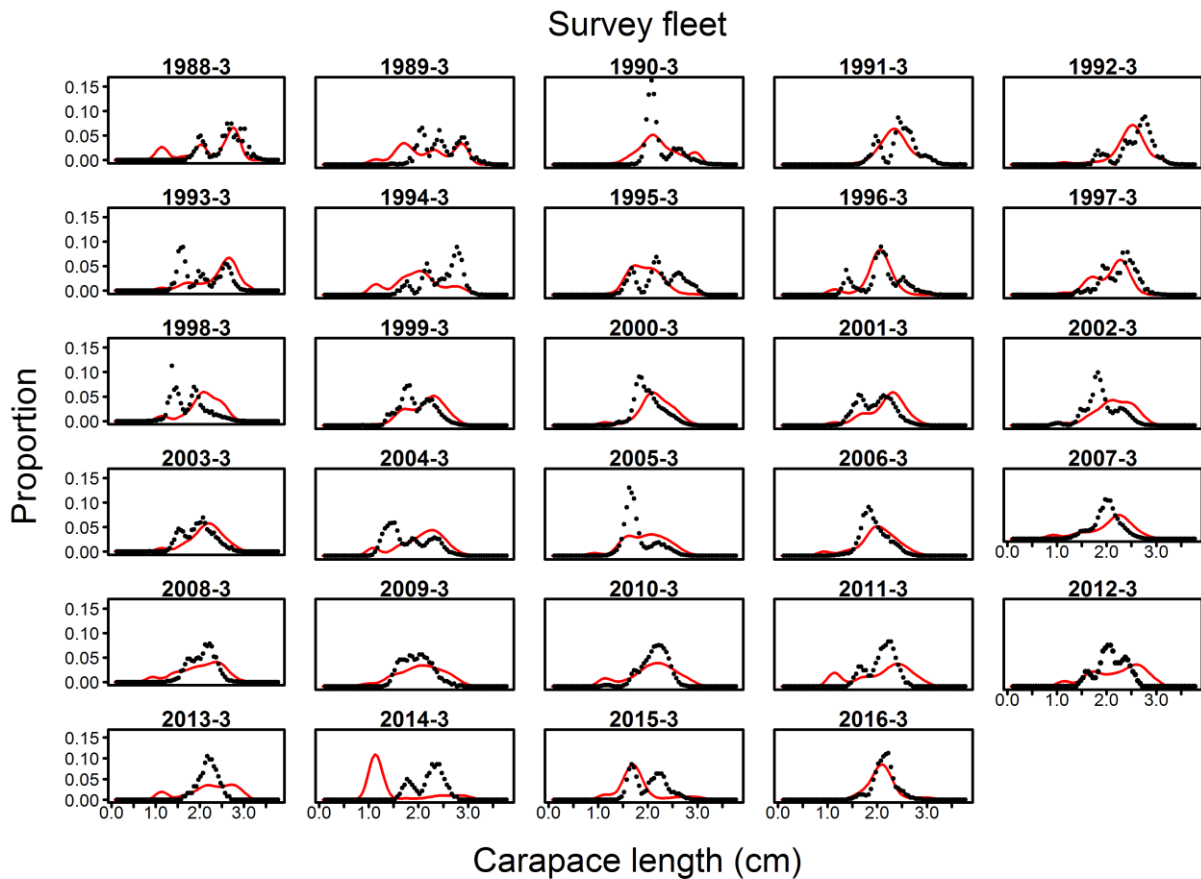
Figure 6.6-16.- Distribution by carapace length (in proportion relative to 1) of shrimp in the survey fleet. The label in each subpanel represents the year (Years: 1988 to 2016). For this fleet the season is always 3, when the survey takes place. Red lines are the estimated values versus black points which represent the observed data.

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 3.2-28), 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.
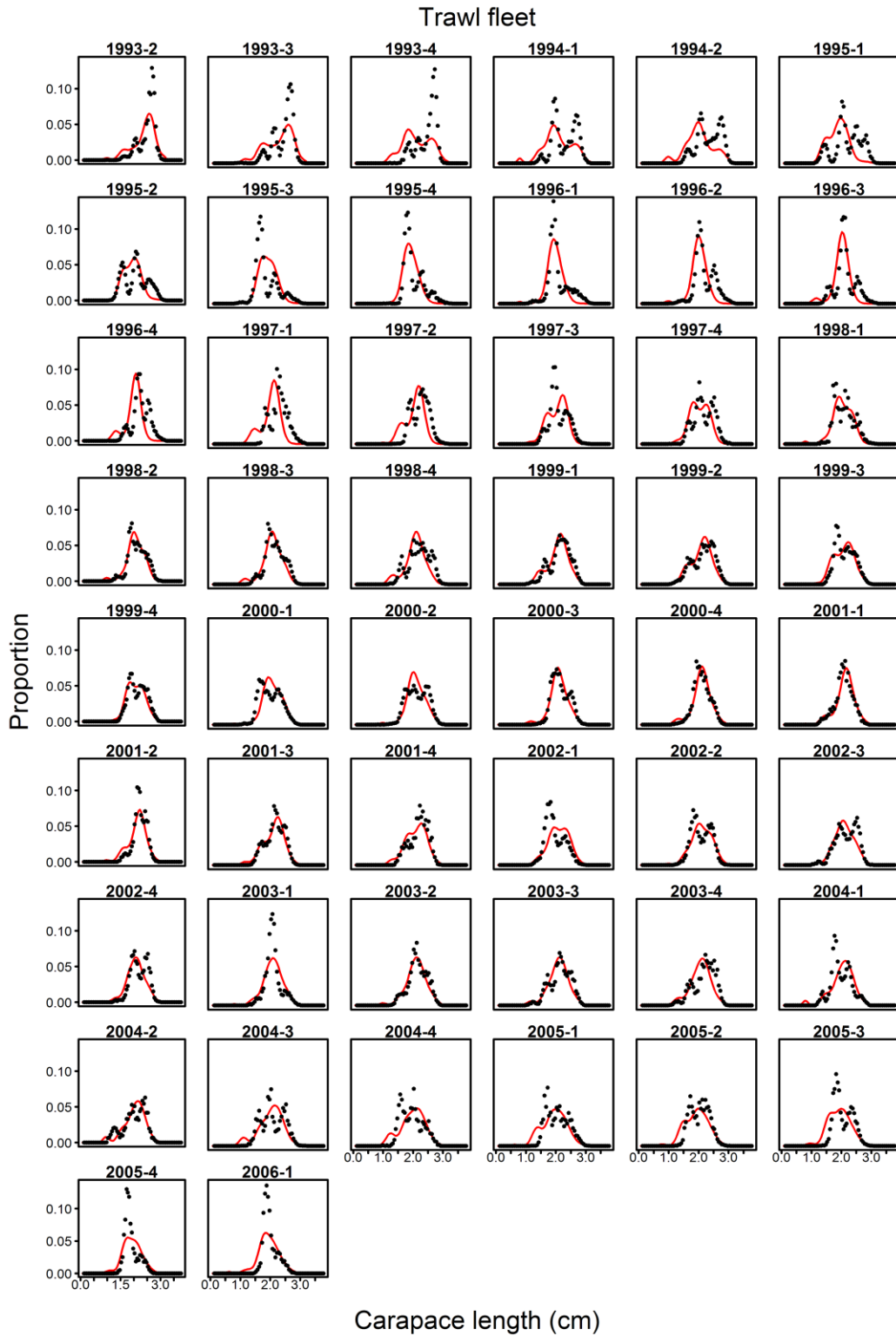
Trawl fleet

Figure 6.6-17.- 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.
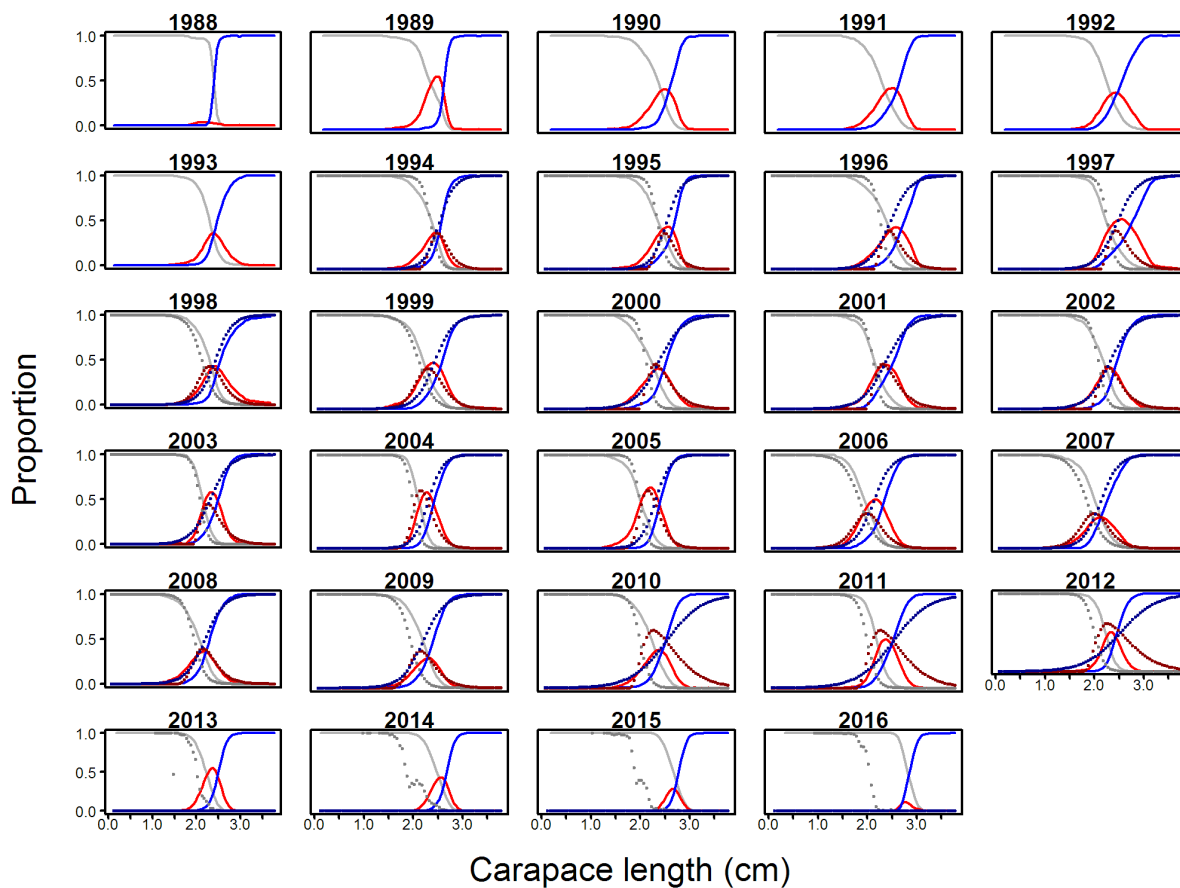
Figure 6.6-18.- Shrimp sex change and maturity ogives as probability, relative to 1, of being male (grey color), female primiparous (red color) and female multiparous (blue color) with carapace length (in cm). Estimated probabilities by the fit model are represented by continuous lines while the observed proportions are represented by points.

- Diet composition

The model estimated diet fit very closely the observed one, both for cod (Figure 3.2-31) and redfish (Figure 3.2-32). 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 2010-2016.

The estimated percentage of the non-modeled prey in the diet of both cod and redfish was noteworthy. Hyperiids, euphausiids and chaetognaths were very important prey for both predators; while copepods were a main prey only for redfish. Wolffishes were a very important prey in the diet of large mature cod, until late 1990s. Pelagic fishes (mostly myctophids) had a prominent role as fish prey in immature, but especially in mature redfish.
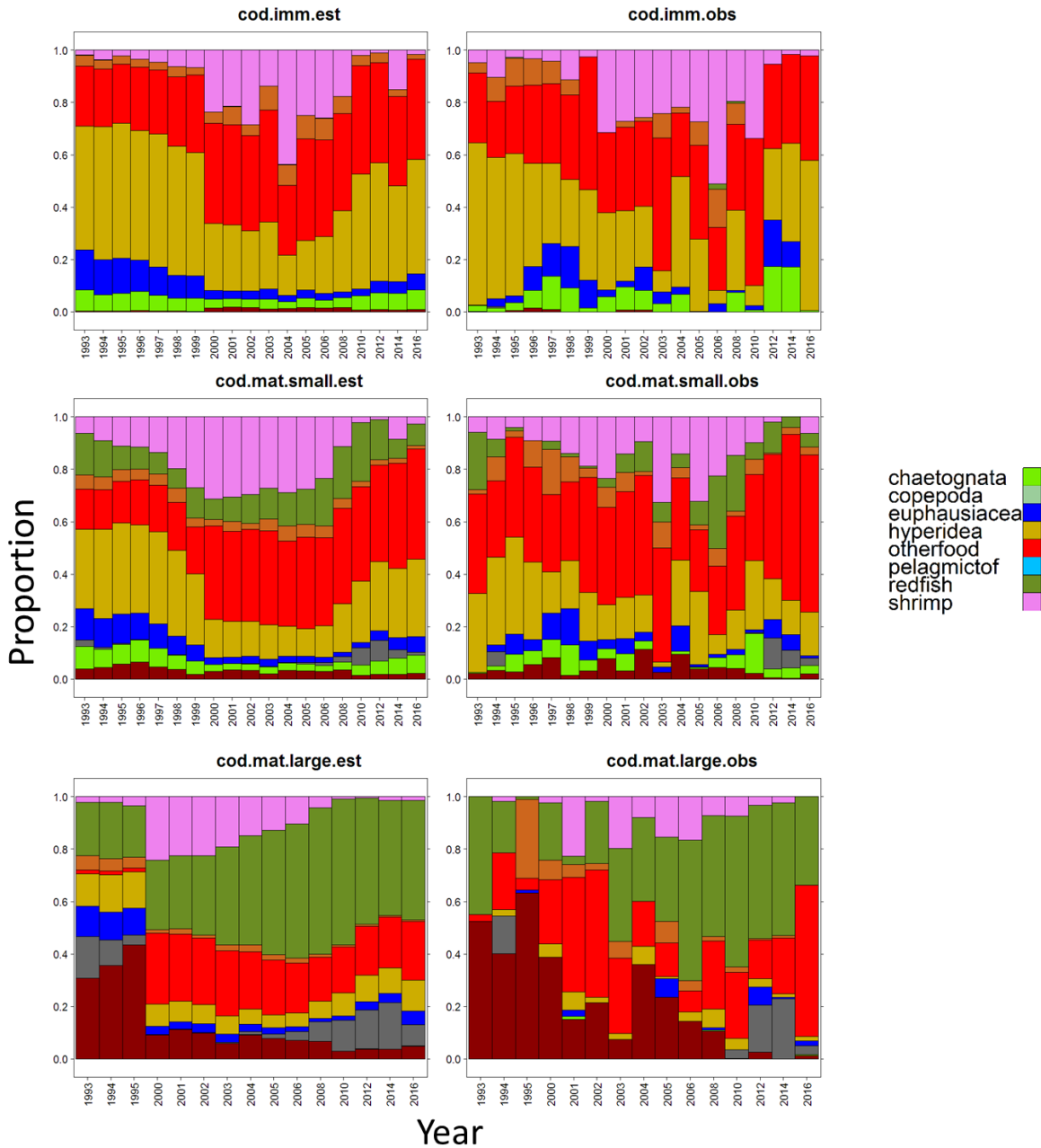
Figure 6.6-19.- Model estimated diet (left column) and observed diet during the EU survey (right column) for immature cod (cod.imm), small mature cod (<85cm; cod.mat.small) and large mature cod (>85cm; cod.mat.large), represented as the average proportion (relative to 1) of each prey in the stomach content from 1993 to 2016.
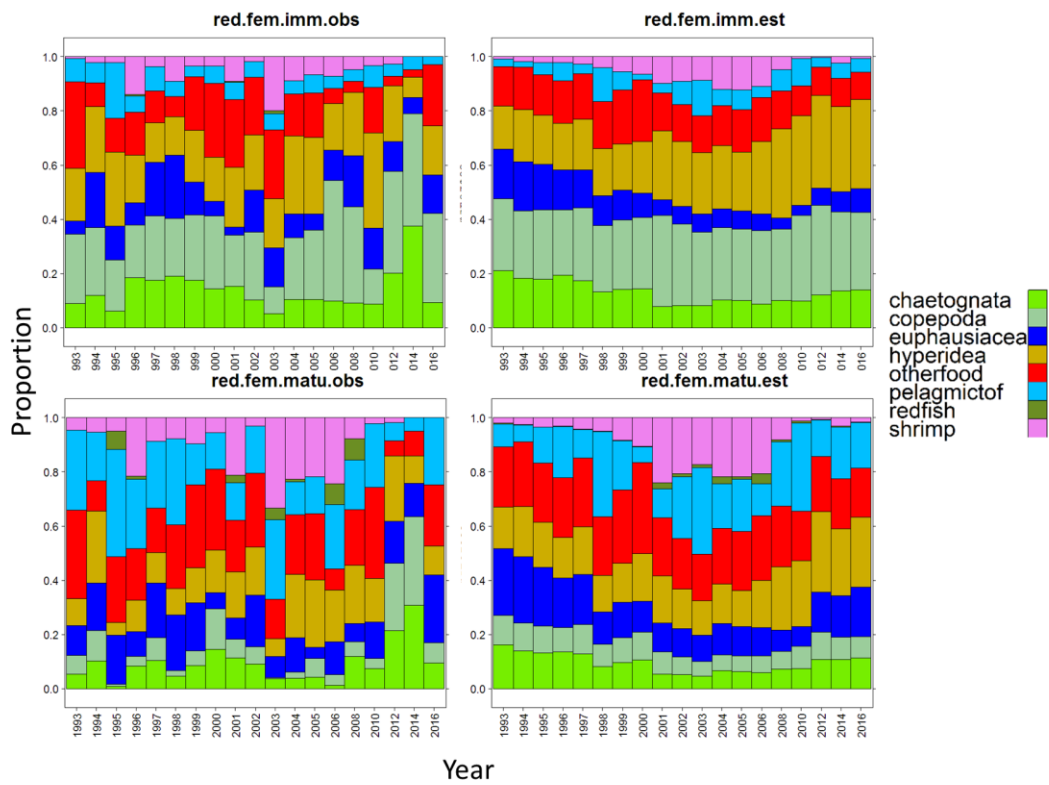
Figure 6.6-20.- Model estimated diet (left column) and observed diet during the EU survey (right column) for immature redfish (red.imm) and mature redfish (red.matu), represented as the average proportion (relative to 1) of each prey in the stomach content from 1993 to 2016.

ANNEX IV: EXPLORATION OF GROWTH MODELS INCORPORATING DENSITY-DEPENDENCE FOR THE FLEMISH CAP COD AND SHRIMP.

1.- Introduction

Mean length-at-age of 3M cod and shrimp stocks have varied markedly over time. Lengths in cod have increased across ages from the early 1990s to the mid-2000s, and decreased sharply since then (figure 1). These variations, indicating changes in the growth pattern, have happened whilst the stock went through a collapse in the mid-2000 and a quick recovery afterwards. Similarly, mean length-at-age of shrimp has decreased for all age-classes from the end of the 1990s to around 2007 and increased again afterwards. These changes in growth are also concomitant with changes in shrimp biomass, with a steep increase from low levels in 1990 to high level between 2000-2005, and a decrease back to low levels afterwards. Such a concomitant pattern of increasing growth while stock size declines (or the opposite) suggests a density dependent effect on growth for both stocks.

Finding definitive evidence that density dependent factors are affecting growth would require the identification of the underlying mechanisms (e.g. reduction of the food available per capita due to the increased number of conspecific individuals). Such studies require the analysis of large amounts for field data, and/or, the development of complex modelling tools (individual based, energy based model).

Investigating the question of density dependent growth using a growth model represents an intermediary step between simple correlation analyses and complex data intensive research projects. Unlike simple correlations which look at correspondence in temporal variations, the growth model used here provides a theoretical framework to represent how life time growth patterns are changed in relation to changing stock size.

Similarly, changes in temperature, affecting individuals metabolism, are also expected to affect growth. These effect can be incorporated together with density dependence in a growth model.

Here, a density-dependent growth model incorporating both density dependence and temperature effects is developed based on the stock mean length at age matrices used in the assessments for both cod and shrimp. The aim is to be able to reproduce the past variations in mean lengths, based on past metrics of stock size (assessment model output) potentially representing the intensity of density-dependent growth limitation and temperature. This model can then be directly incorporated in simulation tools used to estimate reference points and to evaluate the performance of management strategies, in order for instance, to investigate the sensitivity of reference points such as F_{MSY} to the assumption made on future growth.
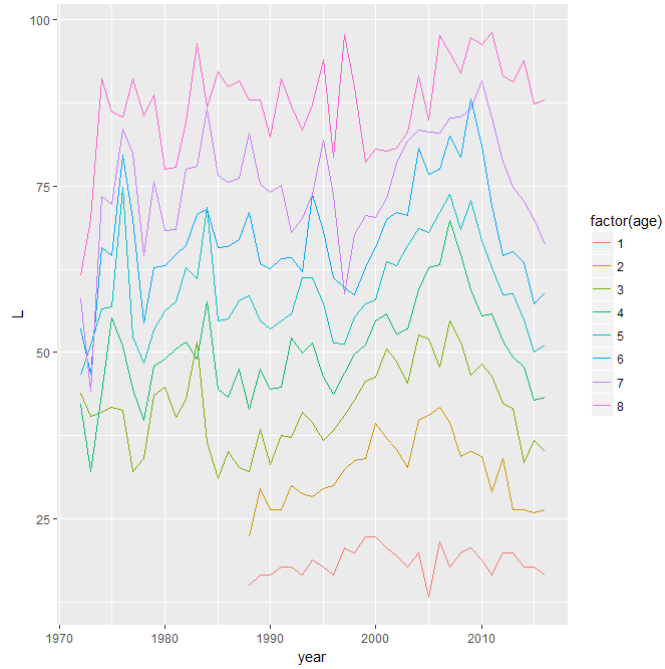
Figure 1 : variation of stock mean length at age at age, cod 3M, use in the assessment.
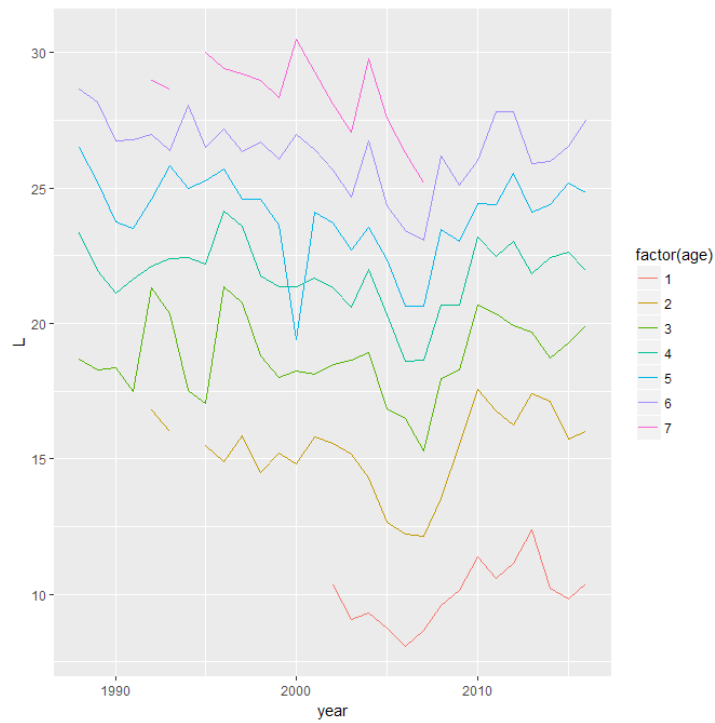
Figure 2 : variation of stock mean length at age at age, shrimp 3M.

2.- Data exploration

Growth changes

Cod

Patterns can be observed in the stock mean lengths matrix (figure 1). The most remarkable feature is the increasing trend followed by a decreasing trend in age 2 to 7. The start of a decreasing part seems to be postponed for older ages, suggesting that the change in growth mostly affected cohorts at younger ages and were not compensated for changes in growth in the later part of their life. Other less pronounced changes in length at age can be followed along the cohorts life, such as small increase followed by a small decrease occurring in the earlier 1990s. In addition to these patterns along cohorts, year effects are also visible, such as the drop in length at age observed in 1978 for most ages, which for some ages (age 5 to 6), imply almost no growth during the year 1977.

One possible explanation for these different patterns is that long term cohort effects could reflect slow changes in growth (for instance linked to changes in stock size) while year-effects could be related to anomalies in factors affecting growth (e.g. extreme environmental conditions). In addition to these patterns, there is noise in the data, as illustrated occasional decrease in mean length in a cohort between successive years.

Finally, variations in length at age 8 were not included in the analyses, since they represent a plus group, combining individuals of different cohorts.

Analysis of the correlations in length at age between the successive ages of a cohort show that the mean length at age 2 is not linked to the length of the cohort at age 1 (figure 3), but that the length at ages older than 2 is highly correlated to the length one year before (except for the plus group). This shows that most of the variation observed in length at age occurs during the second year of life.
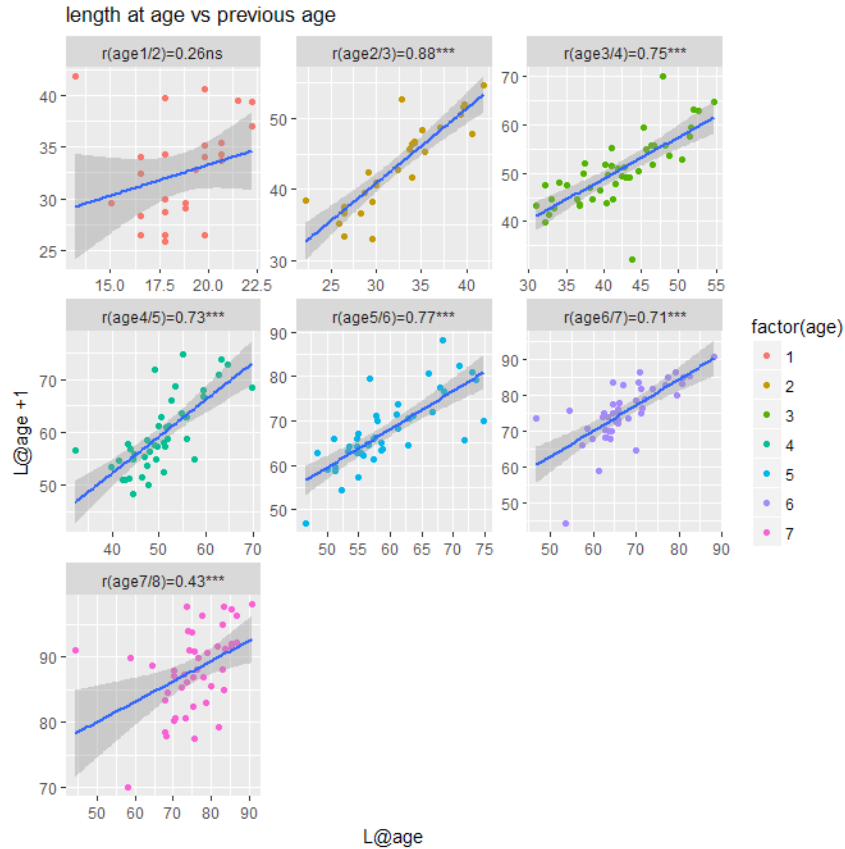
Figure 3 : cod 3M relationship between mean length of a cohort at successive ages (correlation coefficient indicated on top of each panel)

Shrimp

For shrimp, the changes in growth appear concurrently for all ages (no lag from one age-class to the other as for cod).

Correlations between ages show that (unlike for cod), length-at-age is already highly correlated between age 1 and 2, and remains correlated between subsequent ages (figure 4), although less strongly than for cod.
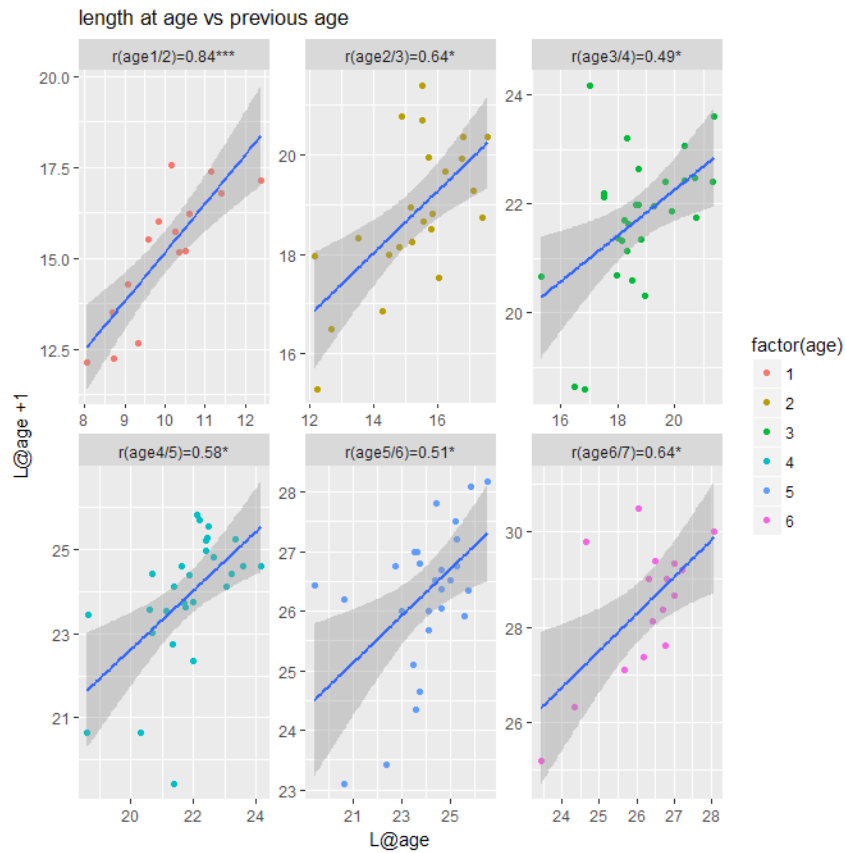
Figure 4 : shrimp 3M relationship between mean length of a cohort at successive ages (correlation coefficient indicated on top of each panel)

Link between length at age 1 and potential descriptors of density dependence

Cod

Correlations between length at age 1 and a series of variables potentially representing the intensity of density dependence mechanisms affecting growth during the first year were investigated. Those variables were the size of the cohort (log of the recruitment of the same cohort), size of previous cohort, the total abundance of juveniles (ages 1-3), all possibly representing the amount of individuals with which young individuals may compete for food during their first year of life. None of the correlations tested was found significant, the highest correlation being observed with log (rec) (figure 5), with a tendency to have fish of smaller length at age 1 for larger cohorts.

Shrimp

For shrimp the only available variable potentially representing the intensity of density dependent limitation of growth was the stock biomass. The length-at-age 1 was found to be significantly correlated to shrimp biomass during the first year of growth (figure 6).
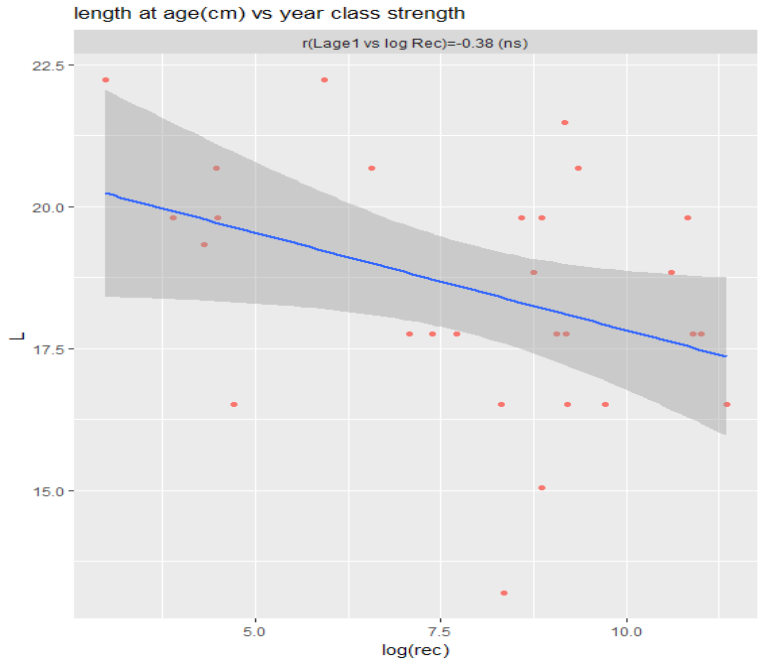
Figure 5 : relationship between cod mean length at age 1 and the size of the cohort (in log).
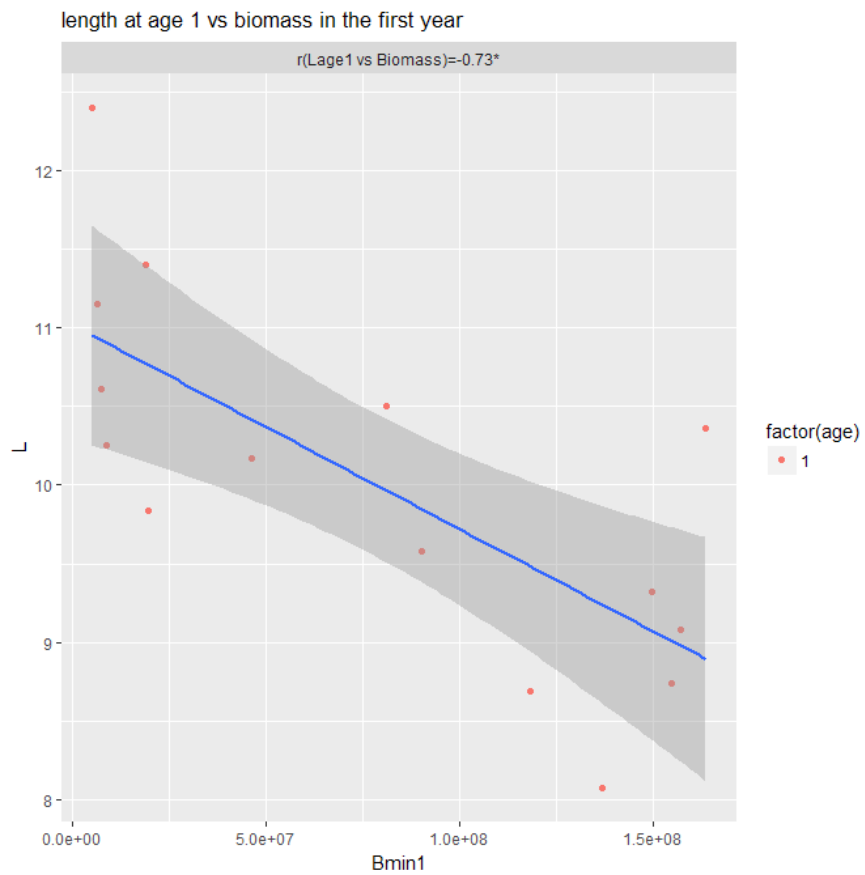
Figure 6 : relationship between shrimp mean length at age 1 and the size of the cohort (in log).

Link between annual growth and density dependence

The Von Bertalanffy model was used to predict the annual growth based on the size observed at the start of the year : $\hat{L}_{t+1,a+1} = L_{inf} - (L_{inf} - L_{t,a}) \exp(-(K))$

The difference between the observed length at age $L_{t,a}$ and the modelled ones $\hat{L}_{t,a}$ represent annual growth anomalies by year and age. In order to investigate the potential density dependent effect, correlation between these growth anomalies and a series of variables were investigated (recruitment of the cohort, total stock biomass, adult stock biomass for cod, and total stock biomass for shrimp).

Cod

The highest correlations were observed with the total stock biomass (figure 7), but correlations are significant only for growth during age 1, 2 and 5, whilst being negative for all ages.

Shrimp

For shrimp correlation between annual growth deviations and stock biomass were negative until age 4-5 (but significant only for ages 1 to 2 and ages 4 to 5) and close to zero for older ages (figure 8).
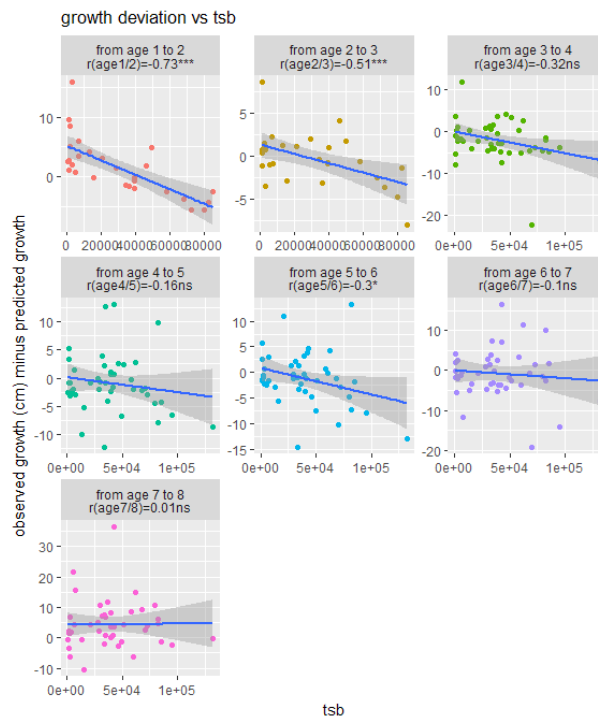
Figure 7 : relationship between cod growth anomalies (observed length minus length predicted from a Von Bertalanffy model) and the total stock biomass.
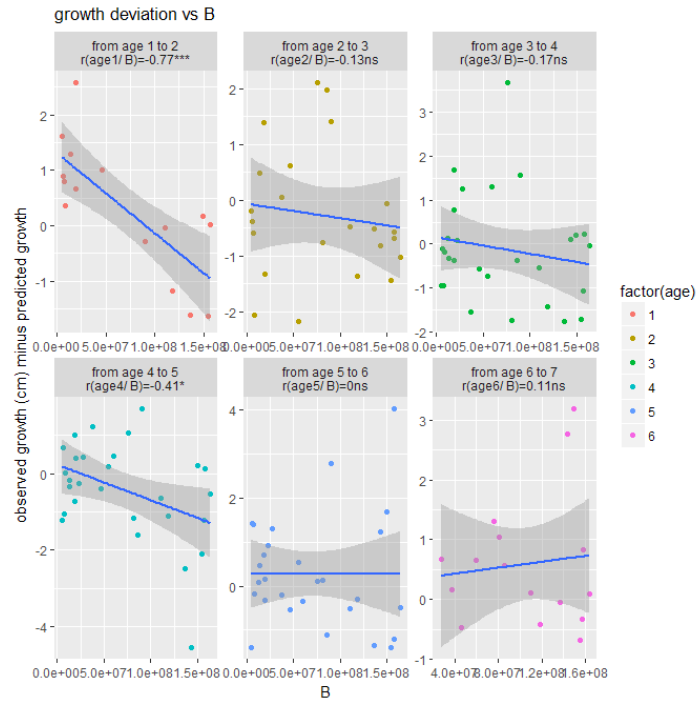
Figure 8 : relationship between shrimp growth anomalies (observed length minus length predicted from a Von Bertalanffy model) and the total stock biomass.

Links with bottom temperature

The relationship between growth at temperature was investigated with similar analysis as for the relationships with metrics chosen to quantify density dependence.

For both cod and shrimp, there was a small positive, though non-significant, correlation between the length at age 1 and the bottom temperature the previous year. Likewise, the correlation between growth anomalies in the subsequent ages and the corresponding temperature were weak and non-significant.

3.- Modelling approach

Based on theoretical expectations[65], Lorentzen and Enberg (2001) proposed a modification of the von Bertalanffy growth model which accounts for density-dependent effects. In this model, the

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[65] *The von Bertalanffy equation is a popular model for growth in fisheries science. It was originally derived from an energy allocation theory of growth, in which instantaneous growth rate is the difference between energy acquisition and energy consumption for maintenance. This can be formalized as follows :*

$$dw/dt = \eta w^{2/3} - \lambda w$$

asymptotic length (model parameter corresponding to the theoretical length of a fish of an infinite age) decreases when the biomass of the stock increases. Here the model was extended to incorporate an effect of temperature on the growth coefficient K :

$$L_{t+1,a+1} = L_{infB,a} - (L_{infB,a} - L_{t,a}) \, exp(-(K_y))$$

Where

$$L_{infB,a} = L_{inf} - g_a \, B_t \text{ , and}$$

$$K_y = K + \tau \, Temp_y$$

The annual growth is modelled as a function of the length of the same cohort at the start of the year $L_{t,a}$, and the parameters K_y (growth coefficient) and L_{infB} (asymptotic length), where L_{infB} is a linear function of total stock biomass B_t with a slope g_a describing the strength of the density dependence for a given age-class and the growth coefficient K_y is influenced by the annual bottom temperature $Temp_y$.

This model was fitted on the historical mean length-at-age in the stock transformed into length. Since the model predicts $L_{t+1,a+1}$ as a function of $L_{t,a}$, it cannot be fitted for the first age in the length at age matrix (age 1). A separate model was therefore developed for length at age 1, based on linear regression between annual length at age 1, the strength of the corresponding cohort (log(Rec)) and the bottom temperature.

Where w is individual weight, t is the age of the fish, η is the coefficient for the energy intake rate and λ is the coefficient for the energy consumption rate for maintenance.

The integration of this differential equation gives the following function for weight as a function of time

$$w(t) = \left(\eta/\lambda\right)^3 \left[1 - e^{-\lambda(t-t_0)/3}\right]^3$$

One can recognize the von Bertalanffy growth equation, in which the coefficients are expressed in terms of energy allocation parameters

$$k = \lambda/3$$

$$w_{inf} = \left(\eta/\lambda\right)^3$$

We can expect that competition for food (which is how density dependence would affect growth) would result in a lower energy acquisition rate (smaller η), but is not likely to modify the basal metabolism (maintenance, same λ). The equations above then imply that the growth coefficient k should be insensitive to density while the asymptotic weight should be negatively affected by density dependence. Both the growth coefficient k and the asymptotic weight w_{inf}, are proportional to λ (inversely for w_{inf}), the rate of energy use for maintenance. Since maintenance is increases with temperature, it is therefore expected that growth coefficient would increase with temperature, while the asymptotic weight would decrease.

After estimating the parameters L_{inf}, K , g_a and τ, the model was used to predict past growth, using the historical TSB values and recruitment values and the temperature time series. Reconstructed length-at-age time series were visually compared to the observed ones to determine whether the model managed to reproduce the past changes in growth, and could therefore be used to simulate future lengths in an MSE.

4.-Results

Model for age 1 length.

- *Cod*

The linear regression model for length at age 1 indicated that the effect of log(recruitment) and of bottom temperature (of the previous year) were significant. The coefficient of the regression are given in the table 1. As expected, the size of the cohort has a negative effect on the length at age 1, while the bottom temperature has a positive effect.

Table 1 : coefficient of the linear regression of length at age 1 of cod against log recruitment and bottom temperature

coefficient	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	11.6031	4.5157	2.569	0.0175 *
log(rec)	-0.4049	0.1650	-2.454	0.0225 *
Btemp	2.6751	1.1800	2.267	0.0336 *
residual standard deviation	1.962			

The predictions from the linear model managed to reproduce quite closely the observed length-at-age 1 (figure 9). The model with effect of log recruitment and the model with effect of log recruitment and temperature were both able to produce a trend very close to the trend observed in the data. The model with both density dependence and temperature also managed to reproduce part of the shorter-term variability (e.g. spikes in 1999 or 2016).

Figure 9: comparison of the predicted length at age 1 of cod with the observed data. modDD : linear regression with effect of log recruitment only, modDD&temp, linear regression with effect of log recruitment and bottom temperature. Note that there is no data for length at age 1 prior to 1988, and that predictions from modDD&Temp cannot be made before 1989 because no temperature data is available before this date.

- *Shrimp*

For shrimp, the linear regression model for length at age 1 indicated that the effect of stock biomass was significant but not temperature. The coefficient of the regression are given in the table 2.

Table 2 : coefficient of the linear regression of length at age 1 of shrimp against stock biomass and bottom temperature

coefficient	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	1.03E+01	5.37^E	1.914	0.0797
Stock biomass	-1.27E-08	4.09E-09	-3.112	0.0089**
btemp	1.81E-01	1.30E	0.139	0.8917
residual standard deviation	0.8478			

Prediction of the model with stock biomass and with or without temperature are very similar and broadly capture the trend in the data (figure 10).
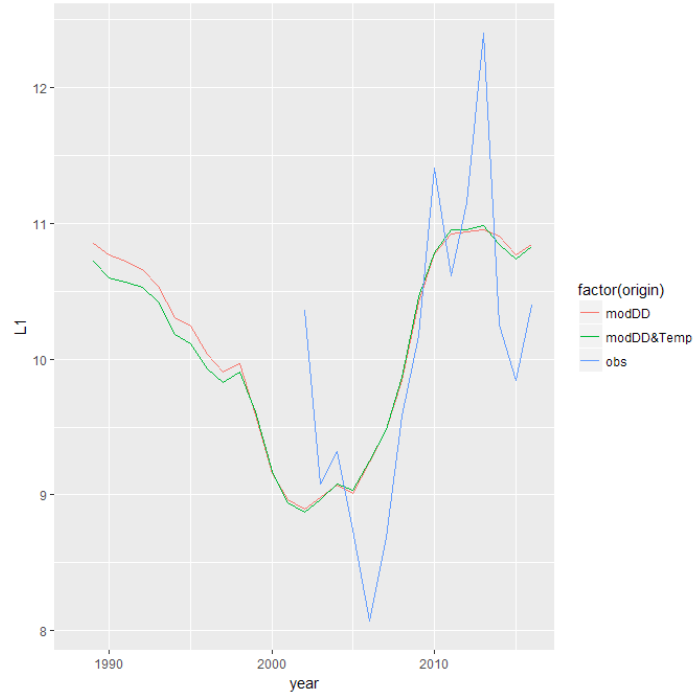
Figure 10: comparison of the predicted length at age 1 of shrimp with the observed data. modDD : linear regression with effect of stock biomass only, modDD&temp, linear regression with effect of stock biomass and bottom temperature. Note that there is no data for length at age 1 prior to 2002, and that predictions go back to 1989 as both stock biomass and temperature are available until these dates.

Growth from age 1 onwards

- _Cod_

Parameter estimation was carried out using maximum likelihood. For the modified Von Bertalanffy model, three configurations were tested :

- DD2pars :   One with only 2 age specific parameters for the density dependence   effect, one for juveniles, g1-2 and one for adults g3-7
- DD7pars :   One with one parameter per age class, g1, ..., g7,
- DD7pars and temp : One with one parameter per age class, g1, ..., g7 and a age independent   parameter for the effect of temperature on K

The estimated parameter values for each model are given in the table 3. For the most simple model, model DD2pars, the inclusion of the 2 additional parameters representing the effect of density-dependence on the juveniles and on the adults, significantly improved model fit compared to a simple von Bertalanffy model (p = 0.008). Further decoupling density dependence parameters into age specific estimates (model DD7 pars) improved model fit again (p<0.001). Finally, incorporating an age-invariant effect of temperature on K further improved model fit (p<0.001).

Table 3 : parameter estimates (and confidence intervals) for the 3 growth models for 3M cod.

Model DD2pars			Model DD7pars			Model DD7pars and temp		
AIC = 1029.064			AIC = 1014.365			AIC = 1000.477		
parameter	estimate	CI	parameter	estimate	CI	parameter	Estimate	CI
L_{inf}	158	126 230	L_{inf}	188	+	L_{inf}	116	103 139
K	1.05e-01	6.18e-02 1.50e-01	K	8.23e-02	+	K	9.13e-02	-3.99e-02 2.19e-01
g_{12}	5.32e-04	1.65e-04 9.08e-04	g_1	5.92e-04	+	g_1	5.77e-04	3.31e-04 8.10e-04
g_{37}	2.24e-04	-2.81e-05 6.02e-04	g_2	5.93e-04	+	g_2	4.73e-04	2.28e-04 7.04e-04
			g_3	6.52e-04	+	g_3	4.10e-04	1.68e-04 6.38e-04
			g_4	8.34e-04	+	g_4	4.10e-04	1.68e-04 6.35e-04
			g_5	7.01e-04	+	g_5	2.67e-04	2.86e-05 4.92e-04
			g_6	3.93e-04	+	g_6	4.08e-05	-2.00e-04 2.67e-04
			g_7	-7.77e-04	+	g_7	-6.15e-04	-8.70e-04 - 3.75e-04
						τ	2.36e-02	-8.90e-03 5.81e-02
residual standard deviation	4.45	4.02 4.96	residual standard deviation	4.21	+	residual standard deviation	3.96	3.58 4.42

+ : model fit has not converged

The predicted length-at-age time series broadly reproduces the trends observed in the historical data (figure 11). The model manages to recreate the increase in growth in the early 2000s and the following decrease. There is however a substantial temporal lag after age 3 where the model's length increase earlier than the observed ones, resulting in a period with modelled lengths higher than observed ones. For the decreasing part, the model is close to observations. There is little difference between the predicted values from the 3 models, except for model DD 2par which results in a little less dynamic variations of lengths at age.
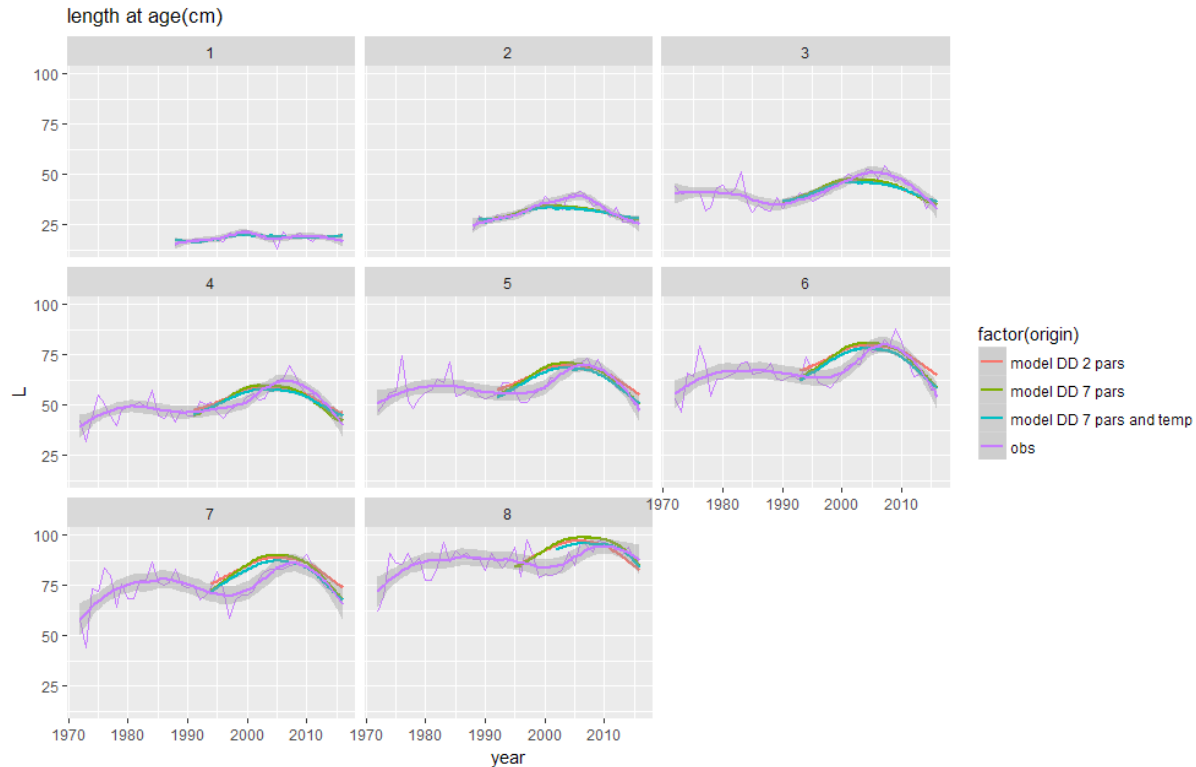
Figure 11 : historical performance of the density dependent growth model : observed (obs) vs. predicted (3 different models) length-at-age

- *Shrimp*

For shrimp, three models were fitted :

- DD2pars : One with only 2 age specific parameters for the density dependence effect, one for juveniles, g1 and one for adults g2-6
- DD6pars :One with one parameter per age class, g1, ..., g6,
- DD6pars and temp : One with one parameter per age class, g1, ..., g6 and a age independent parameter for the effect of temperature on K

The estimated parameter values for each model are given in the table 4. For the most simple model, model DD2pars, the inclusion of the 2 additional parameters representing the effect of density-dependence on the juveniles and on the adults, significantly improved model fit compared to a simple von Bertalanffy model (p <0.001). Further decoupling density dependence parameters into age specific estimates (model DD6pars) did not improved model fit again (p=0.18). Finally, the model with effect of temperature on K (DD6pars and temp) did not converge properly and the output cannot be used.

Table 4 : parameter estimates (and confidence intervals) for the 3 growth models for 3M shrimp.

Model DD2pars			Model DD6pars			Model DD6pars and temp		
AIC = 436.46			AIC = 438.22			AIC = 516.66		
param	estimate	CI	param	estimate	CI	param	Estimate	CI
L_{inf}	32.679	30.766	L_{inf}	30.813	28.750-33.812	L_{inf}	-168.07	+
K	0.307	0.243-0.376	K	0.351	0.269-0.440	K	-0.007	+
g_1	0.050	0.021-0.076	g_1	0.050	0.024-0.072	g_1	0.700	+
g_{26}	0.0356	0.022-0.49	g_2	0.034	0.015-0.052	g_2	0.198	+
			g_3	0.023	0.005-0.041	g_3	-0.130	+
			g_4	0.030	0.012-0.052	g_4	-0.743	+
			g_5	-0.008	-0.026-0.012	g_5	-0.371	+
			g_6	-0.024	-0.042- -0.004	g_6	-0.448	+
						τ	-0.003	+
residual standard deviation	1.135	1.013-1.283	residual standard deviation	1.109	0.990-1.254	residual standard deviation	1.46	+

+ : model fit has not converged

The predicted length-at-age time are shown on figure 12 for the two models that converged. The predictions broadly reproduce the trends observed in the historical data : decrease in length until the mid-2000s and followed by an increase. There is little difference between the predictions of the two models.

length at age(cm)

Figure 11 : historical performance of the density dependent growth model : observed (obs) vs. predicted (2 different models) length-at-age

5.- Conclusions

Exploratory analyses indicate that most of the changes in growth for cod operate on individuals during the first 2 years of their lives, and that less variability occurs during the growth of the subsequent year. Growth during the first years (length at age 1) was inversely related to the size of the cohort (log(recruitment)). Growth during second year (but also later ages also less significantly) correlated best with total stock biomass.

For shrimps, most of the variability seem to occur during the first year of life, with a strong effect of density dependence (as represented here by the stock biomass). Growth in the following years shows less variability, although the model with 2 parameters for density dependence indicates that variations of stock size still affect the growth in subsequent ages (with a stronger effect on growth between age 1 and 2).

Using these observations, a framework was proposed to simulate future lengths at age for 3M cod and shrimp in which changes in growth are driven by changes in stock size, thereby reproducing a density-dependent growth mechanism. On a goodness of fit point of view, the most complex models (with age specific density dependence parameters, effect of temperature)

did perform better than simpler ones. However, when it comes to use the model to simulate weights at age, the different versions of the model managed to recreate trends in stock weights which are reasonably comparable to those observed in the data.

7.- References

Lorentzen K. and Enberg, K. 2001. Density-dependent growth as a key mechanism in the regulation of fish populations: evidence from among-population comparisons. Proc. R. Soc. Lond. B (2002) 269, 49–54.

ANNEX V: EFFORT AND LANDINGS OF THE EU FLEET IN OTHER NAFO AREAS
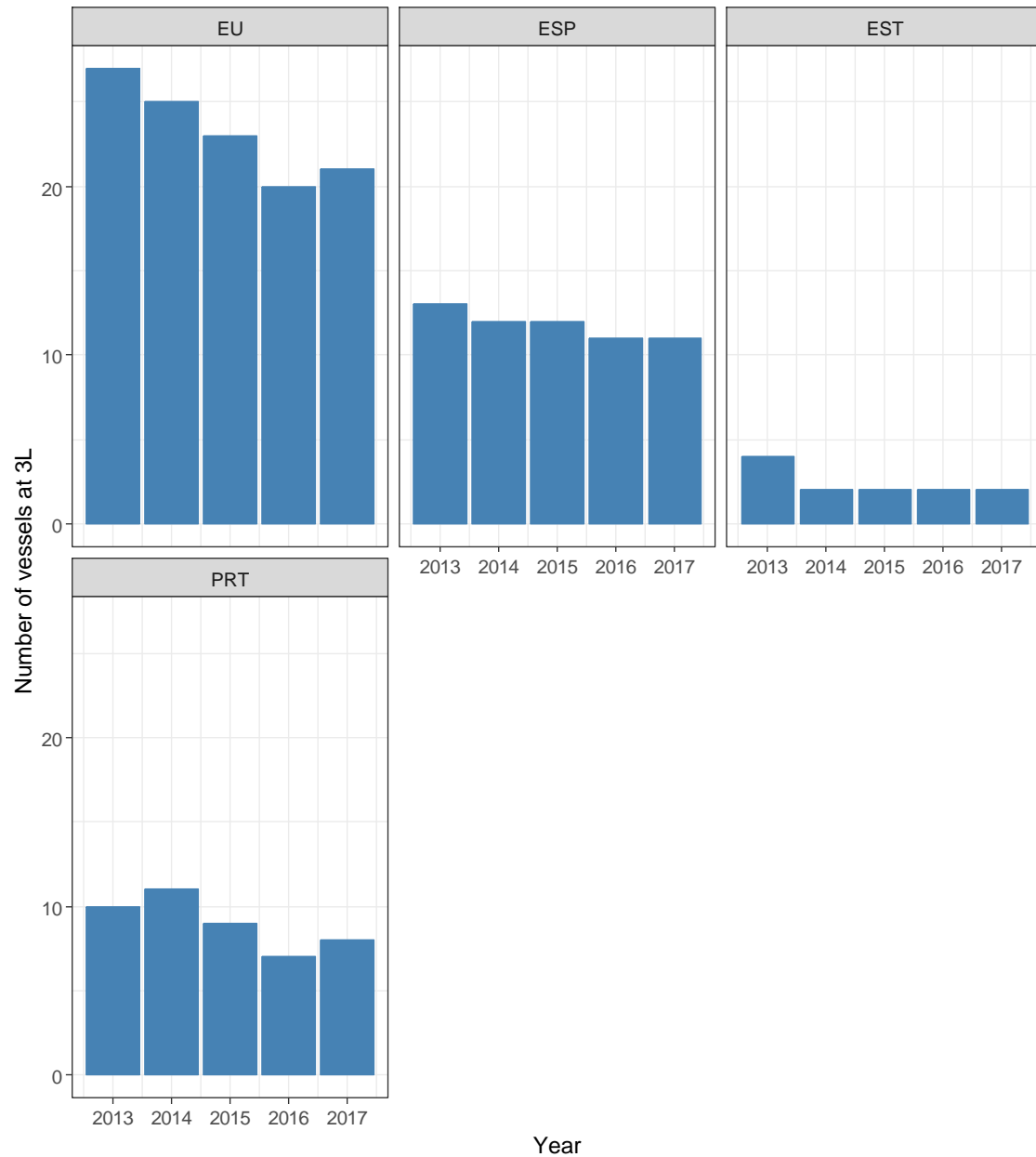
Figure annex III.1.- Evolution of the number of vessels in the period 2013-2017 in the NAFO 3L area of the EU fleet and by EU Member State.
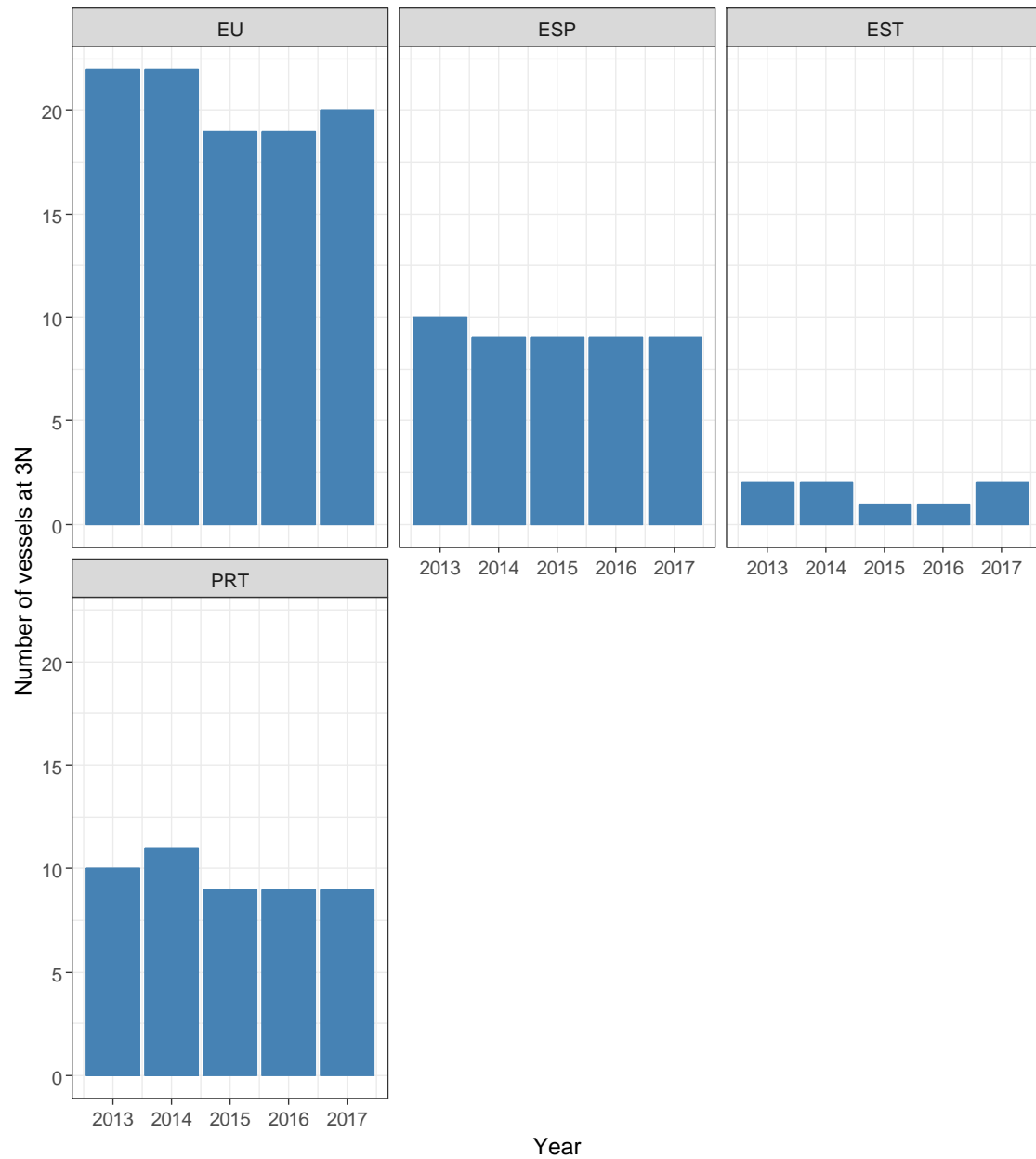
Figure

Figure Annex III.2.- Evolution of the number of vessels in the period 2013-2017 in the NAFO 3N area of the EU fleet and by EU Member State.
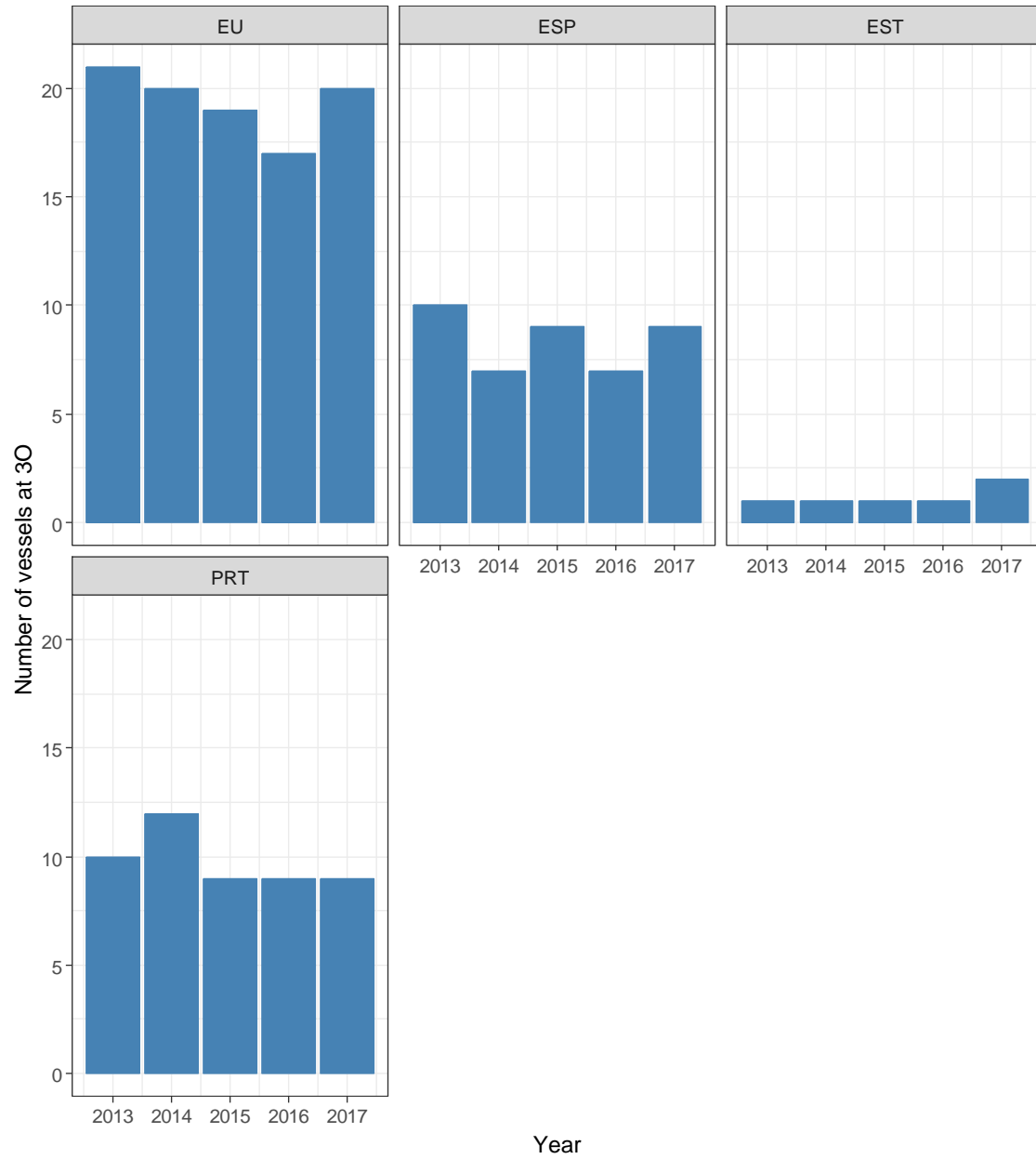
Figure 6.6-1. Annex III.3.- Evolution of the number of vessels in the period 2013-2017 in the NAFO 3O area of the EU fleet and by EU Member State.
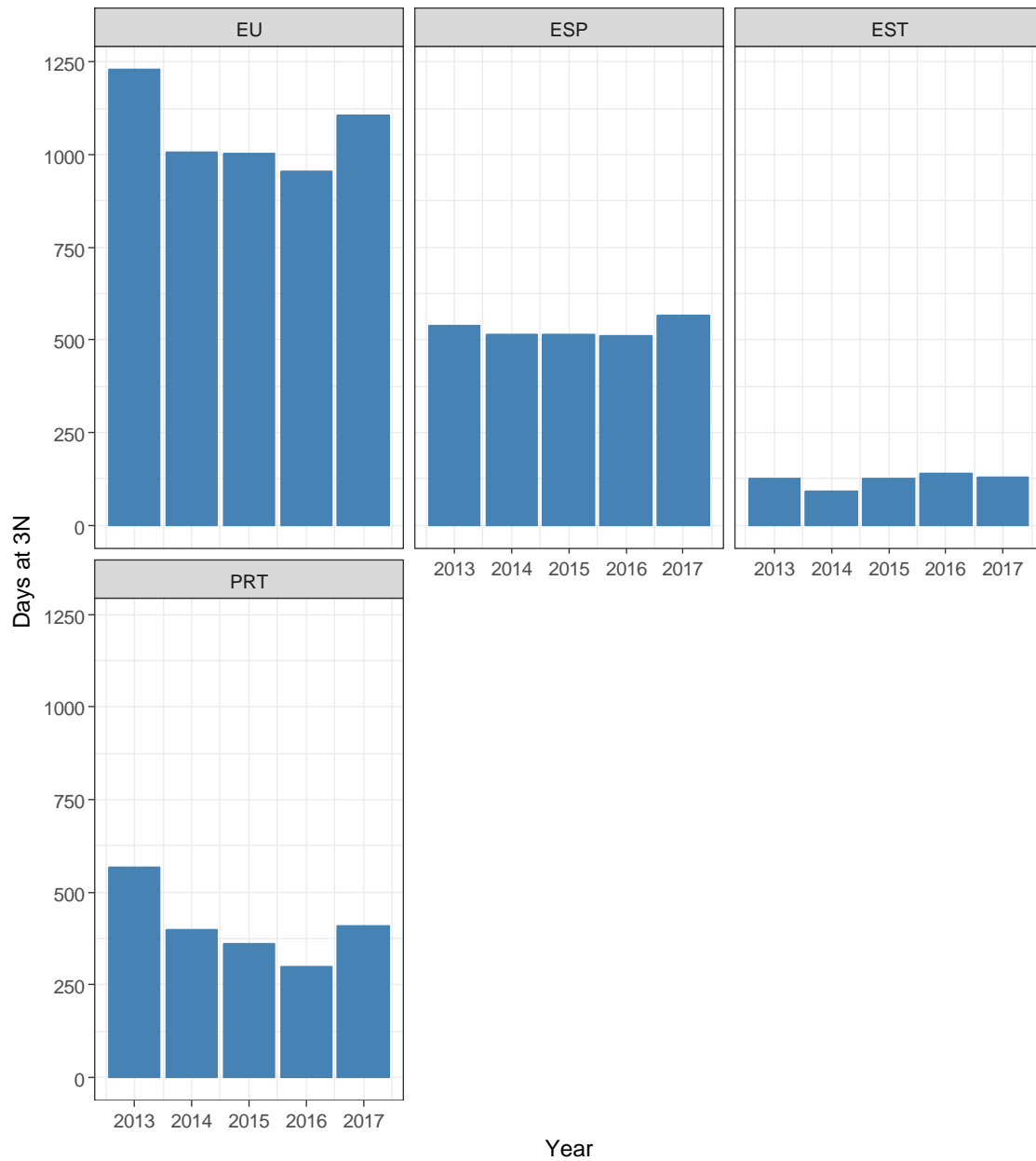
Annex III.4.- Evolution of the days of presence in the NAFO 3N area the period 2013-2017 of the EU fleet and by EU Member State.
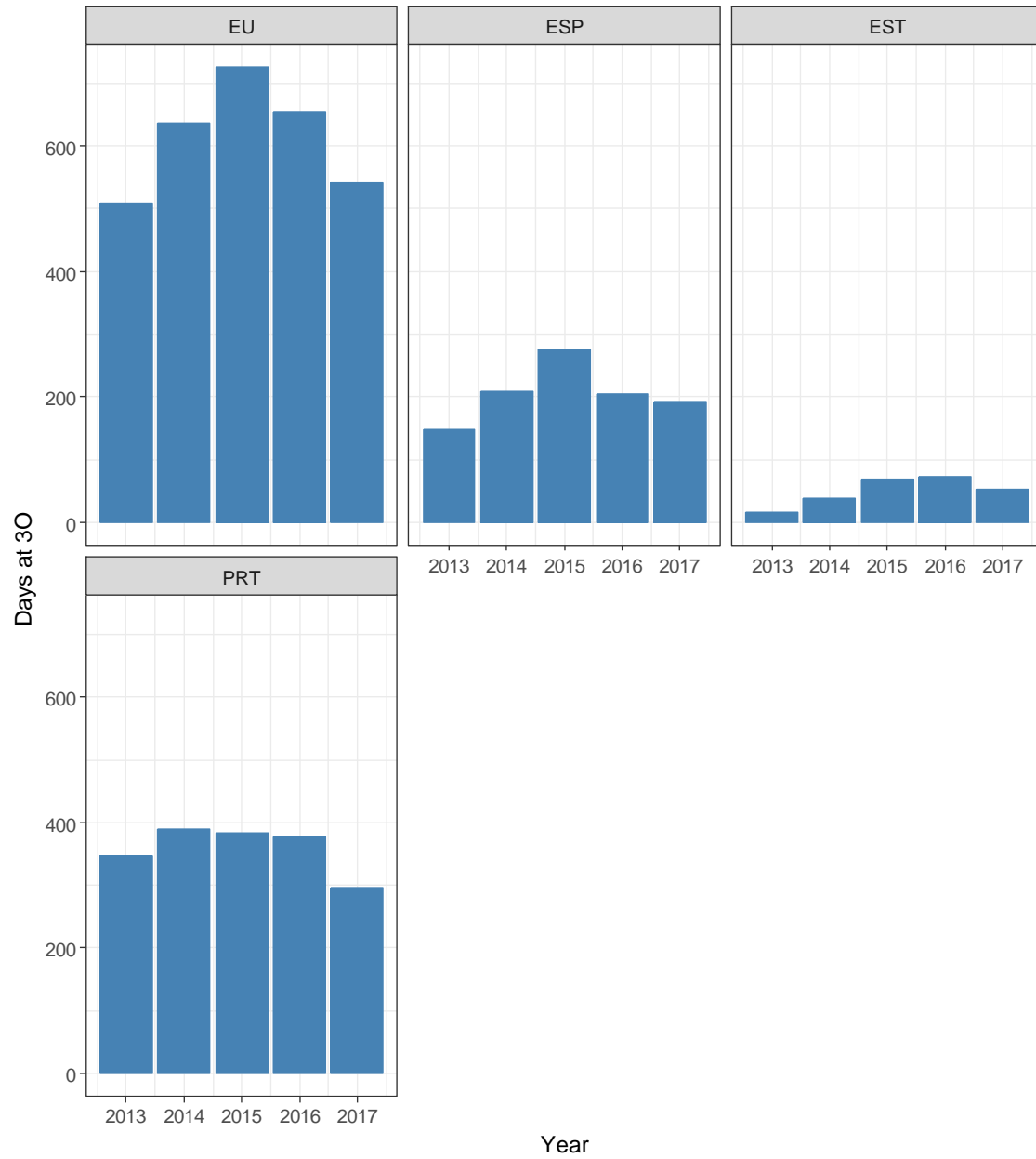
Figure 6.6-2. Annex III.5.- Evolution of the days of presence in the NAFO 3O area the period 2013-2017 of the EU fleet and by EU Member State.
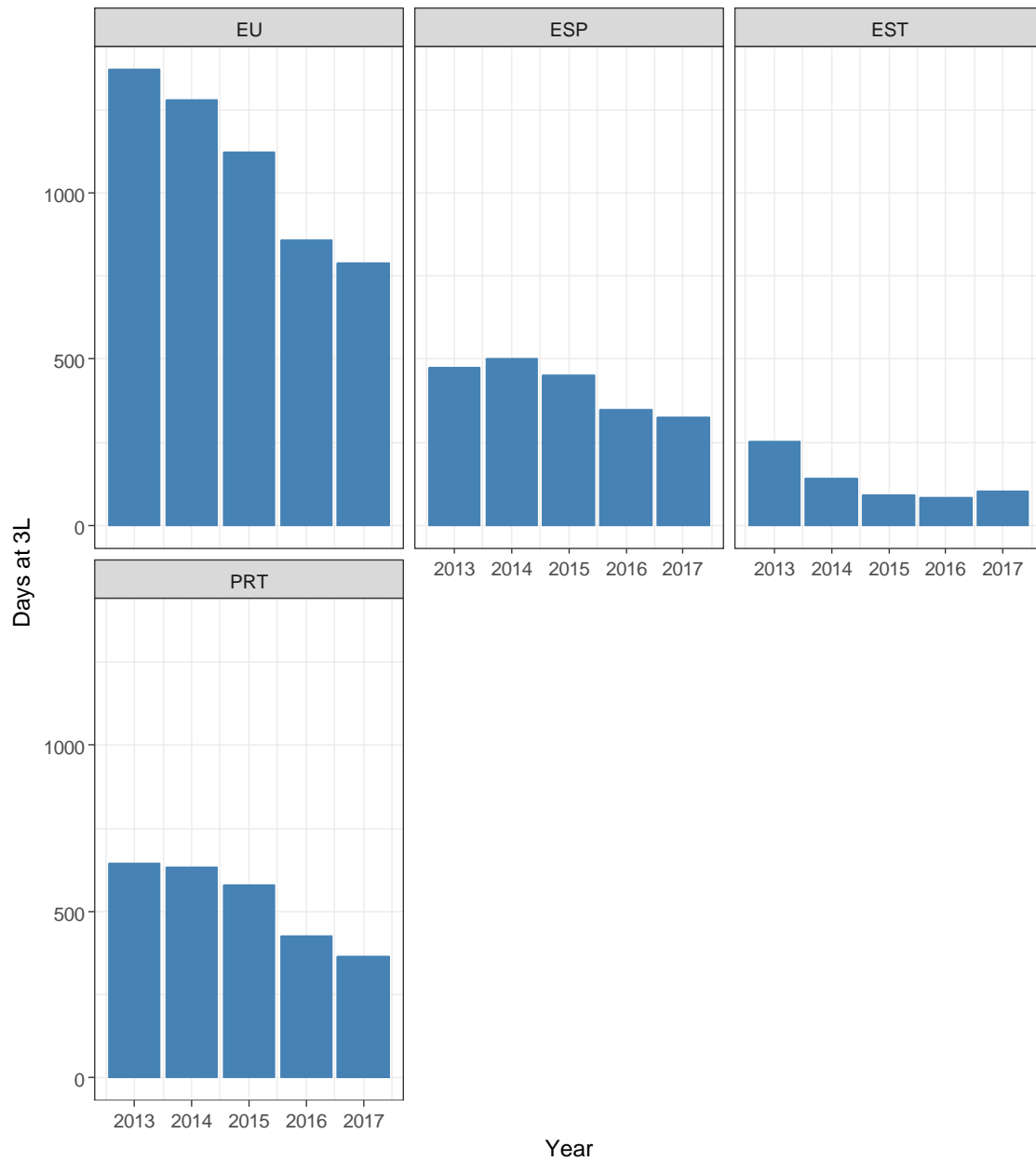
Annex III.6.- Evolution of the days of presence in the NAFO 3L area the period 2013-2017 of the EU fleet and by EU Member State.

Figure 6.6-3. Annex III.7.- Landings of the EU fleet by species and year in the NAFO 3L area in the period 2013-2017.
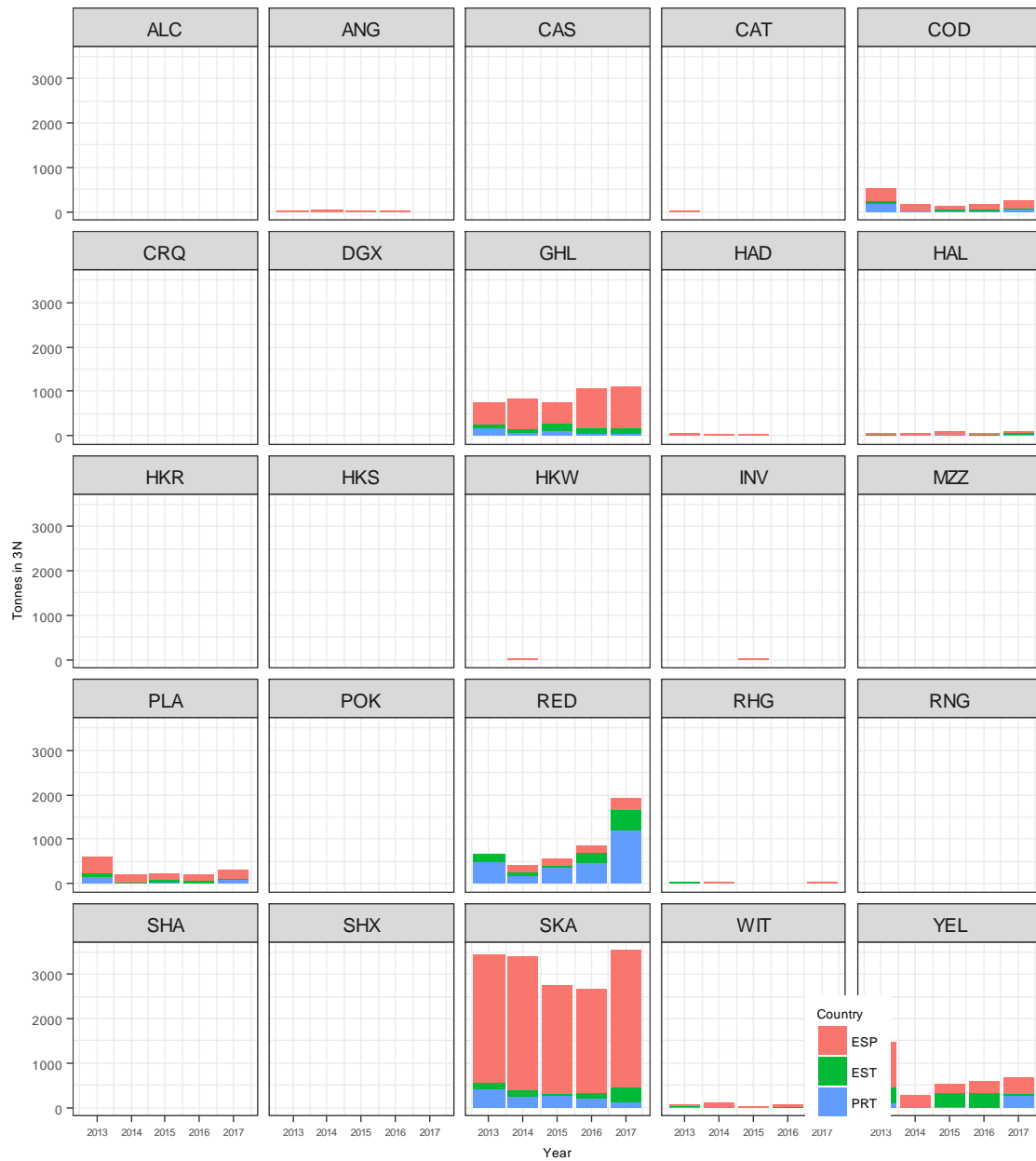
Figure 6.6-4. Annex III.8.- Landings of the EU fleet by species and year in the NAFO 3N area in the period 2013-2017.

Annex III.9.- Landings of the EU fleet by species and year in the NAFO 3O area in the period 2013-2017.

Northwest Atlantic   Fisheries Organization

SCIENTIFIC COUNCIL MEETING – JUNE 2018

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[66] (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 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

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

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[67] (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[68] 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.

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[67] https://www.cprsurvey.org/

[68] http://www.seabird.com/

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. 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[69] 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

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

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) <u>Improvements in the biological processes</u>
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) <u>Individual growth:</u>
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.

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.

Model assemblage

Cod, redfish and shrimp single species model settings

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:

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

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:

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

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:

$$S(l, L) = \begin{cases} p_0 + p_2 e^{\frac{-\left(ln\frac{L}{l} - p_1\right)^2}{p_4}} & if \ ln\frac{L}{l} \le p_1 \\ p_0 + p_2 e^{\frac{-\left(ln\frac{L}{l} - p_1\right)^2}{p_3}} & if \ ln\frac{L}{l} \ge p_1 \end{cases} \tag{4}$$

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).

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

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

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

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.

CONCLUSSIONS

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.

ACKNOWLEDGMENTS

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Figures:
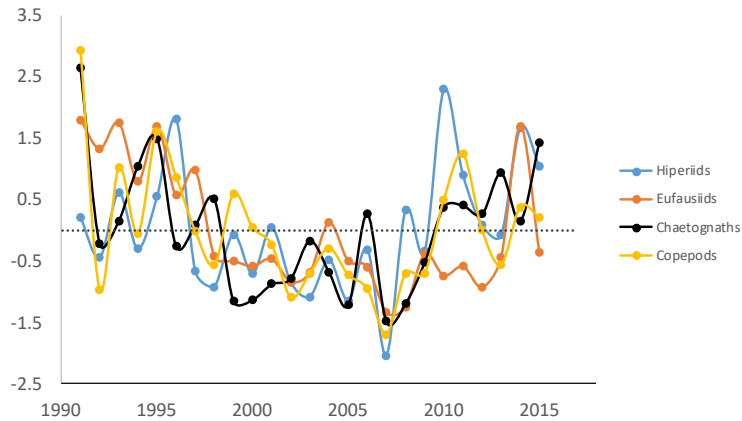
Fig. 1 Standardized abundance index of hyperiids, copepods, eufausiids and chaetognaths in the Flemish   Cap area over the period 1991-2015. This index has been obtained from the Continous Pankton   Recorder sampling program[1].
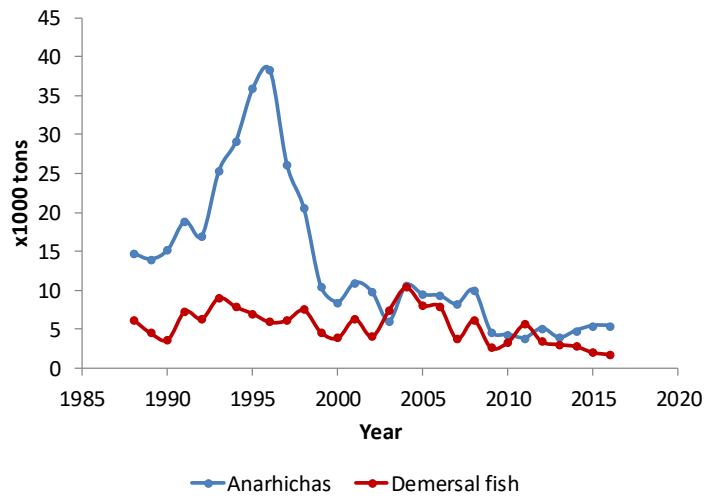
Fig. 2. EU Survey index of biomass in the Flemish Cap area over the period 1988-2016. This index was   obtained by the swept area method used in the Flemish Cap (Vázquez et al. 2013)
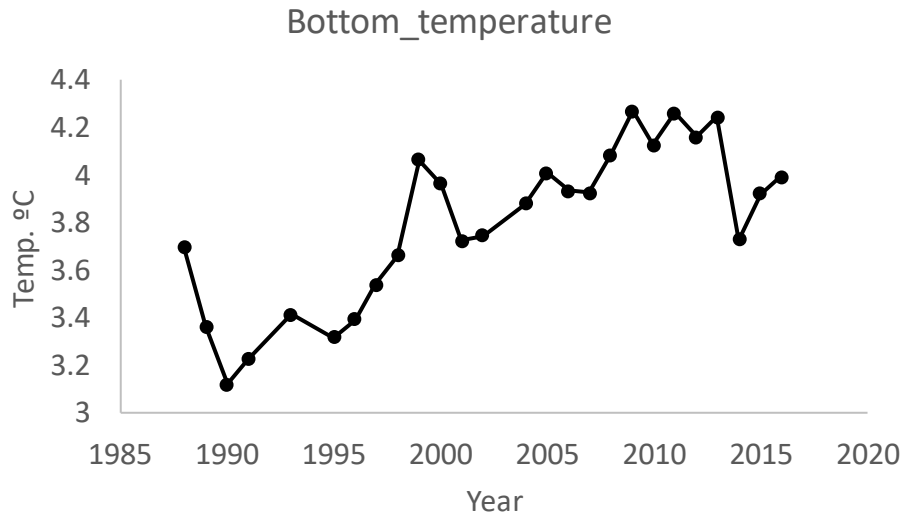
Fig.3. Bottom water temperature in the Flemish Cap during the EU summer bottom trawl survey.
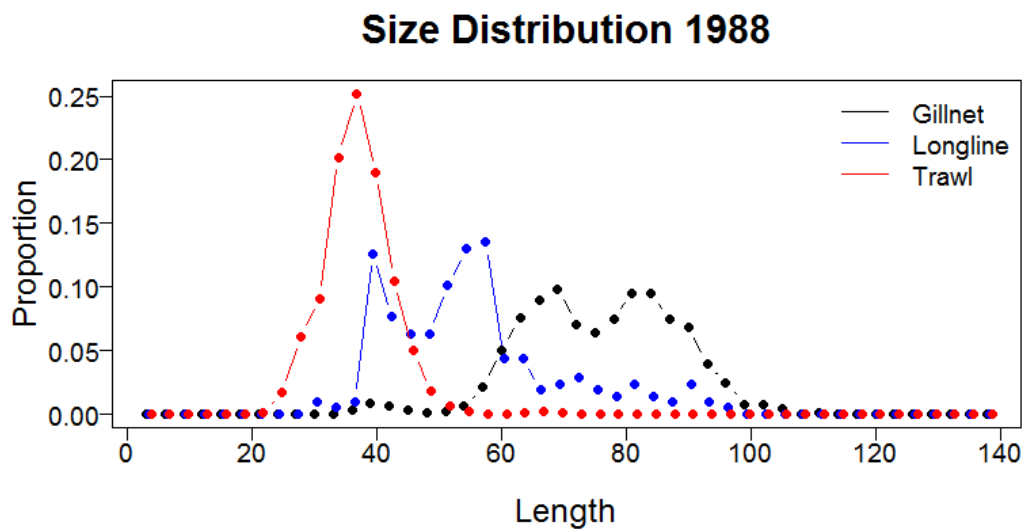
Fig. 4. Size distribution of catches in Gillnet, Longline and Trawl fleets in 1988. Data obtained from the 1989   Research Report of NAFO
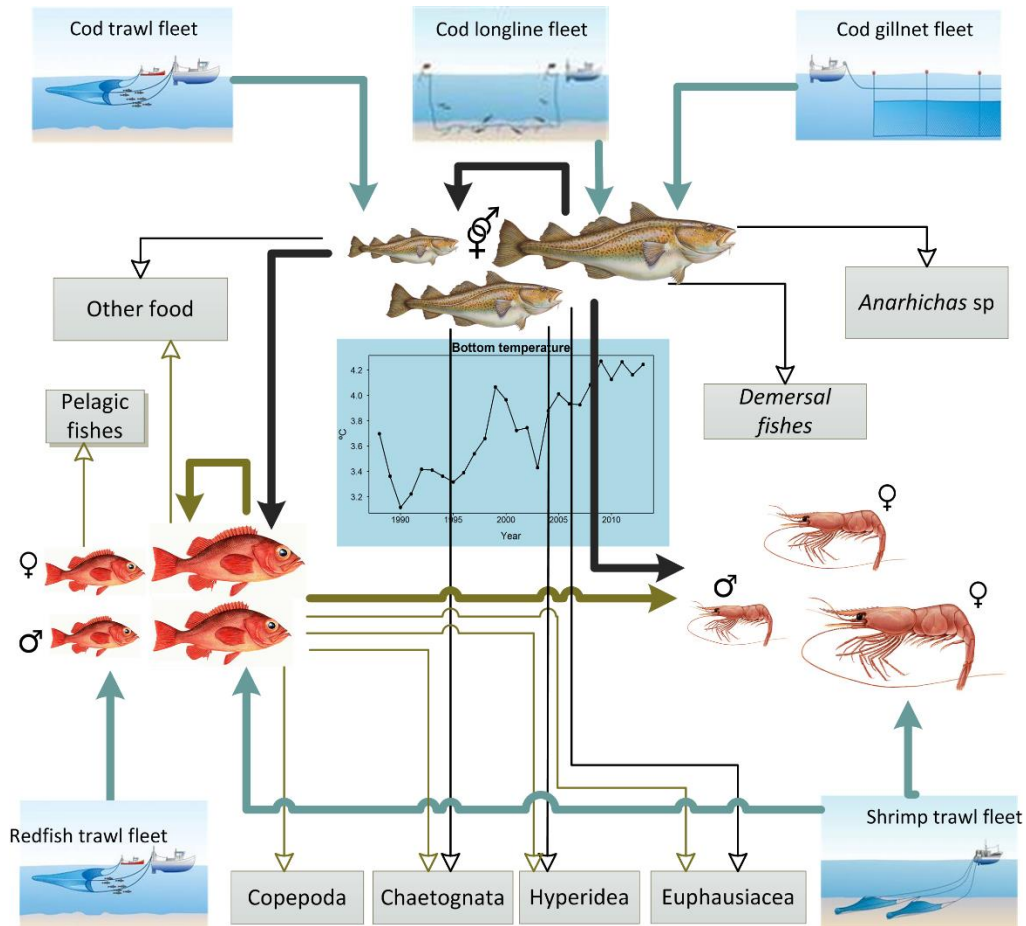
Fig. 5. Species interactions modeled in this study. Cod, redfish and shrimp are fully dynamically modeled,   whereas species/prey groups in grey text boxes are incorporated as time series or constant values.   The fleets fishing each species are also represented, as well as the effect of water temperature in total consumption.
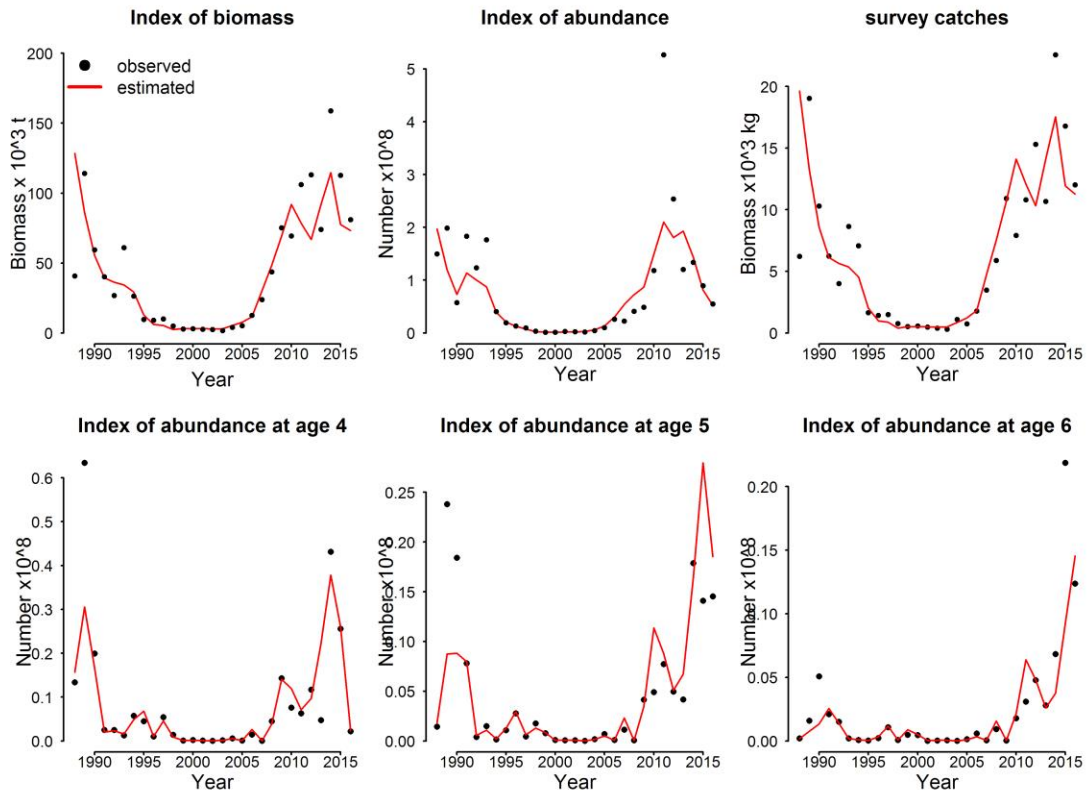
Fig. 6. Cod survey indexes of biomass, abundance and abundance of individuals at ages 4, 5 and 6. Total cod   catches in tones during the EU Flemish Cap survey are also shown. Red lines are the estimated values with GADGET versus black points which represent the observed data.

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.

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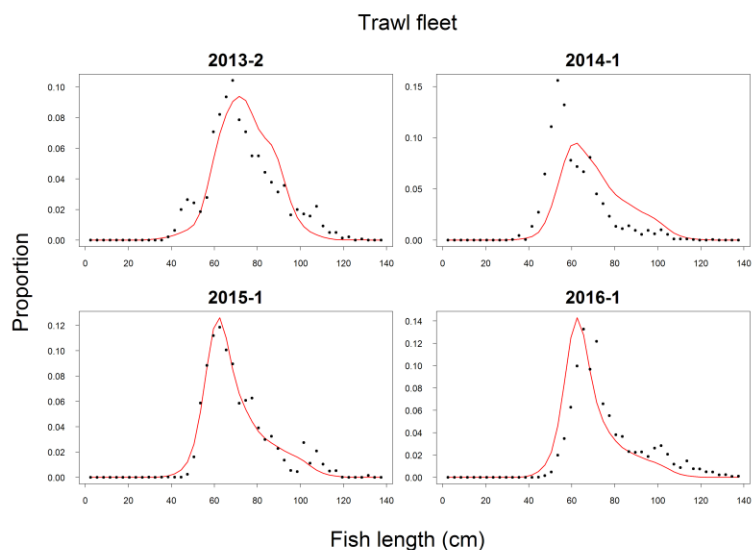
Fig. 8. Size distribution (in proportion relative to 1) of cod catches by the longline fleet. The label in each   subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988- 1 refers to winter of 1988). Red lines are the estimated values versus black points which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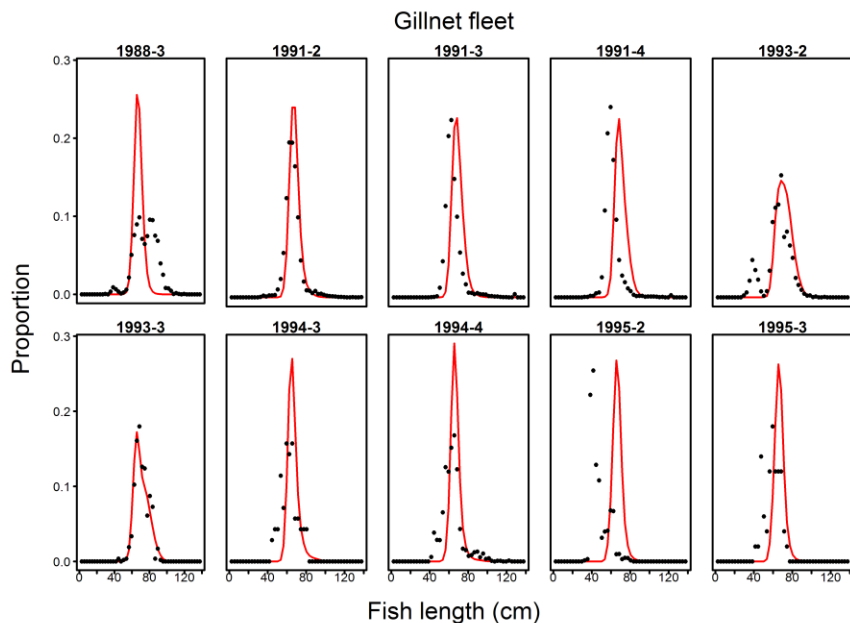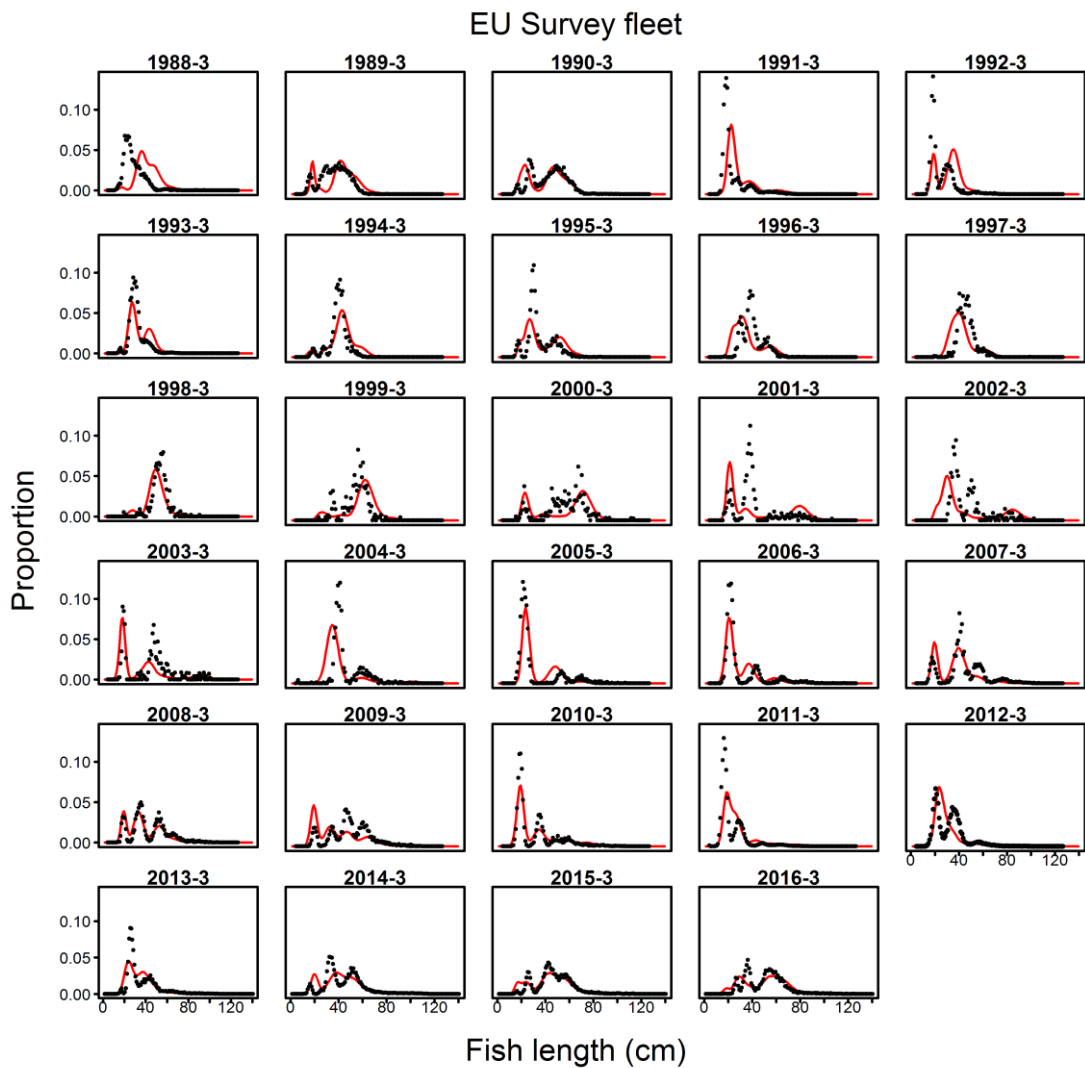

Fig.9. Size distribution (in proportion relative to 1) of cod catches by the gillnet fleet. The label in each   subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 refers to winter of 1988). Red lines are the estimated values versus black points which represent the observed data.
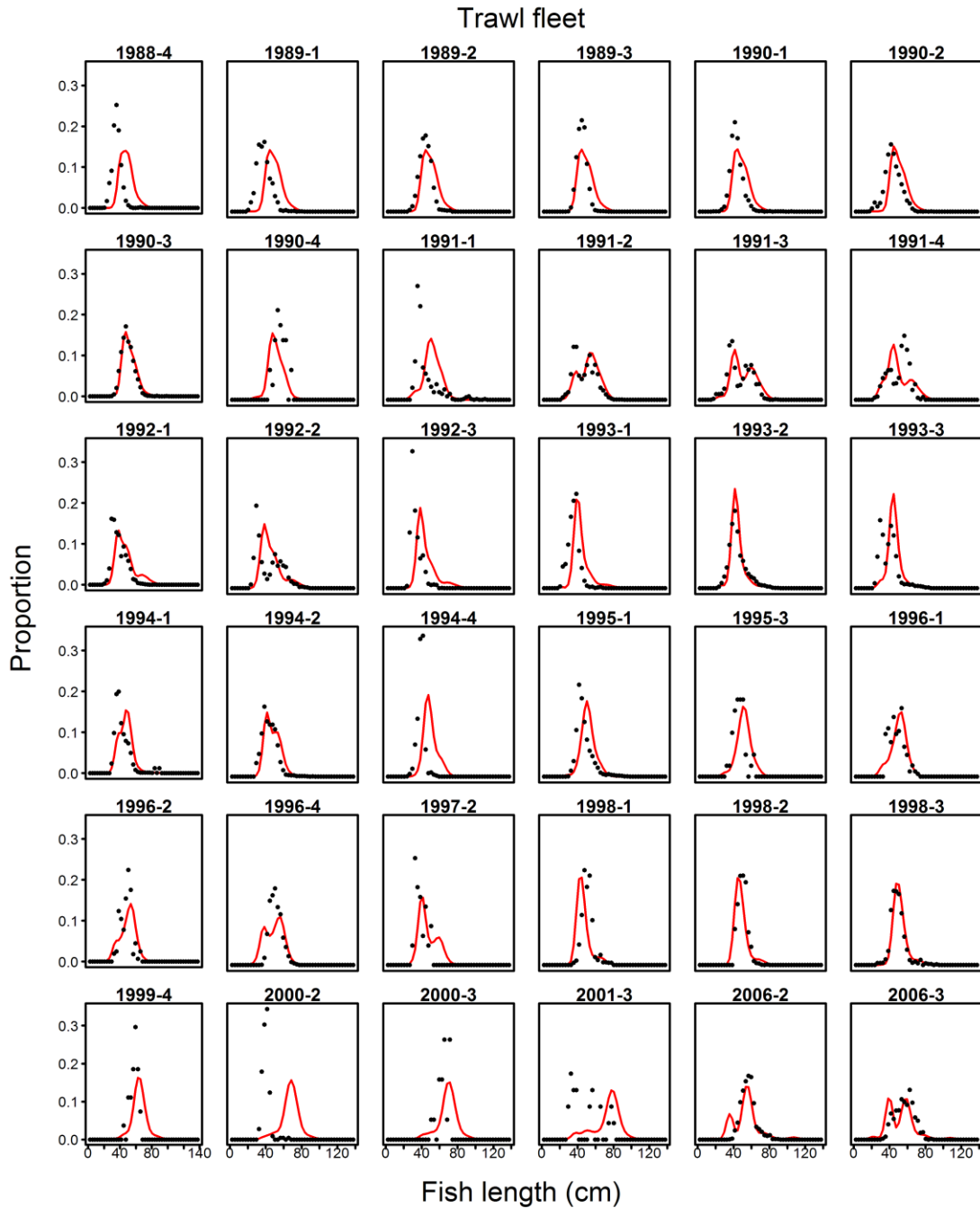
Fig.10.   Size distribution (in proportion relative to 1) of cod catches by the commercial trawl fleet over the   years 1988-2006. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 refers to winter of 1988). Red lines are the estimated values versus black points which represent the observed data.
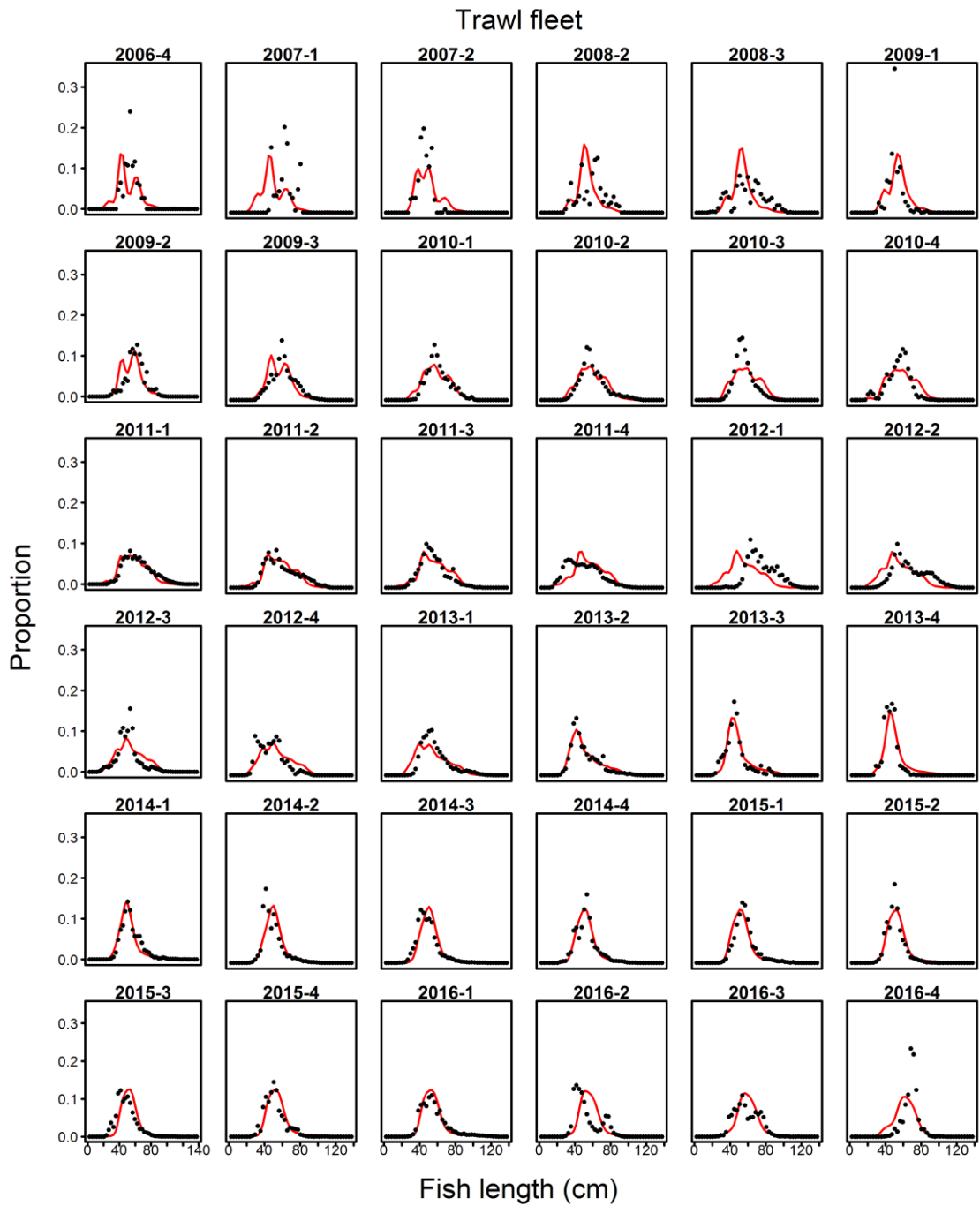
Fig. 11. Size distribution (in proportion relative to 1) of cod catches by the commercial trawl fleet over the years 2006-2016. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 refers to winter of 1988). Red lines are the estimated values versus black points which represent the observed data.
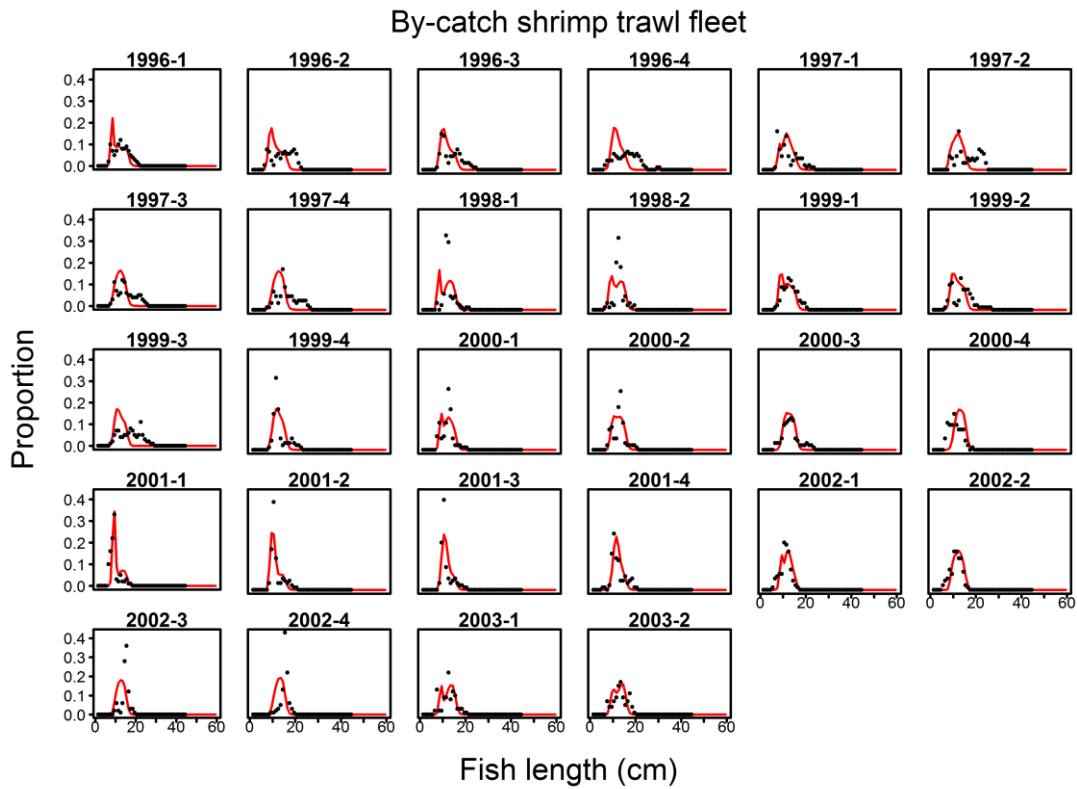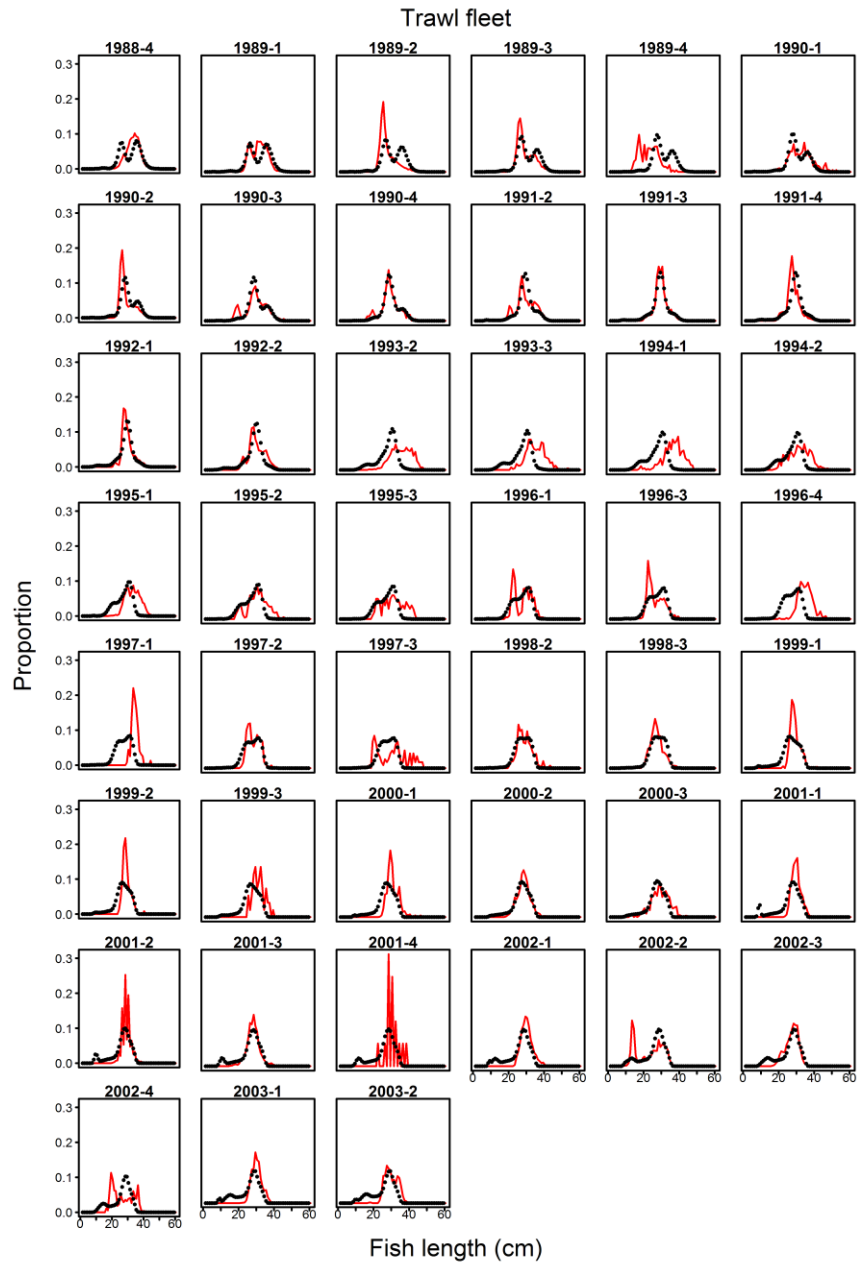
Fig. 12.   Size distribution (in proportion relative to 1) of cod catches by the EU survey fleet. The label in each   subpanel represents the year (Years: 1988 to 2016). For this fleet the season is always 3 (summer),   when the survey takes place. Red lines are the estimated values versus black points which represent   the observed data.
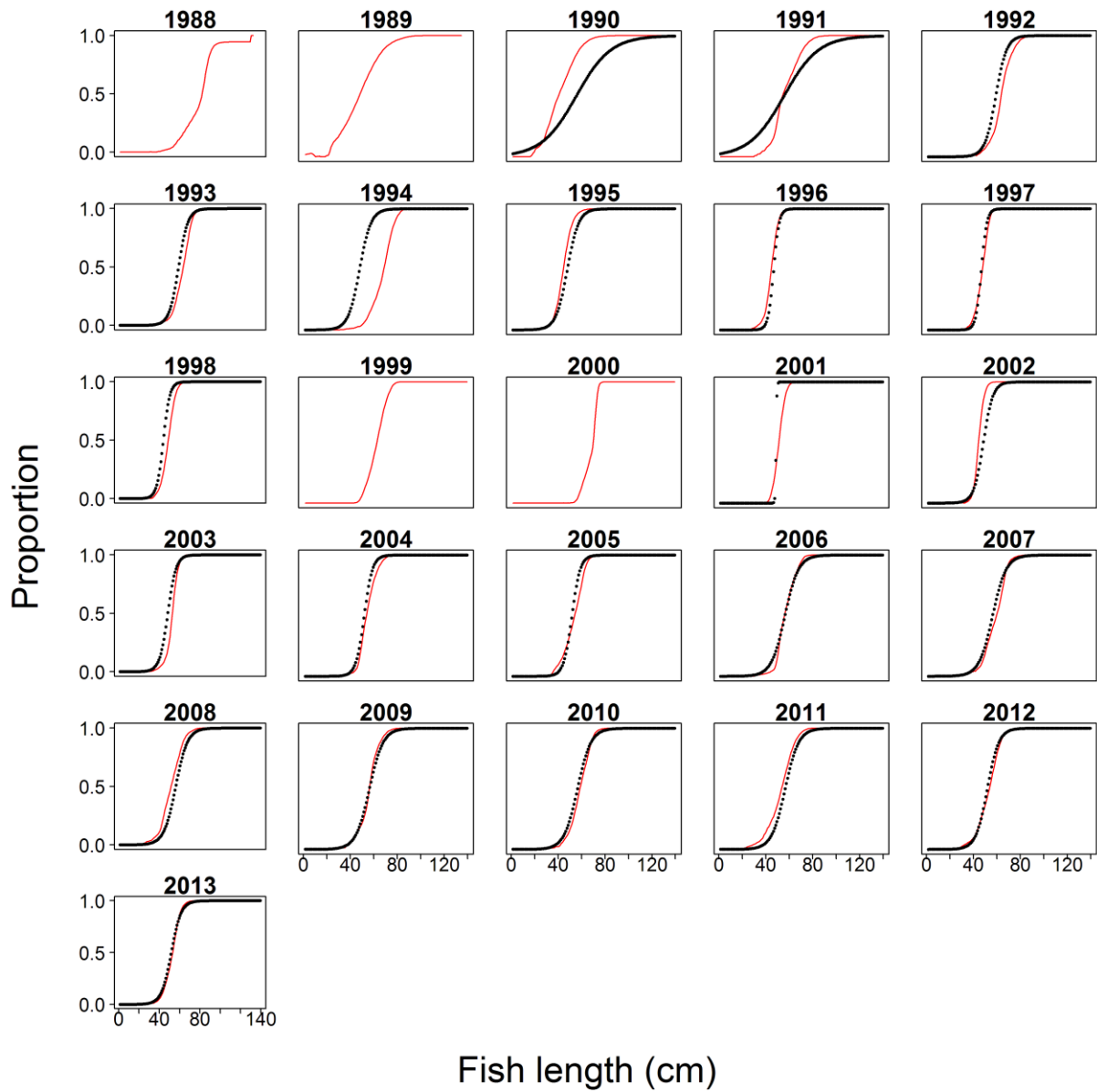
Fig. 13. Cod maturity ogives as probability, relative to 1, of being mature as a function of fish length. Estimated probabilities by the fit model in red color lines; Observed proportions in black color points.
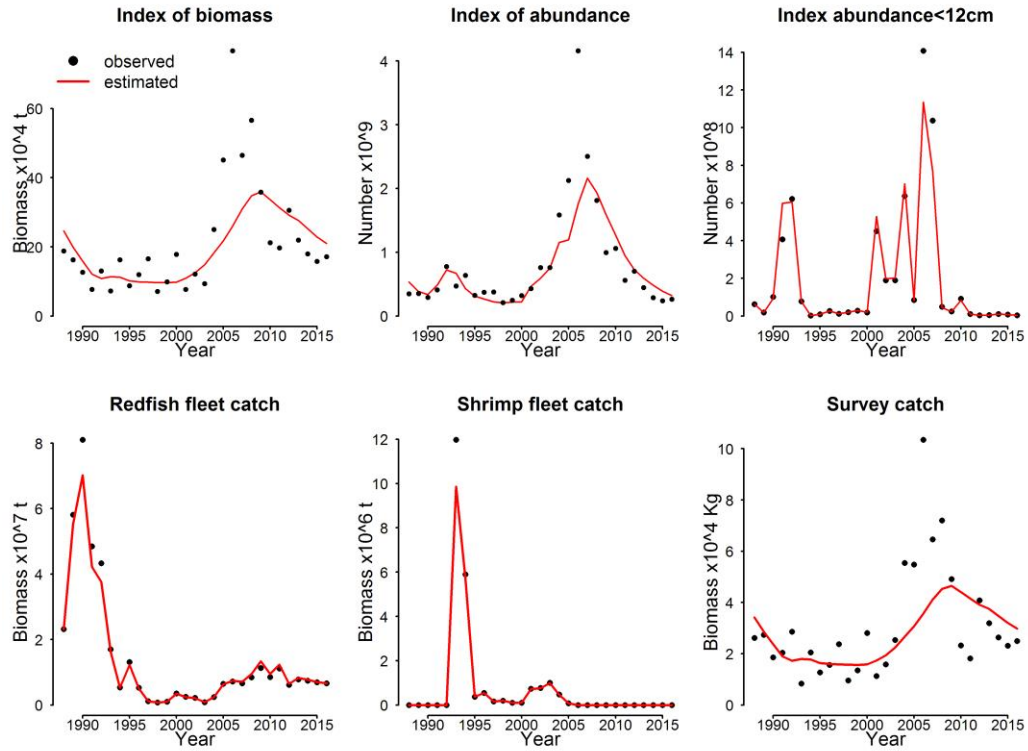
Fig.14. Redfish survey indexes of biomass, abundance and abundance of individuals smaller than 12 cm (from left to right in the first row). Total redfish catches in tones by the international redfish trawl, shrimp trawl (as by-catch) fleets.

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.
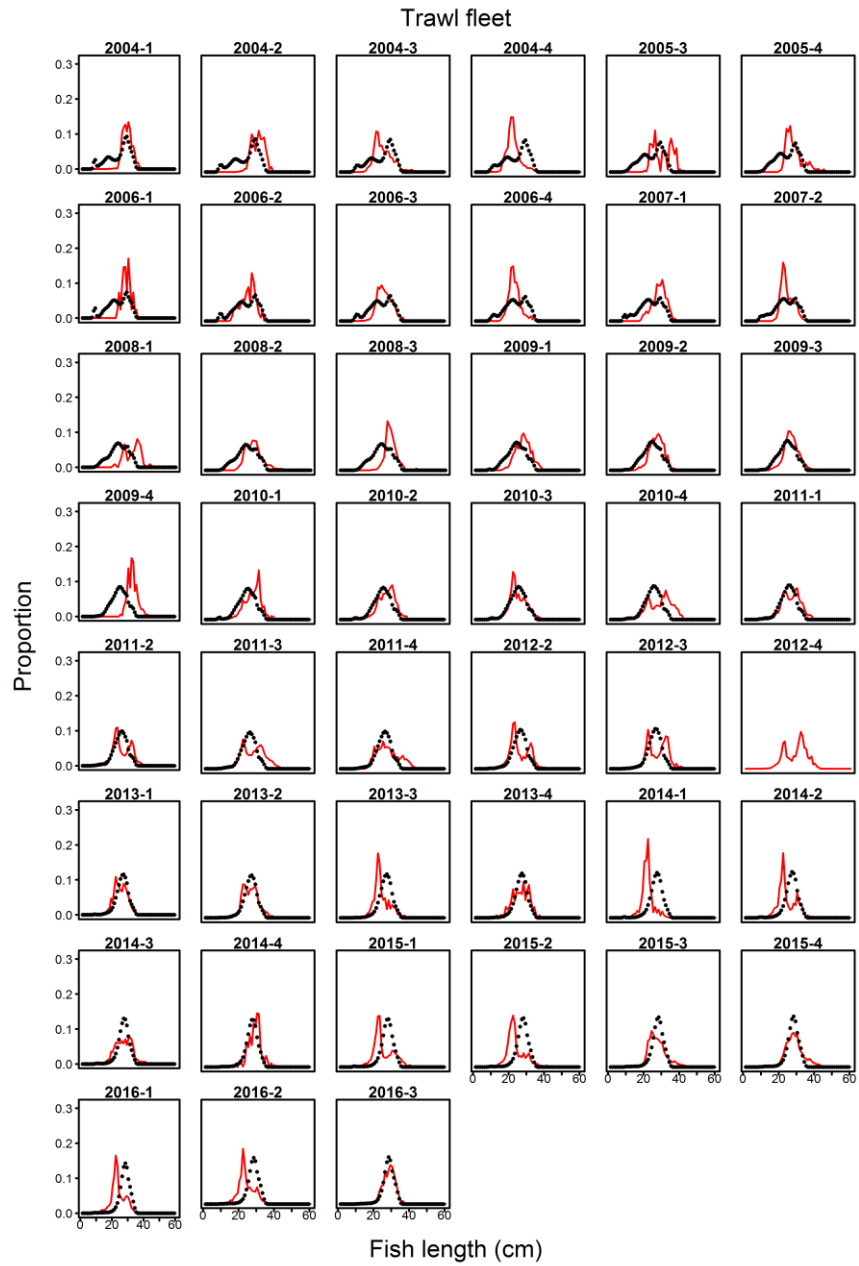
Fig. 16. Size distribution (in proportion relative to 1) of redfish catches in the redfish trawl fleet over the years 1988-2003. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 is winter of 1988). Red lines are the estimated values versus black points which represent the observed data.
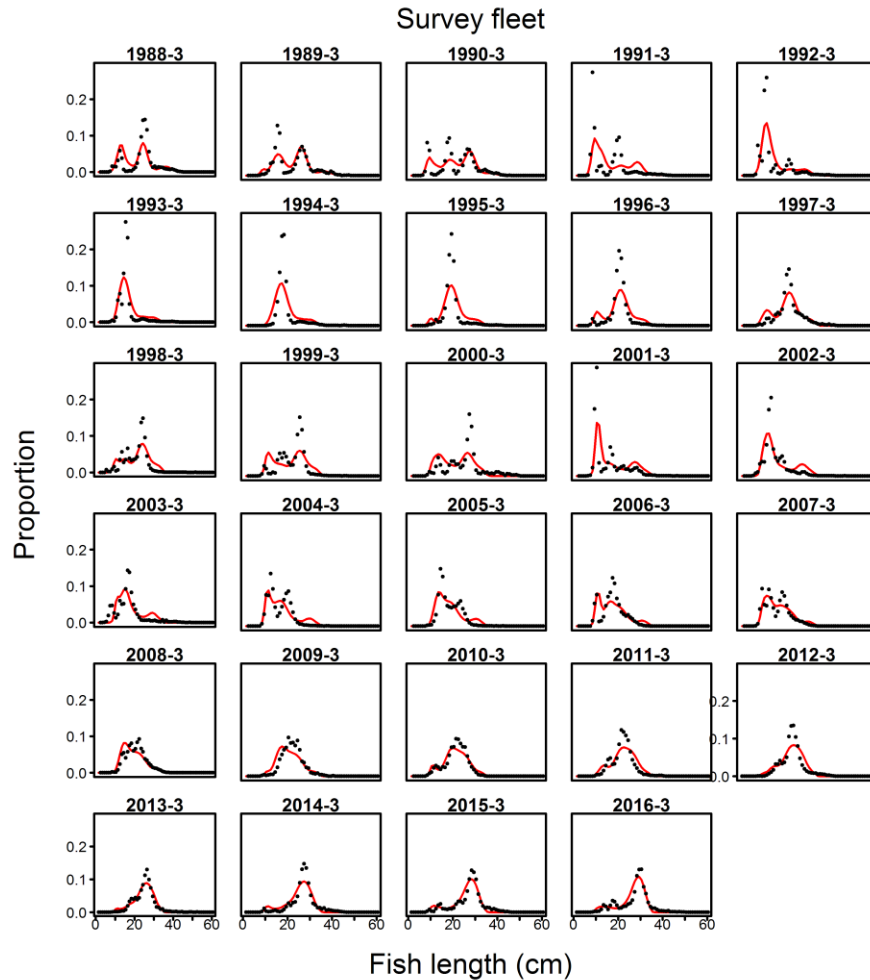
Fig.17. Size distribution (in proportion relative to 1) of redfish catches in the redfish trawl fleet over the years 2003-2016. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 is winter of 1988). Red lines are the estimated values 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.
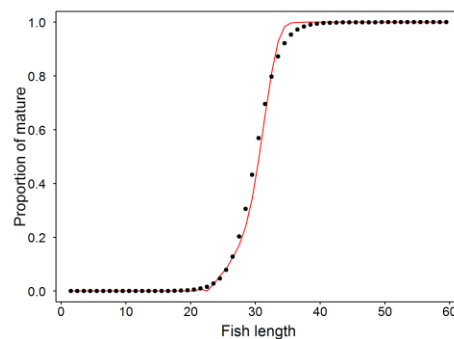

Fig.19. Estimated (red line) and observed (black points) proportion by length of mature female individuals in the redfish stock.
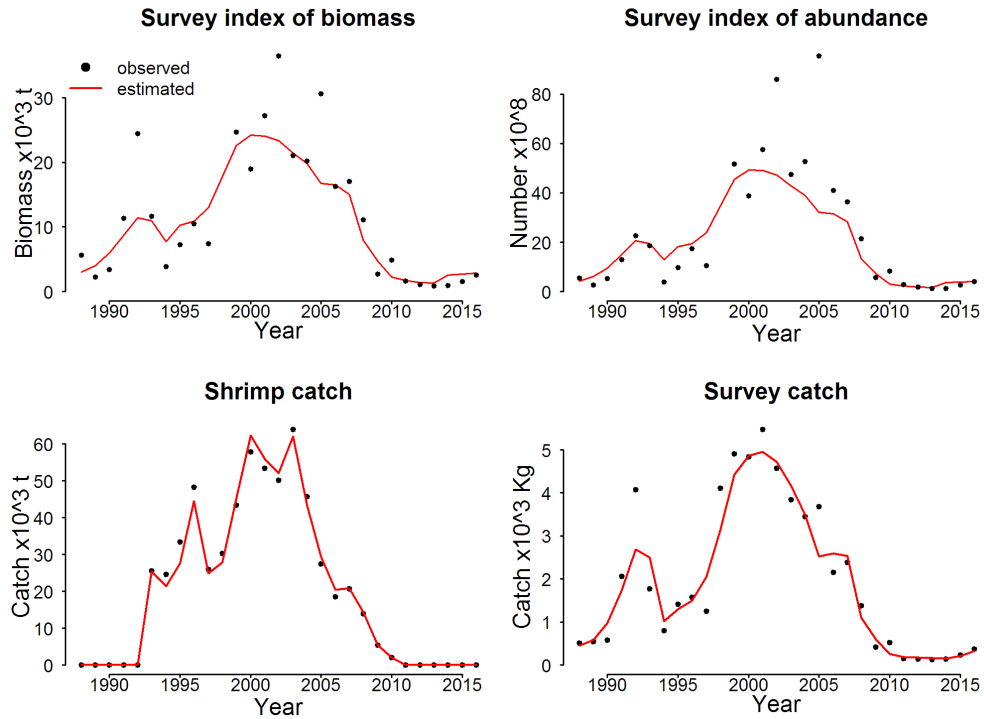
Fig. 20.　　　Shrimp survey indexes (swept area method) of biomass (upper-left panel) and abundance (upper-right), and catch in tones by the international trawl fleet (bottom-left), and in kg for the EU survey fleet (bottom right).
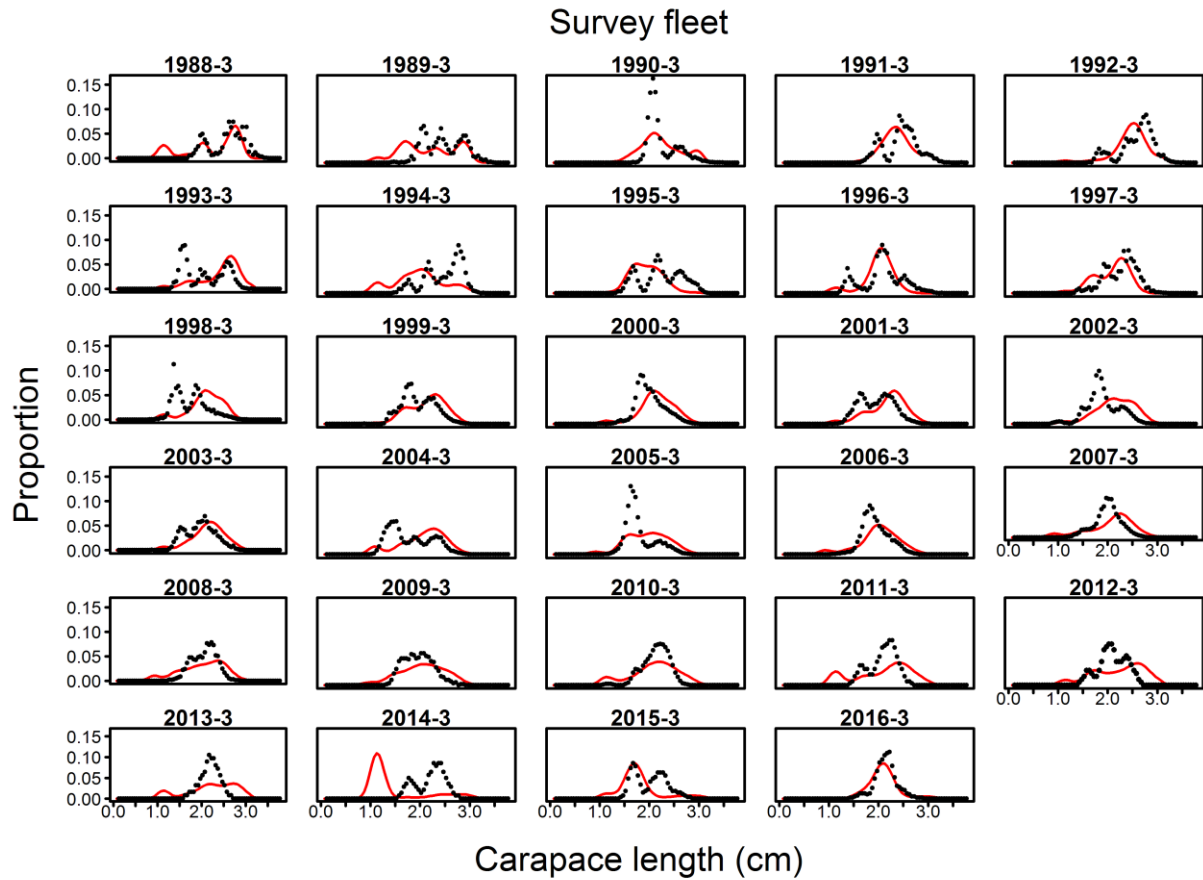
Fig. 21. Distribution by carapace length (in proportion relative to 1) of shrimp in the survey fleet. The label in each subpanel represents the year (Years: 1988 to 2016). For this fleet the season is always 3, when the survey takes place. Red lines are the estimated values versus black points which represent the observed data.
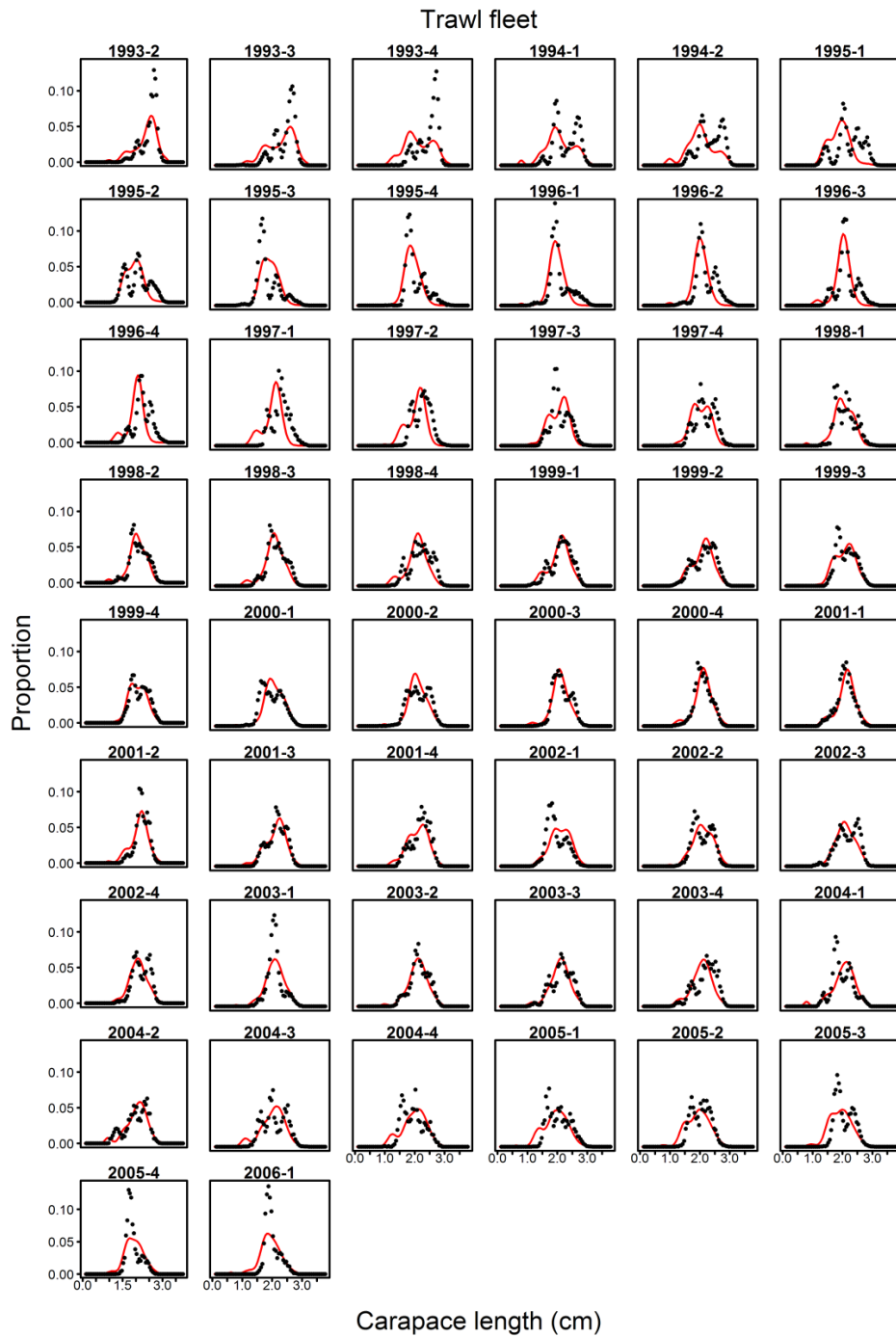
Fig. 22. Distribution by carapace length (in proportion relative to 1) of shrimp catches by the trawl fleets. The label in each subpanel represents the year and the season (Years: 1988 to 2016; Seasons: 1 to 4. For example 1988-1 is winter of 1988). Red lines are the estimated values versus black points which represent the observed data.
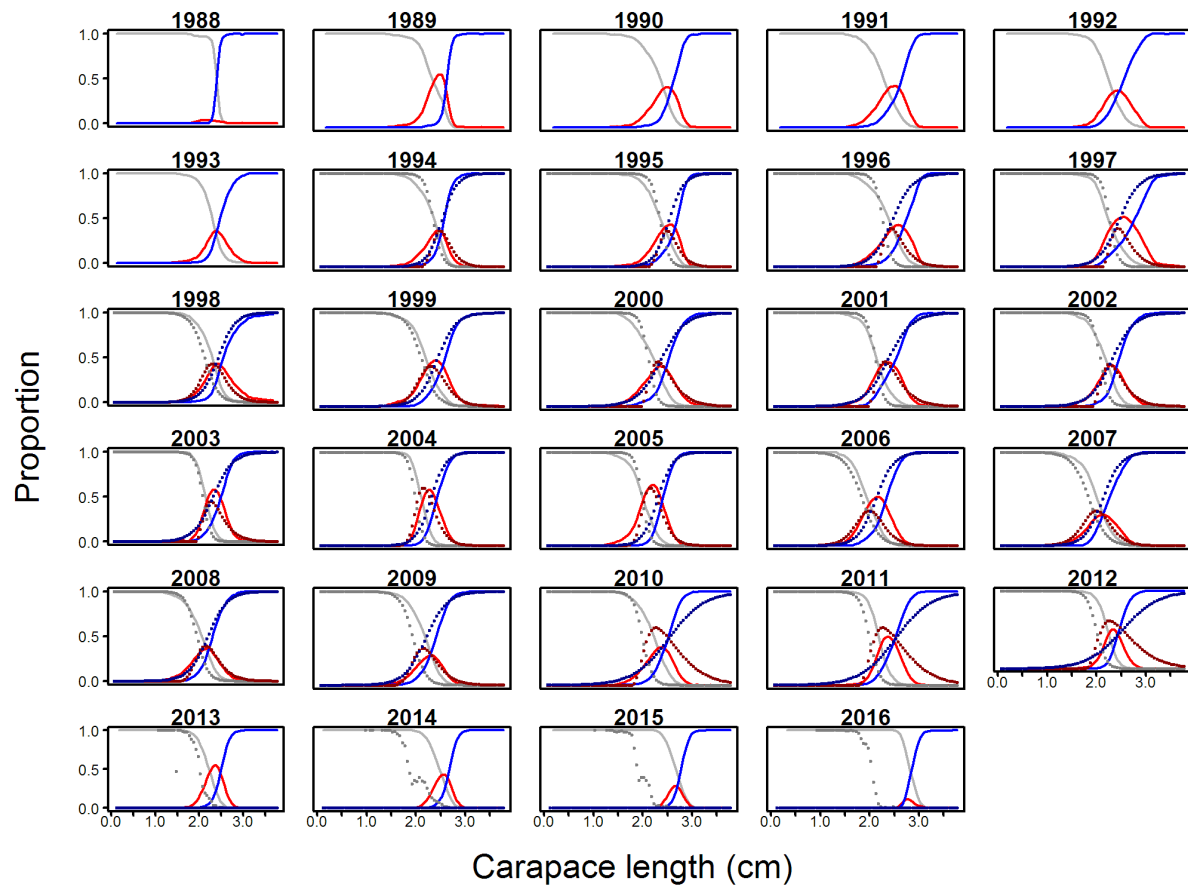
Fig.23. Shrimp sex change and maturity ogives as probability, relative to 1, of being male (grey color), female primiparous (red color) and female multiparous (blue color) with carapace length (in cm). Estimated probabilities by the fit model are represented by continuous lines while the observed proportions are represented by points.
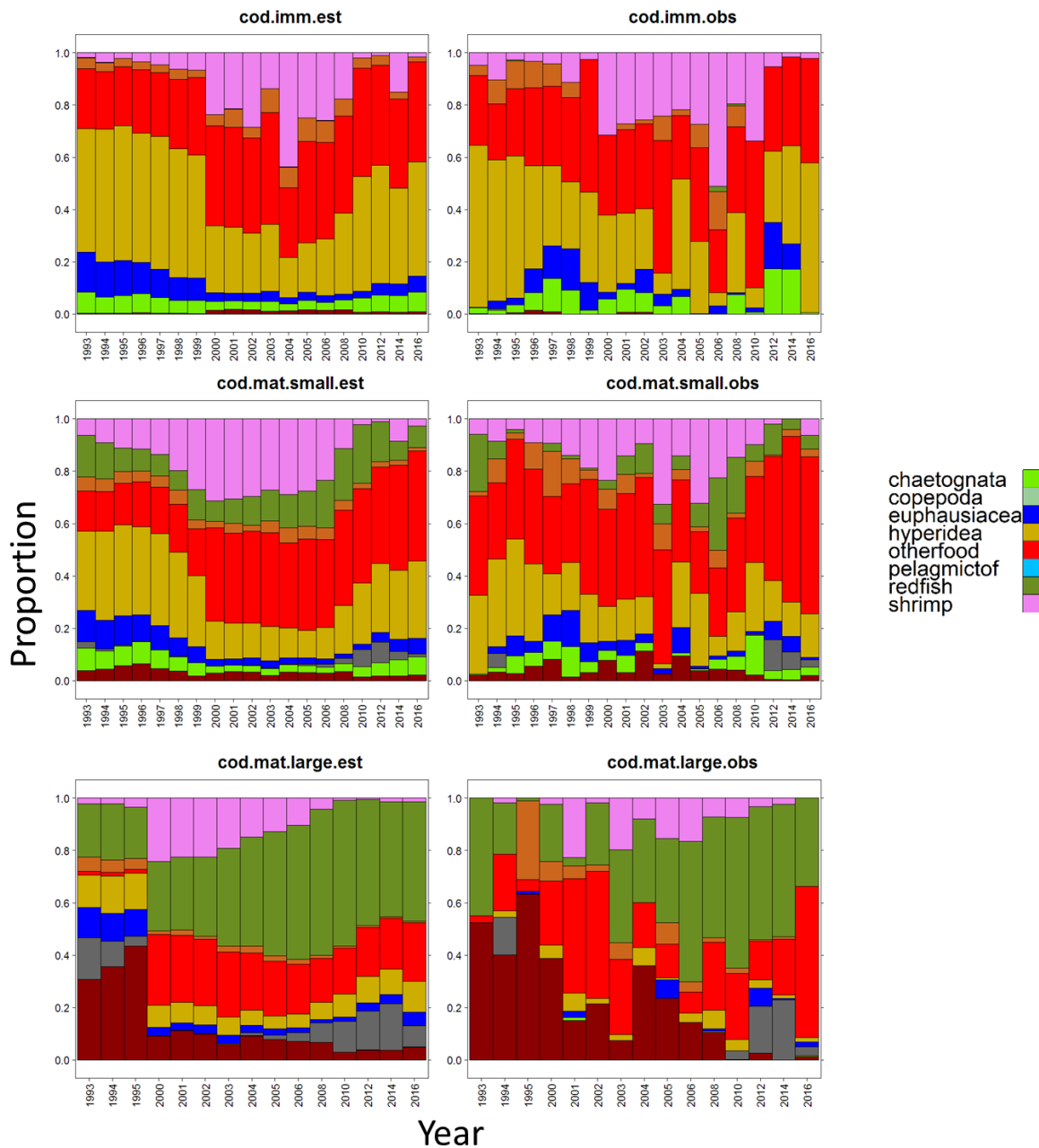
Fig. 24. Model estimated diet (left column) and observed diet during the EU survey (right column) for immature cod (cod.imm), small mature cod (<85cm; cod.mat.small) and large mature cod (>85cm; cod.mat.large), represented as the average proportion (relative to 1) of each prey in the stomach content from 1993 to 2016.

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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.

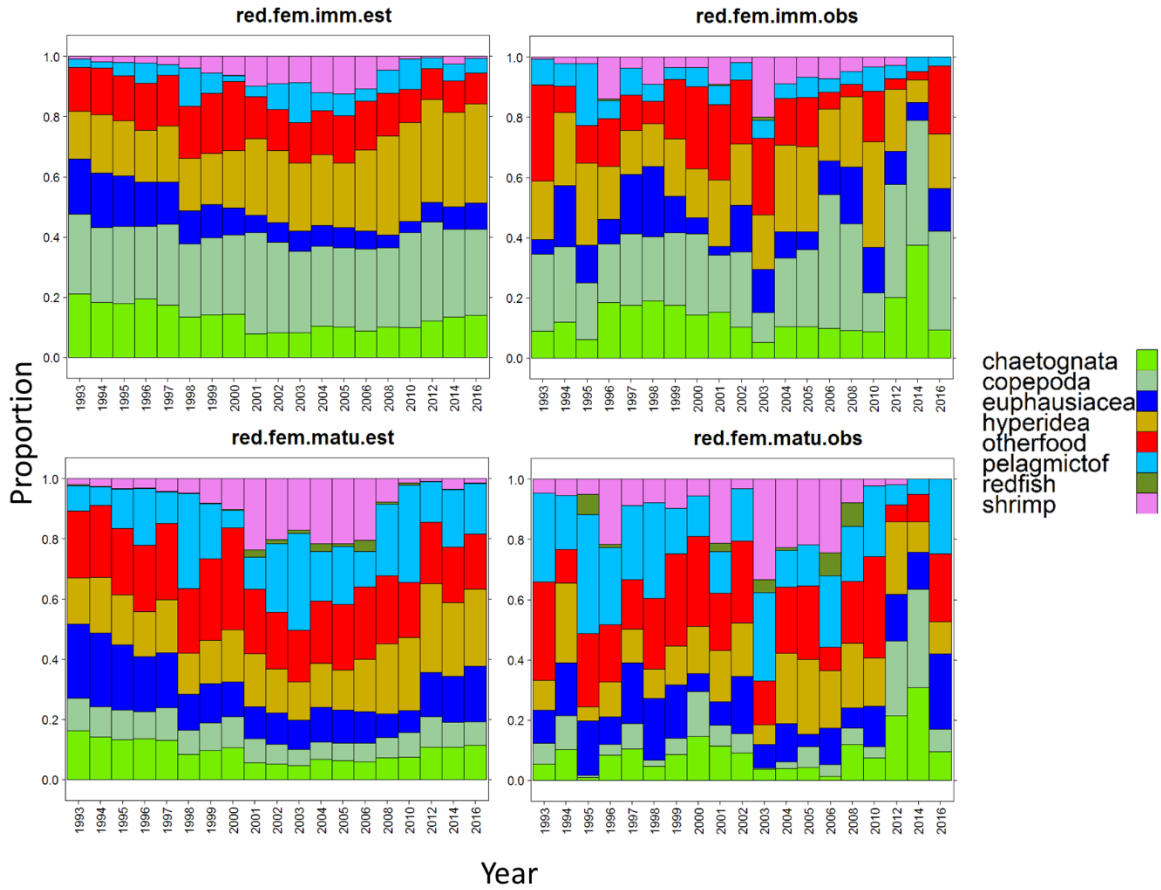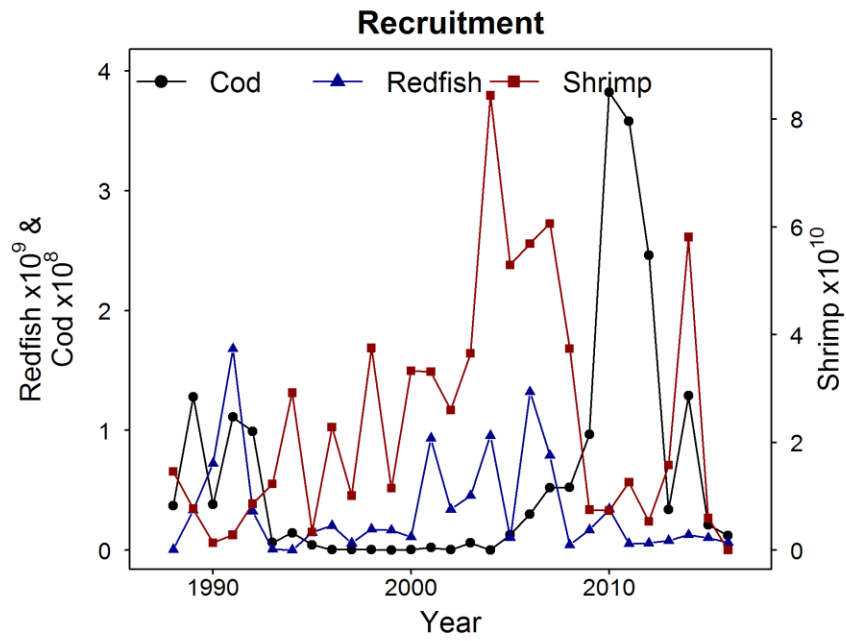**Fig. 26.** Annual recruitment at age 1 as estimated by the GADGET model for each of the three stocks.
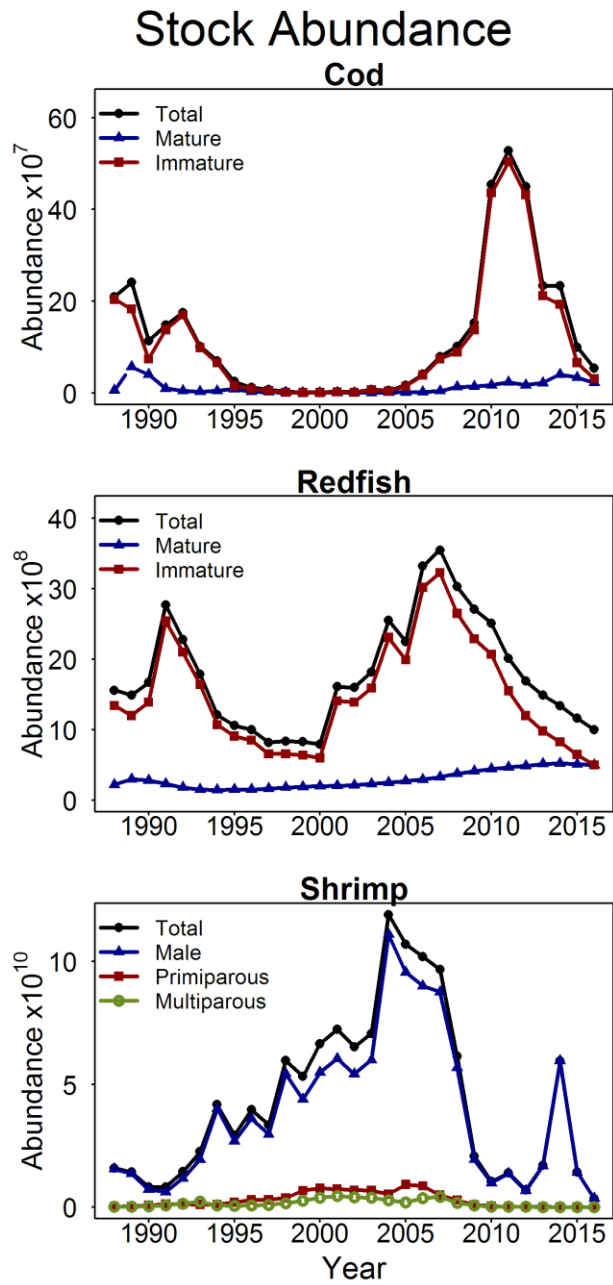
Fig. 27. Annual estimates of stock abundance, total and by maturity stage, for each of the three modeled stock (top: cod, middle: redfish, bottom: shrimp).
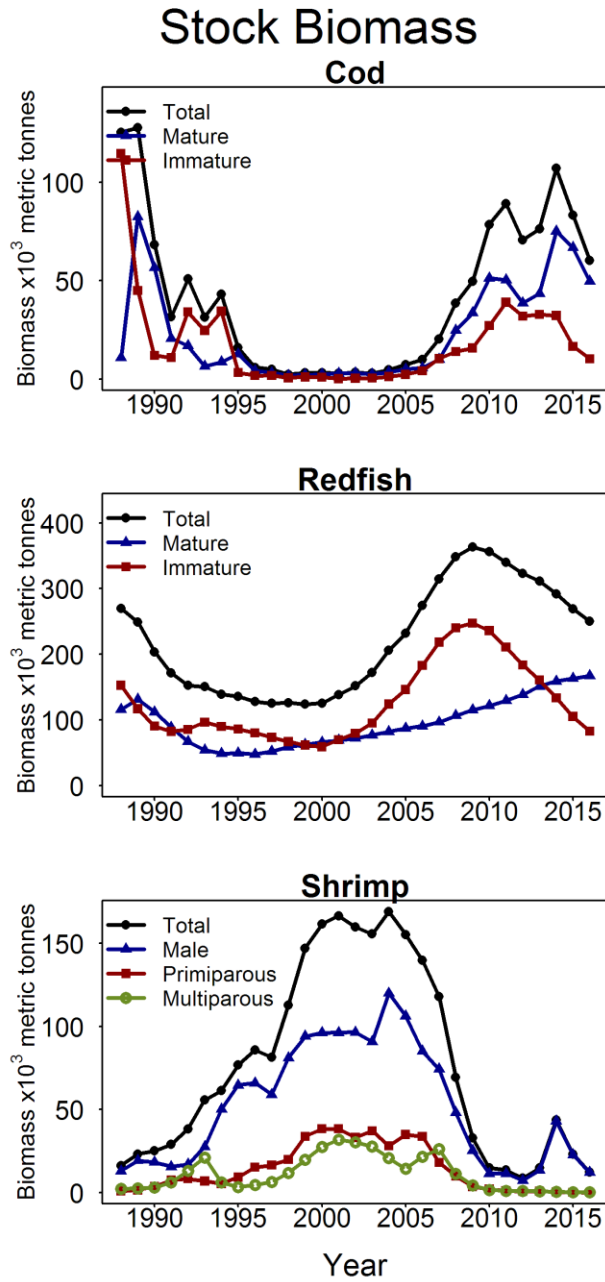
Fig.28. Annual estimates of stock biomass, total and by maturity stage, for each of the three modeled stocks (top: cod, middle: redfish, bottom: shrimp).
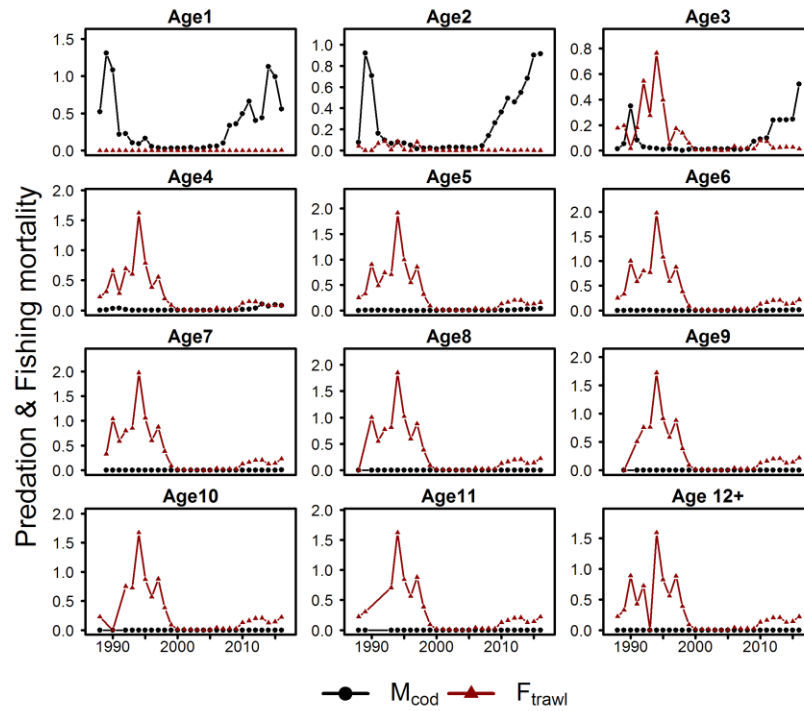
Fig. 29.   Predation mortality by cod (M_pred by cod) and fishing mortality by age in the modeled cod stock. The "Age 12+" pannel shows the mortality rates for individuals of age 12 and older.
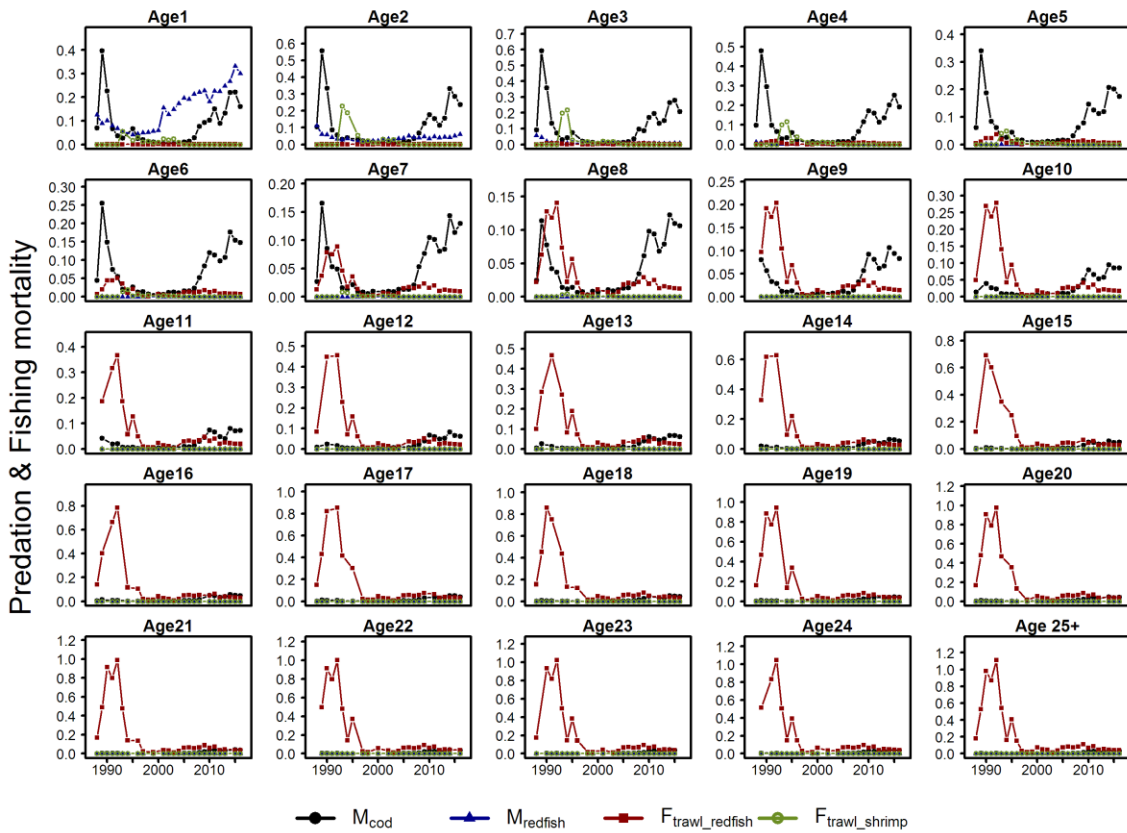
Fig. 30. Predation mortality by age in the modeled redfish stock, by cod (M_pred by cod), by redfish (M_pred by redfish) and fishing mortality by the redfish trawl fleet (F_red_trawl) and the shrimp trawl fishery (F_shrimp_trawl). The "Age 25+" pannel shows the mortality rates for individuals of age 25 and older.
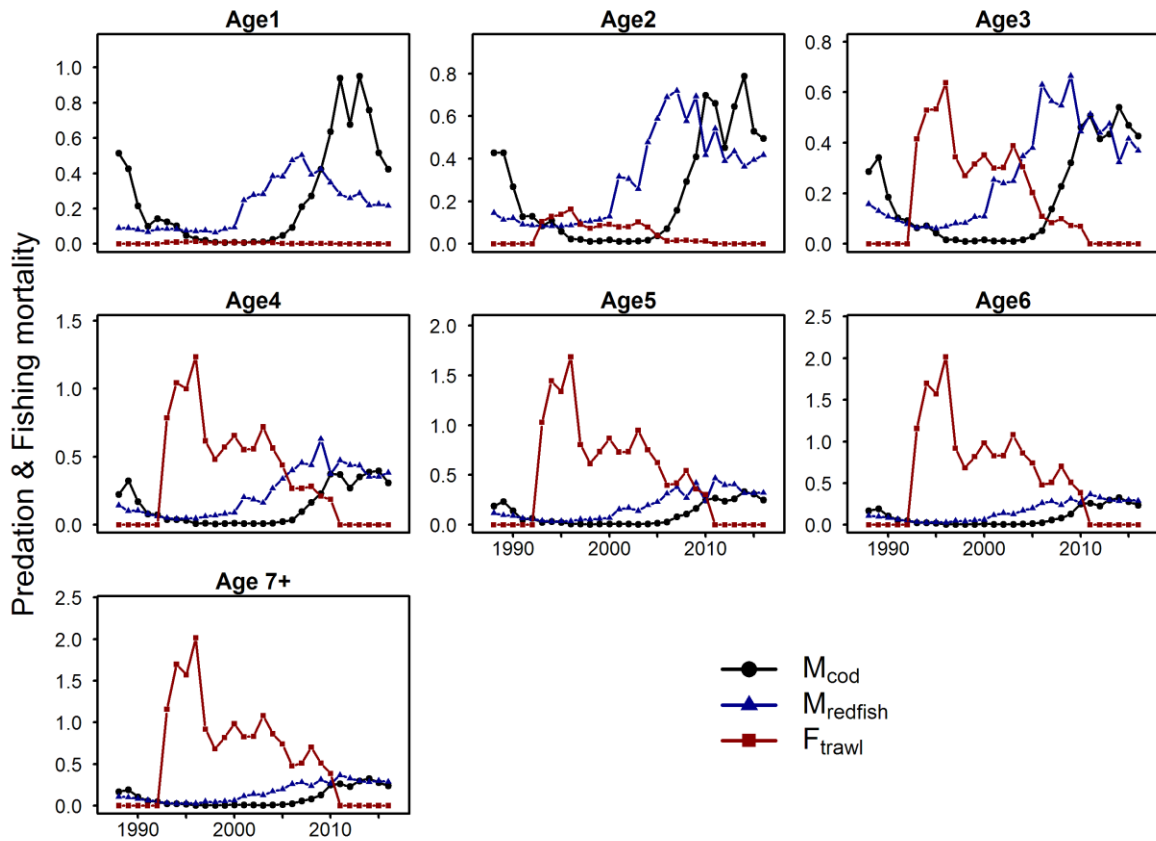
Fig. 31. Predation mortality by cod (M_pred by cod), by redfish (M_pred by redfish) and fishing mortality by the shrimp trawl fleet by age in the modeled shrimp stock.

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	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			
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.

	Male	Female primiparous	Female multiparous
Period	1988-2016		
Time step	3 months		
Age range	1-7		
Length range (cm)	$0.05cm\text{-}L_{50sex}{}^{*}$	$L_{50sex}{}^{*}\text{-}L_{50mat}{}^{*}$	$L_{50mat}{}^{*}\text{-}3.8cm$
Length resolution	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			
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.

Northwest Atlantic   Fisheries Organization

SCIENTIFIC COUNCIL MEETING – JUNE 2018

Estimates of natural predation and residual mortality for the Flemish Cap cod

by

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ABSTRACT

The current 3M cod stock assessment assumes that natural mortality is the same for all ages and constant over time. As part of the EU project SC03 "*Support to a robust model assessment, benchmark and development of a management strategy evaluation for cod in nafo division 3M*", different approaches to set total natural mortality by age and year have been tested. One of these approaches is using the matrix of natural mortality at age estimated with the multispecies model GadCap. These values of mortality at age are the result of predation mortality (M_{pred}) and a residual mortality (M_{resid}). In this document different approaches to estimate the residual natural mortality are explored. An Mresid of 0.35 is finally decided, and it is used to re-optimize the GadCap model parameters. A final matrix of total natural mortality ($M_{pred} + M_{resid}$) was produced to be used in the 3M cod benchmark.

INTRODUCTION

Currently, the assessment of the 3M cod is conducted assuming a constant natural mortality M overtime, the same for all ages. This M constant value is estimated during the fit of the XSA Bayesian model used to conduct the stock assessment. However, it has been discussed during the NAFO Scientific Council (SC) that the estimated values (last accepted value M=0.19) is too low and it seems not to agree with the biological characteristics (high growth rate) and age structure of this stock (shorter than in other cod stocks in the Northwest Atlantic).

The multispecies model GadCap (Pérez-Rodríguez et al. 2017) indicates that cannibalism in cod is a very important driver determining the survivorship or juvenile stages, especially when high recruitment events are coincident with high numbers of large individuals in the stock. The available cod stomach content analysis suggest that this occurred recently, over the period 2010-2014, when the highest recruitment events since 1988 were observed, combined with a high abundance of very large individuals. This above normal abundance of large individuals was the result of high survivorship of cohorts 2005-2008 due to a moratoria of more than 10 years (Pérez-Rodríguez et al. 2017), in combination with above normal growth rates (Pérez-Rodríguez et al. 2013). This increased cannibalism was captured and expressed in terms of higher predation mortality by the multispecies model GadCap.

One of the recommendations of the Workshop that took place in Vigo in March of 2017 (NAFO, 2017) was to estimate M outside the stock assessment model, and that the

benchmark process should further explore this issue and would selected a preferred option between a number of candidates possibilities (see the different options tested in González-Costas and González-Troncoso (2018)). It was decided that one of the candidate options, to be tested during the benchmark, would be the matrix of estimated total M by age and year (residual mortality (M_{resid}) plus predation mortality (M_{pred})) result of the up-to-date best gadget multispecies model GadCap result of the work developed in a parallel European Union Specific Contract, the SC05 ("Multispecies Fisheries Assessment for NAFO").

A direct output of GadCap model is the estimation of M_{pred}, that is estimated as result of the diet composition, consumption estimate, predator-prey length relationship, number of predators and number of prey. However, the M_{resid} is still a portion of remaining M that has to be provided to the model as fixed values. Estimating M internally during model optimization is extremely difficult, and often impossible, due to the interaction of M with the optimization of recruitment, growth and fishing catchability at age. For this reason, M_{resid} has to be estimated externally using an alternative option.

In this work different methods to estimate the Mresid based in the catch curve, the longevity and the loglikelihood methods are explored. Finally, a matrix with values of total M (M_{pred} and M_{resid}) is provided as result of optimizing the up-to-date best version of GadCap (model version GadCap_87) with the selected value of M_{resid}.

MATERIAL & METHODS

Gadget is a process-based model that allows the user to include several biological and ecological features into the model: one or more species each of which may be split into multiple components, multiple areas with migration between areas, predation between and within species, growth, maturation, reproduction and recruitment, as well as multiple commercial and survey fleets taking catches from the populations (Begley 2005, Begley and Howell 2004). The model is age and length structured, allowing length data to be used directly and for processes such as fishing selectivity and predation to be modelled on a length basis. The model is freely available and fully described at http://www.hafro.is/gadget/index.html. In this work the version 2.2.00 was employed. The structure of the multispecies model GadCap (Gadget multispecies model for the Flemish Cap) has been updated and improved over the basic framework presented in Pérez-Rodríguez et al., 2016 (Figure 1), where the main features were:

- Cod, redfish and shrimp were split in different sub-stocks based on sex, maturity state and diet composition.
- Immature and mature cod prey on immature cod, redfish and shrimp, whereas redfish prey on immature redfish and shrimp.
- Two fleets target cod (gillnetters and trawlers), one trawl fleet on redfish, and one trawl fleet on shrimp, which also catches redfish as by-catch, especially in years 1993 and 1994.

The project SC05 "Multispecies Fisheries Assessment for NAFO" is developed within the Framework Contract EASME/EMFF/2016/008 for the Provision of Scientific Advice for Fisheries Beyond EU Waters. The purpose of this specific study is to provide with 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. Finally, future steps and research activities to progress in the implementation of the multispecies assessment in the Flemish Cap, and extensively in the area NAFO will be identified. Within the task 2 an updated version of the multispecies model GadCap (Pérez-Rodríguez et al, 2016) has been produced, by:

- Extending the time period covered and used for model parameters fit to 1988-2016. Commercial fishing and survey data has been updated to cover this whole period:
  o Length distributions in commercial and survey fleets by season
  o Survey indices
  o Diet composition
  o Catch by season
  o Prey abundance estimates:
    ▪ survey data for demersal and pelagic fishes, Anarhichas, Micthophiids.
    ▪ CPR data: copepods, hyperiids, chaetognats, euphausiids.
  o Bottom water temperature
  o Review of trophic related parameters for the new period: suitability, prey-predator length relation.
  o Improvement in length-weight relationships
- A new longline fleet has been introduced for cod.
- The fit of cod growth curves have been improved to improve the fitting to the observed size distribution during the survey.
- Fitting to maturity ogives in cod has been improved to produce a better estimate of SSB and a more reliable estimate of cannibalism consumption.
- Improvement of growth models in redfish to better fit the survey size distributions.
- Introduction of survey indexes of abundance at age for cod and redfish in the model fitting.

- Use of catchdistribution loglikelihood component with mean weight at age

Once the GadCap model was updated, improved and newly optimized, the M_{resid} element was tackled. Three different approaches were used to estimate the M_{resid}:

1.- Catch curve methods

2.- Longevity method

3.- Loglikelihood score selection.

Different catch curve methods were applied: Chapman-Robson, Chapman-Robson corrected, Heincke, Linear Regression, Poisson model, Random intercept Poisson and Weighted Linear Regression (Millar 2014, Smith et al. 2012). The R package Fishmethods[70] was used to estimate the average Z over the group of selected ages. The criteria presented in Smith et al. (2012) were used to select the range of ages to be considered in the analysis, and the cohorts finally included in the study were selected based in the level of fishing effort and predation that those cohorts experienced.

The longevity method to estimate M_{resid} is presented in Hewitt and Hoenig (2005). This method is based in the assumption that the average M at age value is that one that allows that 1.5% of the individuals recruited in a cohort reach to the age defined as maximum longevity. For the Flemish Cap cod it was selected that this age is 12 years, based in the knowledge that the longevity in the Flemish Cap cod is shorter than in other cod stocks in the Northwest Atlantic. The range of cohorts from 1998 to 2002, when cannibalism and fishing was considered negligible, was selected to estimate the Z (Mresid for these cohorts) that would bring the percentage of the individuals at the beginning of the time series to the 1.5%.

The last selected method was the loglikelihood score selection. Different values of M_{resid} (constant for all ages) were tested in the models GadCap_87, and parameters were re-optimized. The M_{resid} that led to the lower Likelihood score was selected.

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[70] https://github.com/cran/fishmethods/tree/master/R

Based in the results of these methods, a final M_{resid} was selected and introduced in the model GadCap_87 as a fixed over time for all ages. Next the model GadCap_87 was re-optimized, and the total natural mortality ($M_{resid}+M_{pred}$) was estimated by age and year. This values would be finally provided to be used during the 3M cod benchmark held in Lisbon from 9th to 13th April.

RESULTS and DISCUSSION

The updated database and the changes introduced in different elements of the models resulted in an improved version with better fit to survey size distribution, abundance indexes and maturity ogives. The results and diagnostics are presented in a different working document (NAFO, 2018).

The criteria presented in Smith et al. (2012) were used to select the range of ages to be considered in the catch curve metods. The application of these criteria resulted in an age range from 4 to 8. The range of cohort selected to estimate the M_{resid} was from 1996 to 2002 based in the fact that for this cohorts, the fishing mortality at ages 4 to 8 was negligible due to the directed cod fishing moratoria, and cannibalism predation mortality was not relevant, based in the information available for the diet composition. Hence, it may be assumed that the estimated average Z mortality with these catch curve methods for the range of ages 4-8 and cohorts 1996-2002 is representative of the M_{resid}.

The logarithm of the EU survey abundance by age is presented in Figure 2. The application of the different methods indicated in previous section produced very diverse and a wide range of Z values (figure 3). The average Z for the cohort groups of (1996-2002) produced values that ranged from 0.4 to 1.29 (table 1).

For the longevity method to estimate M_{resid} it was selected that the maximum longevity of the Flemish Cap cod is age 12, based in the knowledge that the longevity in the Flemish Cap cod is shorter than in other cod stocks in the Northwest Atlantic. The range of cohorts from 1998 to 2002, when cannibalism and fishing was considered negligible, was selected to estimate the Z (Mresid for these cohorts) that would bring the percentage of the individuals at the beginning of the time series to the 1.5%. The resulting Mresid with this method was 0.35.

The last selected method was the loglikelihood score selection. Different values of M_{resid} (constant for all ages) were tested in the models GadCap_87, and parameters were re-optimized. The M_{resid} that led to the lower Likelihood score was selected. Based in this method the M_{resid} is 0.4.

Based in the results of these methods, a final M_{resid} was selected and introduced in the model GadCap_87 as a fixed over time for all ages. The seleted Mresid for a final optimization of GadCap and provision of a matrix of M (M_{resid} + M_{pred}) was 0.35. This matrix is presented in table 3.

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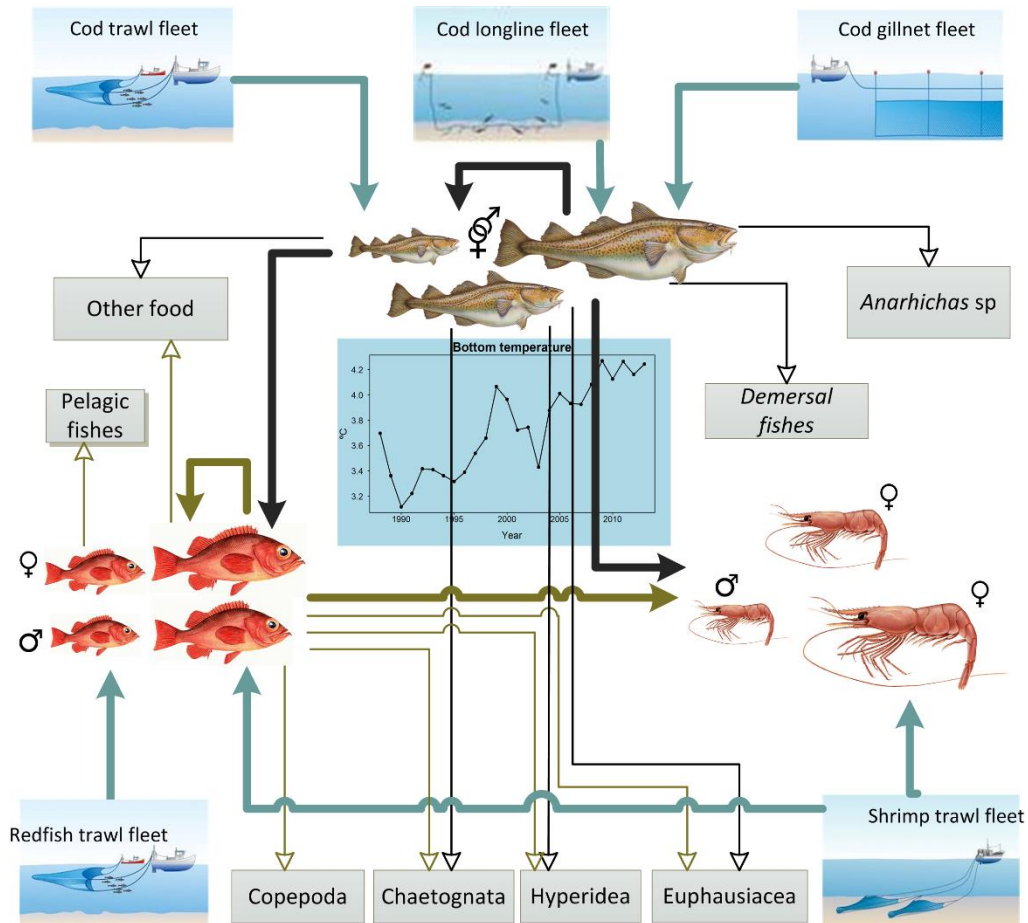
Fig. 1. Trophic interactions and commercial fleets modelled in GadCap Pérez-Rodríguez et al. (2017). Cod, redfish and shrimp are fully dynamically modelled, whereas species/prey groups in dark grey text boxes are incorporated as time series or constant values.
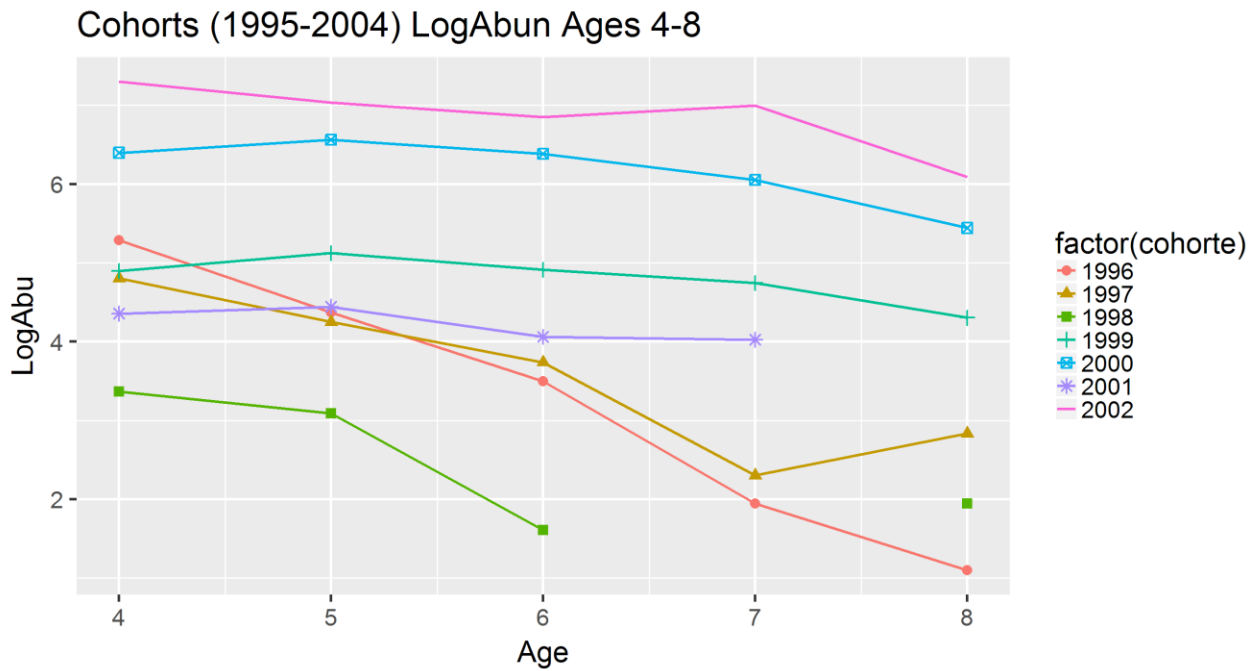
Fig.2. Logarithm of the abundance at age estimated during the EU Flemish Cap survey for the different cohorts used in the catch curve analysis and for the range of ages 4 to 8.
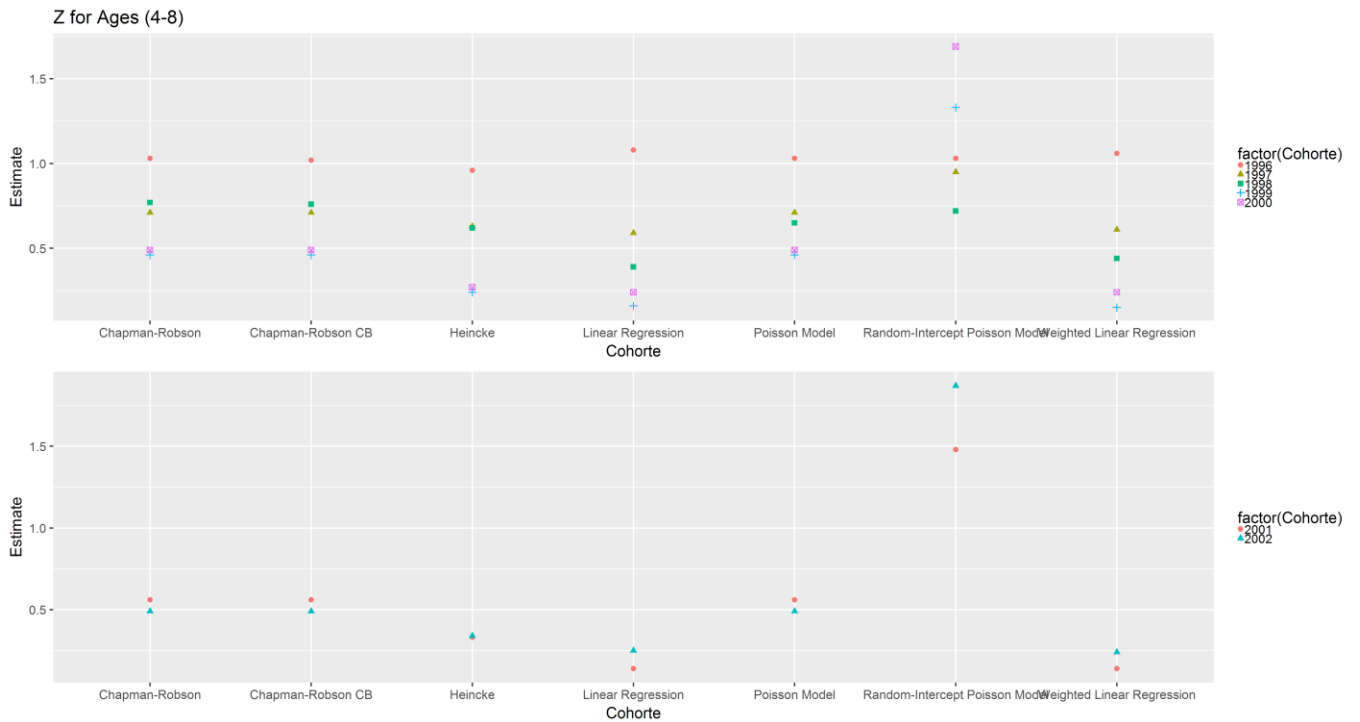
Fig. 3. Z estimate using the different catch curve methods implemented with the R package Fishmethods for cohorts 1996-2002 and range of ages 4 to 8.

Likelihood score

Fig. 4. Loglikelihood score resulting of applying different values of M_{resid} by age and year during the optimization of GadCap.

TABLES

Table 1. Average Z for the group of cohorts 1996-2002 estimated using the different catch curve methods for the group of ages 4 to 8.

Catch curve method	Average Z
Chapman-Robson	0.644285714
Chapman-Robson CB	0.641428571
Heincke	0.484285714
Linear Regression	0.407142857
Poisson Model	0.627142857
Random-Intercept Poisson Model	1.295714286
Weighted Linear Regression	0.411428571

Table 2. Percentage of the recruited number of individuals at age 1 that reach age 12 (maximum longevity)

| cohort	M_0.175	M_0.20	M_0.25	M_0.30	M_0.35	M_0.40	M_0.45	M_0.50
1996	9.57	7.5	4.56	2.69	1.59	0.93	0.54	0.31
1997	11.48	8.74	5.1	2.92	1.69	0.98	0.56	0.32
1998	11.24	8.58	4.98	2.86	1.64	0.95	0.55	0.31
1999	8.14	6.21	3.6	2.07	1.17	0.67	0.39	0.22
2000	6.5	4.93	2.85	1.62	0.9	0.51	0.29	0.16
2001	4.71	3.57	2.04	1.14	0.63	0.35	0.19	0.1
2002	2.61	1.96	1.12	0.6	0.31	0.17	0.09	0.04
Average	7.75	5.92714	3.46429	1.98571	1.13286	0.65143	0.37286	0.20857

Table 3. Total M ($M_{resid} + M_{pred}$) estimated with the model GadCap once M_{resid} is fixed as 0.35 for all ages and years.

age	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
1	0.766	1.125	0.91	0.455	0.479	0.406	0.41	0.471	0.392	0.373
2	0.397	0.842	0.656	0.41	0.374	0.389	0.395	0.419	0.385	0.362
3	0.358	0.388	0.581	0.367	0.355	0.355	0.36	0.357	0.362	0.358
4	0.352	0.356	0.368	0.361	0.352	0.351	0.351	0.351	0.351	0.353
5	0.35	0.351	0.353	0.351	0.351	0.35	0.35	0.35	0.35	0.35
6	0.35	0.35	0.351	0.35	0.35	0.35	0.35	0.35	0.35	0.35
7	NA	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
8	0.35	NA	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
9	0.35	0.35	NA	0.35	0.35	0.35	0.35	0.35	0.35	0.35
10	0.35	0.35	NA	NA	0.35	0.35	0.35	0.35	0.35	0.35
11	0.35	0.35	0.35	NA	NA	0.35	0.35	0.35	0.35	0.35
12	0.35	0.35	0.35	0.35	0.35	NA	0.35	0.35	0.35	0.35

age	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
1	0.362	0.367	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
2	0.359	0.363	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
3	0.351	0.353	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
4	0.351	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
5	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
6	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
7	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
8	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
9	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
10	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
11	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
12	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35

age	2008	2009	2010	2011	2012	2013	2014	2015	2016
1	0.35	0.35	0.876	0.822	0.581	0.592	1.441	1.425	0.809
2	0.35	0.35	0.692	0.683	0.622	0.656	0.693	0.894	0.789
3	0.35	0.35	0.412	0.457	0.506	0.497	0.517	0.48	0.527
4	0.35	0.35	0.365	0.37	0.392	0.403	0.384	0.415	0.392
5	0.35	0.35	0.352	0.354	0.356	0.363	0.361	0.364	0.373
6	0.35	0.35	0.35	0.351	0.352	0.353	0.353	0.356	0.356
7	0.35	0.35	0.35	0.35	0.35	0.351	0.351	0.352	0.352
8	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
9	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
10	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
11	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
12	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35

ANNEX VⅡI: NAFO SCR Dᴏᴄ. 19/017

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SCIENTIFIC COUNCIL MEETING – JUNE 2019

EU SC05 project: "Multispecies Fisheries Assessment for NAFO". Estimation of multispecies based HCRs and use of a multispecies MSE framework to assess the risk of collapse and the fishery-ecological trade-offs.

by

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ABSTRACT

The multispecies tier is an essential part of the NAFO roadmap for an Ecosystem Approach to Fisheries management, connecting the "Ecosystem" tier with the "Single species" tier. 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 a multispecies approach in NAFO, with the Flemish Cap as a case study. In this paper, an MSE framework is developed, with GadCap (cod, redfish and shrimp Gadget multispecies model in the Flemish Cap) as operating model. Reference points and Harvest Control Rules (HCR) are designed taking into account the multispecies interactions. Finally, traditional single species and new multispecies HCRs are assessed from the precautionary and MSY perspectives. The results suggest that HCRs designed under a single species approach are not precautionary for all the stocks and that it is not possible maintaining the 3 stocks above B_{lim} at the same time due to strong trophic interactions. Disregarding one stock may allow finding precautionary multispecies reference points for the other stocks. Precautionary HCRs for two stocks at once were only found when shrimp SSB in relation to B_{lim} was disregarded. The results

showed that the two stages HCRs for cod reduces predation and increases probability of cod and redfish being above B$_{lim}$. This result supports that alternative two stage HCRs, or some other HCRs with other shapes, may increase the possible combinations of fishing pressure for these three stocks.

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 (EAF) roadmap. With the aim of contributing to the development of an EAF in the NAFO area, the EU DG-MARE launched, in year 2017, 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. As a first step (Task 2 of SC05 project) the multispecies model GadCap (Flemish Cap cod, redfish and shrimp multispecies Gadget model; Pérez-Rodríguez et al. (2016)) was updated until 2016, and several biological, ecological and fisheries components were improved (Pérez-Rodríguez and González Troncoso 2018). This model was used to provide alternative values of natural

mortality during the 3M cod benchmark (see Pérez-Rodríguez and González-Costas (2018)).

However, within the NAFO roadmap for an EAF (NAFO 2010), the interaction between the tier 2 (multispecies level) and tier 3 (single species level) is envisioned not only by providing estimates of ecological parameters like the natural mortality, but specially supporting decisions about management strategies. With the intention of contributing in this task, the SC05 project aims at developing an MSE framework, with GadCap as operating model (i.e. a multispecies MSE), that allows estimating reference points and designing Harvest Control Rules (HCR) that take into account the multispecies interactions, and where traditional single species and potential new multispecies HCRs could be assessed from the precautionary and MSY perspectives (Task 3 of SC05 project). This MSE framework could then be used to provide a first analysis of the implications of moving from single to multispecies assessment and management, the trade-offs from an ecological perspective. In the present working document, the methods, main achievements and future work is presented, HCRs are defined using single and multispecies criteria, and their performance is assessed using the multispecies MSE framework.

MATERIAL AND METHODS

Criteria for the definition of Precautionary and MSY reference points in NAFO

NAFO Scientific Council (SC) PA framework commenced to be developed in 1997. This initial framework incorporated limit, buffer and target reference points, specified in terms of both fishing mortality and SSB. In 2003 a new PA framework was developed (NAFO 2004), that described zones of gradual increase in collapse risk and defined proposed management strategies and courses of action within each zone. These zones (Figure 1) were delimited by limit and buffer reference points (B_{lim}, B_{buf}, F_{lim} and F_{buf}). The reference points associated with the 2003 Framework were defined as follows:

Fishing Mortality Reference Points

• F_{lim} = F limit, is a fishing mortality rate that should only have a low probability of being exceeded (usually around 10% risk). F_{lim} cannot be greater than fishing mortality providing MSY (F_{MSY}).

• F_{buf} = F_{target}: F target, is a fishing mortality rate lower than F_{lim} that is required in the absence of analyses of the probability that current or projected F exceeds F_{lim}. It is an common approach in NAFO estimating F_{target} as $2/3*F_{lim}$. This is the approach that will be followed in this project, since gadget is a deterministic type model that does not produce estimates of uncertainty.

Spawning stock biomass reference points

• B_{lim}: B limit, is a spawning stock biomass level, below which stock productivity is likely to be seriously impaired, that should have a very low probability of being violated (usually around 10% risk).

• B_{buf} = $B_{trigger}$: B trigger, is a stock biomass level above B_{lim} that is required in the absence of analyses of the probability that current or projected biomass is below B_{lim}.

In this study the NAFO PA framework has been followed in the determination of the precautionary (B_{lim} and $B_{trigger}$) and MSY based reference points (F_{MSY} and F_{target}) to define single and multispecies HCRs. B_{lim} and $B_{trigger}$ were estimated for cod, redfish and shrimp using their respective SSB-Recruitment relationship, as it is explained in the next section. F_{MSY} and F_{target} were estimated for each stock using the multispecies model GadCap to run long term simulations. The settings that allowed GadCap being used as a simulation model are explained in the next section. HCRs were designed in a way that F=0 when SSB≤B_{lim} (Figure 6.3-3), i.e. a traditional one stage hokey stick HCR. However, as it is presented later, two stage HCRs were also tested.

Modelling the SSB-Recruitment relationship and the estimation of B_{lim} and $B_{trigger}$

The SSB estimated annually in GadCap over the period 1988-2015 (Pérez-Rodríguez and González Troncoso 2018) was used to model the recruitment estimated in the period 1989-2016, i.e. a one year delay between the SSB and the recruitment values that accounts for the fact that the recruitment in GadCap is modeled at age 1 for all the three stocks. There is little evidence in the available data to select the form of the SSB-recruitment function for the Flemish Cap stocks. However, the Ricker SSB-Recruitment model has been used due to its capacity to avoid unrealistic high estimates of recruitment produced by extremely high levels of SSB in some of the scenarios, as well as contributing to account for the cannibalistic behaviour observed in cod and redfish in the Flemish Cap (Pérez-Rodríguez et al, 2016).

$$R = \mu \, SSB \, e^{-\lambda \, SSB} \qquad (1)$$

Where *R* is the recruitment in number of individuals at age 1, the SSB is the Spawning Stock Biomass, and μ and λ are parameters estimated when fitting the model.

The fitted Ricker SSB-Recruitment models was used in the estimation of both precautionary and MSY reference points. For the estimation of precautionary reference points it is used directly, and B_{lim} (B_{lim_50} and B_{lim_75}) and $B_{trigger}$ were defined as the SSB at which the recruitment was, respectively, 50%, 75% and 90% of maximum predicted recruitment. For the calculation of MSY related reference points, these SSB-recruitment models were used as part of the simulation model (GadCap), allowing the long term projection of the modelled system by determining the number of recruits that will enter in the population every year as a function of the SSB.

Adapting GadCap for long term projections

GadCap is a gadget stock assessment model which structure has been created to assess the state and dynamic of the cod, redfish and shrimp Flemish Cap stocks and their respective fisheries as a function of the recruitment process, the fishing activity itself and the ecological interactions that occur between them (Pérez-Rodríguez and González Troncoso

2018). In order to estimate the MSY reference points (F_{target}) for cod, redfish and shrimp, GadCap has been used to run long term forecast simulations. Several different fishing pressure values have been used in these simulations with the intention of finding the F value that produce the highest productivity with the lowest ecological risk. In preparing the GadCap model to run forward simulations, several elements have to be modified in the structure of the model.

The first element changed in the structure of GadCap was the time frame, which was modified to cover the period from 2017 to 2050. This time period was considered enough for the three stocks to reach the equilibrium in their dynamics, necessary to define the F_{target}. Next, the Ricker SSB-Recruitment model described in the previous section, was incorporated to the structure of GadCap. When running the long term simulations, this model determined the new individuals that entered in the population at age 1 every year based in the level of the SSB in the previous year.

After setting the time period and the SSB-Recruitment, all the parameters needed to simulate the different processes affecting the dynamic of the three stocks were defined using the parameter values that were optimized when fitting the historic period databases. These processes were: annual growth, length-weight relationship, maturation, sex change (from male to female primiparous shrimp), suitability of each prey for each of the predators, gear selectivity for the trawl fleets, residual natural mortality at age. These parameters were defined as the average value of the values optimized/fixed in GadCap during the period 2014-2016.

Deterministic long term forecast and selection criteria to define single and multispecies F_{target} reference points

Once the multispecies model GadCap was set up as described in the previous section, fishing activity was the only process to be defined, the level of fishing mortality F that each of the three trawl fleets (one per stock) was going to produce on each targeted stock in those long term simulations over the period 2017-2050. Running multiple independent simulation over this period with different fishing pressure allows assessing how the stock dynamic and the fishing catches (SSB and yield) changes over time as a function of F. This is the traditional method used to find the optimal F (usually F_{MSY}) when using numerical models. In a single species approach, for each stock several levels of F need to be tested. In this work, 20 different values of fishing mortality F were simulated for cod, redfish and shrimp (Table 1). However, in a multispecies approach it is necessary assessing the effect of combined levels of F for all the stocks that show strong interactions, since the level of F in one stock will affect the productivity in the other stocks. In our study, this resulted in 20^3=8000 combinations of Fs, i.e. 8000 different long term forecast simulations.

Gadget is a deterministic model, and hence, for each combination of F the forecast simulation produced, by stock, a single estimate of catch, SSB, abundance at age, etc. Accordingly, the probability of a given combination of Fs to drive the SSB of each of the stocks bellow B_{lim} cannot be assessed with GadCap at this first stage. The risk assessment associated to each F level combination will be conducted in a second stage using the

multispecies MSE framework developed as part of the subtask 3.3 (see the next section). Despite of this limitation the deterministic approach developed in this task 3.2 can be used as a first step to reject those combinations of F that, already in a deterministic simulation, would bring the stocks below their respective B_{lim}.

In order to assess if a given combination of F would, in the equilibrium, bring the stocks bellow B_{lim} in a deterministic way, the mean SSB in the last 15 years of the simulated period (2035-2050) was estimated. The long term yield or catch associated to that combination of Fs was also assessed by estimating for each stock the mean catch during the that same period. This information about mean SSB and yield in the period 2035-2050 for each stock was used to select combinations of reference points for all the three stocks that will be used to define candidate HCRs. As indicated, in a second stage the risk assessment considering uncertainty in some of the biological processes (at this stage mostly uncertainty in the recruitment process) will be used to finally select the reference points by stock. As it is described next, the approaches to define the candidate reference points are different from a single and multispecies approach.

Criteria to determine MSY reference points from a single-species perspective:

As the name indicates, in a single species approach, interactions between species are disregarded. Accordingly, there is no interest in considering the result of combining different values of F for the three stocks. For this reason, when assessing the performance of each of the 20 different F levels for one of the three stocks, the different fishing levels for the other two stocks are disregarded. In this process, the steps followed were:

4. Calculate, for each stock and each F level, the mean SSB and yield over the period 2035-2050 (average SSB and yield obtained in the 400 simulations of the 20x20 Fs of the other two stocks).
5. For each stock, select the F that produces the highest yield while SSB is above B_{lim} in a deterministic way. This is a candidate $F_{lim}=F_{MSY}$.
6. Estimate F_{target} as $2/3*F_{lim}$: as explained above this is a standard procedure in NAFO when using a deterministic model like gadget.

Criteria to determine MSY reference points from a multi-species perspective:

As indicated above, whether a single or a multi-species approach is being developed, the precautionary reference points (B_{lim} and $B_{trigger}$) used when designing a HCR will be the same. However, the criteria for the determination of F_{target} are very different. The basic and essencial difference between a multispecies and a single species approach is that in the multispecies approach there is not a single solution to define F_{target} as it is the case in the single species approach, but multiple potential valid combinations of F_{target} for the stocks under consideration. Which combination/s of F_{target} are the most convenient will be determined by management priorities and the level of accepted ecological risk. Experience in previous projects indicated that the selection of management objectives, performance measures, constraints and the final HCRs should be agreed with all the stakeholders (Kempf et al. 2016, Rindorf et al. 2017).

In this study, the selection of potential candidate F combinations for F_{target} was guided exclusively by ecological criteria. Those combinations of F that resulted in mean SSB above B_{lim} in the long term (period 2035-2050) in a deterministic simulation were selected for a further step in the selection of candidate HCRs combinations. That step is presented next and consisted on a risk analysis using the multispecies MSE framework to estimate the probability that each of those combinations of F_{target} drives one or more stocks below B_{lim} in the long term. In this study, a variety of posibilites is explored, and presented in the results section.

One and two stage hockey stick HCRs

The most common HCR is, as presented in figure 2, a rule with a minimum level of SSB (B_{lim}) bellow which the adviced F becomes zero; and an SSB level ($B_{trigger}$) above which the adviced F is set constant at the level of F_{target}. Between $B_{trigger}$ and B_{lim} the adviced F decreases linearly. This is the so-called one stage hockey stick HCR, and is the one currently used in NAFO.

A more innovative type of HCR is the so-called two stage hockey stick HCR, which includes a second set of B_{lim}, $B_{trigger}$ and F_{target} defining a second slope and flat areas for F advice as a function of SSB (Figure 2). This HCR produces higher F values at high stock sizes and is implicitly multispecies, as it aims to avoid excessive stock sizes that may cause reduced productivity due to increased natural mortality, but also density-dependent processes. Two stage HCRs are currently used for Barents Sea cod.

Although the main effort in this study is focused on the standard single stage HCRs, with the intention of exploring new HCRs that take into account the species interactions, the two stage HCRs have also been tested. In first place several single stage HCRs have been tested for all the three stocks. Second, from those combinations of HCRs that succeeded in the risk analysis, a reduced number was used to set up two stage HCRs by adding a second set of B_{lim}, $B_{trigger}$ and F_{target}. The first set of reference points was taken from the one stage HCR, while the second was defined based the historic information. These two-stage HCRs were also tested in a probabilistic multispecies MSE framework.

Multispecies Management Strategy Evaluation framework and risk assessment

In this work a multispecies MSE framework is developed, where the multispecies model GadCap is used as an operating model (OM). This framework allows for an ecosystem approach when selecting the best management practices, by assessing the performance of single and multispecies based HCRs when the species interactions are taken into account. A full MSE has not been conducted in this study due to resources and time limitations, however, as a first step, uncertainty has been considered in the recruitment and the stock assessment.

The MSE framework developed within the SC05 project is based in the a4a approach to MSE[71]. This a4a-MSE framework was developed as a set of common methods and procedures to build a minimal standard MSE algorithm, including the most common elements of both uncertainty and management options. The FLR platform has been used with a modular design framework. The advantages of a modular design for MSE algorithms are the ability to easily reuse code across case studies. Each element of the MSE framework (Figure 3) maps to a single module, allowing the practitioner to focus on each part of the model without having to build new interactions with other relevant parts. One of this modular components is the operating model (OM), that represents the natural and human system and allow simulating the dynamic of the population or populations of interest as well as their fisheries. It is commonly generated by formally conditioning on the available sources of data, through statistical fitting of a fishery and population model. The complexity of an OM can vary widely, from biomass dynamics models to ecosystem model with spatial components and seasonal time steps. The complexity of the OM will have a direct influence on the complexity of the management options that can be explored with it, and on the range of future robustness scenarios they can be tested against. The type of OM for which this a4a-MSE framework has been initially designed is a single stock, age-based, yearly population model, exploited by an aggregated fleet. However, both the FLR tools and the a4a MSE framework allow extensions of this structure in various ways.

In this project SC05, the modular structure of the a4a-MSE framework was modified to develop a multispecies MSE framework for the Flemish Cap cod, redfish and shrimp, that can be used to conduct risk assessments for different combinations of HCRs selected in the previous step. The a4a-MSE framework was deeply modified to 1) introduce in the OM module a gadget multispecies model (and specifically GadCap as a case study) 2) running several MPs in parallel, as many as stocks considered in the multispecies model 3) Include different sources of structural, process and observation uncertainty and error. At this stage, the structural uncertainty was only considered through the uncertainty in the recruitment process.

Introduction of uncertainty in the recruitment process in forward simulations

In order to assess the importance of recruitment uncertainty in the risk associated with a given combination of HCRs for the three stocks, it is necessary introducing variability in the number of recruits that a given level of SSB will produce every year during the long term simulations (period 2017-2050). Although there are different ways to do that, in our study we chose the option of estimating the year factor as the residuals from the optimized Ricker model for each of the three stocks, calculated as the ratio between the observed recruitment (output from GadCap) and the predicted recruitment (Ricker model). The year factor can be thought of as representative of the deviations from the recruitment expected due to the SSB level, produced by the effect of particular annual environmental conditions in the recruitment success of each stock. These environmental conditions may be water

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[71] (http://www.flr-project.org/)

temperature or other oceanographic factors, but also predation, diseases or any other factor affecting survivorship of early recruits before age 1. Accordingly, by estimating the residuals of the observed-estimated recruitment for the historic time period, we obtain a time series of year effect on recruitment for each of the three species from 1989 to 2016. These year effects on recruitment can then be used to simulated long time series of year effects over the period 2017-2050. Each of these time series of year factors will produce variability in the SSB-Recruitment relationships between years, by multiplying the parameter α of the fitted Ricker model for each stock times the year factor (equation 1).

$$Recruitment = year\_factor \ x \ \alpha SSBe^{-\mu SSB} \qquad (2)$$

The uncertainty in the SSB-Recruitment relationship is traditionally the most important source of uncertainty when running forward simulations, and hence, the risk assessment of different management strategies is highly sensitive to the assumptions made to produce stochasticity in the recruitment process when running long term simulations. In this study, for each of the three stocks, 100 time series of year factors over the period 2017-2050 were produced by randomly selecting with replacement from the year factors estimated in the historic period. These 100 time series of year factors for each of the three stocks were then be provided to the GadCap operating model (OM) in the multispecies MSE framework to run 100 forward simulations over the period 2017-2050. Each of these 100 time series of year factors will produce variability in the SSB-Recruitment relationships and hence will produce 100 of different dynamics in the three exploited stocks, in their fisheries, trophic interactions and population structures.

Considering error in the assessment:

At this initial stage, the assessment option that has been selected is the so-called *'shortcut option'* (ICES 2008). This assessment option consist on taking the information of the SSB directly from the OM for each of the three stocks and apply an assessment error to that SSB. This will result in an approximation to the SSB that the actual assessment conducted by the NAFO SC would have estimated. Accordingly, the error in the assessment of the SSB by the currently approved stock assessment methods in NAFO has to be estimated. The approach followed in this study has been analyzing the retrospective patterns obtained in the last year that the stock assessment has been conducted for each of the stocks. The mean error at age has been calculated as the ratio between the estimated abundance at age in the last year of each retrospective pattern and the abundance at age estimated for that year in the most updated assessment. In addition to the mean ratio by age, the variance-covariance matrix of the ratios between the different ages was also estimated. The mean ratio at age and the variance-covariance matrix defines a multivariate distribution of the error between ages, which allow producing new error ratios sampled randomly every year but with certain covariance between ages. During the long term simulations, every year the information about the 'real' abundance at age for each stock coming from the OM in the MSE framework will be transformed by multiplying it times the sampled ratio. In the case of shrimp currently there is not an assessment model. In this case it was assumed that the assessment error for cod was applicable.

Risk assessment of the HCRs considering the recruitment uncertainty, observation and assessment errors. First selection of candidate HCRs for economic calculation.

As indicated above, the MSE framework was used for the risk assessment running simulations using the estimated 100 different recruitment time series. On each of these 100 different simulations, the average SSB and yield was estimated in the last 15 years of the simulation period (2035-2050). Therefore, 100 SSB and yield values were obtained for each combination of HCRs. The NAFO precautionary approach considers that a management strategy is not precautionary when more than 10% of the simulations the SSB is driven below B_{lim}. This is the criterion that has been followed in this study to consider a precautionary strategy or not. It should be noted that this 10% criterion is considered approximate, and that, especially in a context with a multispecies approach some flexibility is allowed.

The risk assessment was conducted separately for single and multispecies HCRs. In the case of the single species approach three HCRs were selected from the work conducted on subtask 3.2, one HCR per species and were implemented simultaneously in the multispecies MSE framework. In the multispecies approach, unlike the single species approach, there is not a single solution when defining the HCRs. The management of a stock as result of the application of a given HCR will affect the dynamic of the other stocks, and may even involve higher risks of being below B_{lim}. In this project different options have been tested, and risk assessment was conducted on combinations of HCRs for which, in a deterministic way (subtask 3.2), priority was given to 1) keeping all stocks above B_{lim} or 2) subgroups of stocks or 3) individual stocks.

To avoid excessive and unrealistic population growth during the long term simulations, limitations were introduced to the shrimp and redfish population growth. This was done by introducing a carrying capacity in the OM, based on the maximum population sizes observed in the historical period. It was assumed that the collapse of cod allowed its prey stocks shrimp and redfish, reaching values that may be close to the maximum carrying capacity. To simulate this limitation to population growth, a source of extra mortality has been introduced in the shrimp submodel when it approached 150000 tons of total biomass, and a source of extra mortality for the redfish submodel when it was approaching a SSB of 70000 tons. For cod, it has not been necessary, since cannibalism has worked as a source of mortality limiting the productivity of the stock.

RESULTS and DISCUSSION

Precautionary reference points: B_{lim} and $B_{trigger}$

The relation of the recruitment with the SSB showed the typical dome shaped Ricker model shape, with recruitment decreasing at higher values of SSB (Figure 4). The fit Ricker SSB-Recruitment curve was then used to estimate the precautionary reference points, B_{lim_50}, B_{lim_75} and $B_{trigger}$, as the SSB at which the recruitment is, respectively, 50%, 75% and 90%

of maximum predicted recruitment (Figure 4). The criteria followed to define the precautionary reference points were different for each of the three stocks, and this is something that may be subjected to discussion. As a first approach, in this study it was decided that B_{lim} for shrimp would be taken as the SSB at B_{lim_50} (10206 tons), while for cod B_{lim} would be taken as the SSB at B_{lim_75} (17906 tons). The reason is that it was deemed that for cod B_{lim_50} (9892 tons) was an excessively low SSB value based in what have been previously defined as reference points for cod (González-Troncoso et al. 2013). For shrimp, B_{lim_50} was approximately four times higher than the B_{lim} value (2564 tons) defined for the survey index stock assessment (Casas-Sánchez 2012), and this value was consider appropriate based in the relationship between the biomass survey index and the estimated total stock biomass (approx. 5 times higher stock biomass than survey index). In relation to redfish, both the B_{lim_50} and B_{lim_75} seemed very low in relation to the observed values over the historic period. For this reason, the criteria used for redfish was changed, and B_{lim} was considered for this stock the level of SSB for which the first above average recruitment was observed (see Figure 6.3-10Figure 4, right bottom panel), while $B_{trigger}$ was defined the SSB at maximum recruitment. Following this criteria, B_{lim} was defined at 22027 tons and $B_{trigger}$ at 35361 tons. The table 2 shows the B_{lim} and $B_{trigger}$ to be used in the HCRs for each of the three stocks in this study.

Deterministic long term forecast and definition of single and multispecies F_{target} reference points

Once the precautionary reference points were defined for each of the three stocks, the next parameter required to define the one stage HCRs was the F_{target}, for which long term simulations over the period 2017-2050 were run using the GadCap model. As described in the methodology section, 20 different values of F were defined for each species, resulting in 8000 different combinations for the three stocks (see **Error! Reference source not found.** in the methodology section). In this simulations the fitted Ricker SSB-Recruitment models were used to generate every year in the long term simulation the new recruits at age one in a deterministic way, i.e. each SSB would produce an only value of recruitment for each stock. Once the 8000 long term simulations were run, the mean SSB and mean Yield over the period 2035-2050 was estimated for each stock. From Figure 6.3-11 to Figure 6.3-13 the mean long term SSB and yield are shown for each of the three species as a function of the fishing pressure applied to the three stocks.

For the cod stock, the impact of changes in fishing pressure on redfish didn´t seem to have an important effect when the fishing pressure on shrimp is low. However, when fishing pressure on shrimp is increased there is a decline in cod mean SSB as the F on redfish is increased. It is when the fishing pressure on shrimp is increased when the most important differences in the estimated mean long term cod SSB is observed. This is especially evident when the fishing pressure on cod is low. This negative effects on cod SSB in the long term simulation as result of a higher fishing pressure on redfish and shrimp were due to the increased cannibalism occurring on cod when the availability of these prey stocks is reduced due to the high fishing pressure. In the case of fishing pressure on cod, as expected, the SSB decreased as the F on cod was increased. It is interesting to note that the fishing pressure that cod is able to stand before the SSB (in a deterministic way, without

uncertainty ranges around it) goes bellow the B_{lim} (17906 tons) is very high. Specifically in the three F shrimp values presented in the figure 5, cod SSB was below B_{lim} only when F was above 0.8. Variations in the mean long term cod yield showed a similar pattern to that explained in relation to the SSB, i.e. increased fishing pressure on redfish and shrimp produced reduced productivity on cod, being especially evident when both F on shrimp and redfish was high. However, unlike the SSB, the increase of fishing pressure on cod showed a dome shaped curve, irrespective of the F value applied for redfish and shrimp. The maximum yield for cod was always observed when the F for cod was between 0.45 and 0.65.

In the case of the redfish stock, the mean long term SSB was very independent of the fishing pressure applied on shrimp. However, it was extremely dependent on the F applied on cod (figure 6). For a given F value on redfish, the lower the F on cod the lower the redfish long term SSB. In different words, higher fishing pressure on cod allows higher F on redfish before the redfish SSB declined below the B_{lim}. The results indicate that the absence of fishing on cod could bring redfish below B_{lim} even at very low fishing pressure. However, it is important highlighting that those SSB and Yield values obtained in situations that have not been observed before should be taken with caution, as it is the case for a scenario of very low fishing on cod when cod is at very high biomass level. In relation to the fishing pressure on redfish, increasing the F lead to lower values of SSB, but this relation was highly dependent on the fishing activity on cod. Regarding the long term yield for redfish, it also showed the typical dome shape as a function of fishing effort. This shape was independent of the fishing pressure on shrimp, but it was very dependent on the fishing pressure on cod. The higher the F on cod the higher the peak of yield for redfish. Unlike for cod, in redfish the peak of yield was always observed at low F values, being usually between 0.1 and 0.2.

Shrimp, due to its trophic role being a very important prey of two dominant species in the Flemish Cap, showed (in the SSB and Yield) a high sensitivity and dependency on the fishing strategies selected for these two predators. Only when fishing pressure on cod was very low or, interestingly, very high, the mean shrimp SSB in the long term could achieve values above the B_{lim}. At intermediate levels of fishing pressure on cod, the shrimp SSB was bellow B_{lim} independently of what fishing pressure was set on redfish (figure 7). The reason for this pattern is that cod is a main predator of shrimp, and hence very intense fishing on cod would benefit the development of the shrimp sotck, and would bring the SSB above B_{lim}. However, cod is also a main predator for redfish, which in turn is also a main predator for shrimp. For this reason a low fishing pressure on cod would involve high predation on redfish and hence a decrease in redfish stock (as it was already indicated in the previous paragraph). That decrease in redfish biomass would allow also an increase in the shrimp SSB above B_{lim}. However, as indicated above, this is a scenario that has never being observed before and hence the model is getting into the extrapolation territory, which should be taken with caution. In both cases (high or low fishing pressure on cod) the long term shrimp SSB was very dependent on redfish fishing pressure: low fishing pressure did not allowed shrimp SSB above B_{lim}. The long term mean yield on shrimp showed also a dome shape as a function of F on shrimp, but only when, as indicated for the SSB, the

fishing pressure on cod was either very high or very low. The peak on the shrimp stock was hence very dependent on the fishing pressure on cod and redfish, but, in any case was always very low (bellow 0.15).

Once the long term SSB and yield have been calculated for each combination of fishing pressures (F_{cod}, $F_{redfish}$ and F_{shrimp}), the next step is selecting those HCRs that produce the highest and sustainable yields. However, as explained in the methodology section, the way the single and multispecies approaches will use all the information showed in figures 5 to 7 is very different. In the next sections the procedures used in both approaches are explained in depth and the F reference points and hence the HCRs are estimated from a single and multispecies perspectives.

- *Single species based reference points*

In a single species approach all that variability in the long term mean SSB and yield as a function of the fishing pressure on the three stocks is disregarded. In this study, in order to simulate that approach, for each of the 20 different F levels tested for each species the mean SSB and Yield was estimated, and the yield and SSB curves were plotted disregarding the variability due to different management strategies in other species (Figure 8). Based in this approach, the F_{MSY} is selected as the F value that produces the highest yield while the SSB is above B_{lim}. The resulting F_{MSY} is, as explained in the methodology section, a limit to the fishing pressure, and usually a lower value is used as F_{target}. It is a standard in NAFO that the F_{target} is calculated as 2/3 of F_{MSY}. Both F_{MSY} and F_{target} are presented in table 3.

- *Multispecies based reference points*

In the multispecies approach the value of F_{target} for a stock is decided considering the F_{target} for the rest of species, following a list of management objectives that must be defined a priori by all the stakeholders. In this study the criteria have been based exclusively on biological aspects, following as much as possible the NAFO precatory approach defined for a single species approach. Five different criteria have been defined to select combinations of F_{target}:

6. Combinations of F_{target} (and hence HCRs) that allowed the SSB being above B_{lim} at the end of the simulation period (2035-2050) for all the 3 stocks.

7. Combinations of F_{target} for which at the end of the simulation period cod and redfish SSB is above their B_{lim}, but disregarding the estate of the SSB for shrimp.

8. Combinations of F_{target} for which at the end of the simulation period shrimp and redfish SSB is above their B_{lim}, but disregarding the estate of the SSB for cod.

9. Combinations of F_{target} for which at the end of the simulation period shrimp and cod SSB is above their B_{lim}, but disregarding the estate of the SSB for redfish.

10. Combinations of F_{target} for which at the end of the simulation period shrimp SSB is above their B_{lim}, but disregarding the estate of the SSB for redfish and cod.

Out of 8000 F combinations, only 96 maintained all the three stocks above their respective B_{lim} values (criteria 1) at the end of the simulation period. A subset of 13 cases representative of the range of Fs applied for each of the three stocks that fulfilled this criteria 1 was selected (see table 4), maintaining all stocks above B_{lim} at the same time. It is important to note that the F values for cod and redfish were very high, and very close to the B_{lim} (see figure 9).

However, when the restrictions were released by allowing the shrimp stock going below its B_{lim} (criteria 2), the number of combinations of Fs for which the SSB in cod and redfish was maintained above B_{lim} was increased substantially, with 2595 possible combinations. It is not possible conducting a risk analysis to all those combinations, and hence, a reduced number of 19 combinations were selected (table 5). It was decided that in the selected F combinations, for simplicity the F values for shrimp would be set to zero. The reason is that in all the 2595 combinations, catches for shrimp were very low, and hence, in practice the shrimp fishery wouldnt have occurred. As it can be observed in the figure 10, even when the F was set to zero for shrimp the SSB was clearly bellow the Blim.

When the state of the cod SSB was disregarded, a total of 365 F combinations maintaind redfish and shrimp SSB above their respective B_{lim} values in a deterministic way. A subset of 17 F combinations were selected for risk analysis (table 6). The selected combinations showed that for cod, in a deterministic way, the fishing pressure brought the SSB bellow or very close to B_{lim} (figure 11).

When the state of the SSB for redfish is disregarded (criteria 4), again the number of possible F combinations is higher, with 1068 combinations that allow maintaining the SSB for cod and shrimp above their respective B_{lim}. A subset of 40 F combinations was selected for a risk assessment (table 7). In a deterministic way it is already evident that these combinations resulted in the redfish SSB being much lower than B_{lim} (figure 12), and producing a very low yield, while for cod and shrimp the SSB was above B_{lim}, in line with the criteria. In cod, with the exception of a few F combinations, most of the cases the SSB was much larger than B_{lim}.

When the state of both cod and redfish was disregarded (criteria 5), 1604 F combinations resulted in shrimp SSB above its established B_{lim}. A subset of 21 F combinations was selected for risk analysis (table 8). In these combinations, the deterministic long term simulations showed that in the equilibrium the SSB for redfish was bellow B_{lim} most of the cases, while for cod, it was close to B_{lim} in several combinations, but never below it (figure 13).

Multispecies Management Strategy Evaluation framework and risk analysis.

Running long term simulations with 8000 combinations of F for the 3 stocks (20 F levels per stock determining the fishing pressure on each scenario) has allowed identifying candidate HCRs combinations from a single species perspective and from a multispecies approach considering 5 different criteria. In total 110 combinations of F have been selected for risk analysis. The risk analysis will show if, when the uncertainty in the recruitment and the error in the assessment processes are considered, these combinations of F will still maintain the stocks above B_{lim} with high probability.

- *Adaptation of the a4a-MSE framework:*

The MSE framework developed is based in the a4a-MSE R package, on which four main modifications have been introduced:

- Introduction of the multispecies model GadCap as OM
- Parallel Management Procedures (MPs)
- Implementation of a "shortcut" assessment option with assessment error
- Integration of the MSE framework in a loop to account for uncertainty in the recruitment process and the assessment error.

The first challenge was replacing the single species a4a model with the gadget multispecies model GadCap as an operational model. The a4a-MSE belongs to the FLR project and is an R package. For this reason it was necessary creating another R package that was able to interact and execute gadget as well as serving as bridge between gadget and a4a-MSE. This package has been called gadgetR[72] and provides the user with a two-way interface to Hafro's Globally applicable Area Disaggregated General Ecosystem Toolbox (Gadget)[73]. The next step was modifying the code and the structure of the a4a-MSE framework to create multiple MPs, as many as stock in the multispecies model, which can be run in parallel during the long term simulations. In the case of GadCap, the gadget-a4a-MSE framework was modified to run three MPs in parallel: cod, redfish and shrimp MPs (Figure 14). Within each of the three MPs, each stock will have a different stock assessment (so far designed to be an a4a catch at age assessment model or a shortcut option), a different HCR (with different values for B_{lim}, $B_{trigger}$ and F_{target}), and separate management decisions, that, after passing through their respective implementation error model, will indicate the fleets in the GadCap OM the catch that has to be targeted for each of the three stocks.

As indicated, at in this project the so-called 'shortcut assessment' option was applied to simulate the assessment in the MSE framework. In this study, two options were possible for the shortcut assessment. The first option was 'no error shortcut', and, as the name indicates, no any error was applied to the SSB provided by the OM. Hence, this may be considered a perfect assessment option. The second option was a 'truth plus error shortcut' option, and consisted of multiplying the abundance at age in the

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[72] https://github.com/REDUS-IMR/gadget

[73] http://www.hafro.is/gadget/

assessment year provided by the OM times an error value. As described in the methodology section, the mean ratio of the difference between the estimated abundance at age in the last approved assessment for each of the three stocks, and the abundance at age estimated in the retrospective pattern. This ratio is usually close to 1, but can be lower or higher. A ratio higher than one means that usually the estimated abundance in the assessment is higher than in reality, and the opposite when the ratio is smaller than one. With the exception of ages 2 to 3 in cod, and 11 to 15 in redfish, in both stocks the estimated ratio was lower than 1 for most ages (see Table 6.3-13 and

Table 6.3-14). In addition to the mean ratio at age, the analysis of relationship in the ratio between ages over time in the retrospective pattern allows estimating a variance-covariance matrix. Assuming a multivariate normal distribution, the mean ratio at age and the variance-covariance matrix were used during the long term simulations to produce new values of assessment error at age every year, considering the covariance of this ratio bewteen ages.

Finally the gadget-a4a-FLR tool was integrated in a framework that would run simulations one after another, using, at each time a different time series of 'recruitment success' level. The estimated year factors in the recruitment process (Figure 15) were selected randomly with replacement for each of the three species to produce 100 time series of year factors covering the long term simulation period, i.e. from 2017 to 2050. As indicated in the material and methods section, the gadget-a4a-MSE framework will use these time series, one at a time, to produce variability in the relationship between the SSB and the recruitment every year.

- *Risk assessment of single species and multispecies one stage HCRs combinations considering recruitment uncertainty*

The MSE framework was used to perform the risk analysis. The 'no error shortcut' option was used as a first option in the risk assessment for all the selected combinations of HCRs. The 'truth plus error shortcut' option was used for a reduced number of HCRs combinations, with the intention of assessing if the selected best combinations of HCRs are still precautionary when the assessment error is considered.

- *Single species based HCRs combinations*

When the HCRs selected based in single species criteria were used in long term simulations and the uncertainty in the SSB-recruitment relationship was considered, the SSB went bellow the B_{lim} in the three stocks all over the simulated period 2017-2050 (Figure 16), but especially on shrimp and cod. In the equilibrium (over the period 2035-2050), the probability of being below B_{lim} at least one year was clearly above the 10% limit considered in NAFO to be precautionary in cod and shrimp, while in redfish the combinations of HCRs maintained the stock in the safe zone, with less than 10% of the simulations being below Blim at least one year (Table 11).

- *Multispecies based HCRs combinations: 3 species above B_{lim}*

The results indicate that none of the HCR combinations selected as potentially being able to maintain the three stocks above their respective B_{lim} were precautionary for cod and shrimp, while for redfish the probability of being below B_{lim} was lower than 10%. Despite the high risk of collapse, the median yield over the period 2035-2050 was high for cod. However, the percentage of interannual variability (percentage of the median yield) was very high, being usually above 100% due to the frequent collapses and closures of the fishery. The low risk of collapse, high median yield and low interannual variability for redfish was probably due to the released predation from cod.

  o *Multispecies based HCRs combinations: disregarding shrimp*
The candidate combinations of HCRs selected when the level of SSB on shrimp in relation to its B_{lim} reference point is disregarded showed better performance than those combinations of HCRs intended to maintain the three stocks above B_{lim}. Although none of the options were precautionary for shrimp, some combinations maintained cod below or around the 10% probability, while a larger number allowed redfish to be at precautionary levels (table 13). But the most interesting output is that there was a number of combinations for which the probability of being below B_{lim} was lower or only slightly higher than 10% both for cod and redfish at the same time (e.g. combinations 5 and 6). Hence, when the shrimp is disregarded it is possible finding combinations of HCRs that allow exploiting cod and redfish within the precautionary constraints. With these HCRs combinations yield values are comparable to the TACs for Flemish Cap cod and redfish in the last years (see (Ávila de Melo et al. 2017, González-Troncoso 2017), and the interannual variability is lower than 20% of the median yield.

  o *Multispecies based HCRs combinations: disregarding redfish*
The HCRs combinations where the redfish state in relation to B_{lim} was disregarded while prioritizing cod and shrimp resulted in very low probability of cod SSB being bellow B_{lim} (less than 10%) with the exception of those combinations where the F_{target} for cod was above 0.35. However, shrimp did not get risk lower than 45% in any of these combinations, and redfish risk of being below Blim was very high (above 80%), with the exception of those combinations for which the risk was higher for cod (see HCRs combinations 38-40 in Table 6.3-18). Yield in redfish was relatively low (table 14), and interannual variability high (above 100% in most cases) in those years for which the risk was high, while the opposite pattern was observed in HCR combinations 38-40. For shrimp yield was always low in comparison to historical catches (Casas-Sánchez 2017), and interannual variability was above 50%, although it was higher when yield was high, due to the higher risk of collapse result of higher fishing pressure. Interannual variability was low in cod in all HCRs combination, excepting 39-40 when F_{target} was high. Cod yield increased when F_{target} on cod was higher, however, it was clear that, for each level of F_{target} on cod, yield decreased when the F_{target} on redfish and shrimp was increased. This was the result of an increased cannibalism on cod in reaction to a lower availability and higher collapse risk of prey (redfish and shrimp) due to higher fishing removals.

  o *Multispecies based HCRs combinations: disregarding cod*

In those HCRs combinations selected when the state of cod SSB in relation to B_{lim} was disregarded, the risk of being bellow B_{lim} for cod was, as expected, very high (table 15). Still the yield was high for cod, but this was at the cost of an extremely high interannual variability, usually above 200% of the median yield (often closed fishery). On the contrary, for redfish the risk was very low due to the release from cod predation, resulting in an increased productivity and hence higher yield for the fishery. However, shrimp did not benefitted from these scenarios, probably due to the high predation from redfish.

  o *Multispecies based HCRs combinations: disregarding cod and redfish*

The HCRs combinations where cod and redfish were ignored, regarding to their SSB in relation to B_{lim}, were expected to result in a lower collapse risk for shrimp. However, the simulations showed that the risk of shrimp SSB being below B_{lim}, despite being lower than in previous scenarios for some HCRs combinations, it was still very high, far from the precautionary limits (table 16). This may be related with the fact that, when the F_{target} and hence the risk of collapse was low for cod, the predation on shrimp was high. And, when F_{target} was high on cod, the redfish benefited of that, and even when the fishing pressure was high the risk of collapse was relatively low, involving high predation on shrimp.

  • *Risk assessment of one stage HCRs combinations considering the error in the stock assessment (in addition to the recruitment uncertainty).*

The result indicate that the selected HCR are more precautionary for cod when the error in the assessment is included in the simulations (table 17). The retrospective pattern indicated that the assessment tend to underestimate the real biomass of the stock (see Table 6.3-13). Accordingly, the advised quota is lower than what it could be based in the real stock biomass. This lead to a higher survivorship of the cod stock, and then lower risk of being below B_{lim}. However, although the retrospective pattern in redfish also indicated a tendency to underestimate the real population biomass (see

Table 6.3-14), the fact that cod biomass is increased when considering the assessment error, predation on redfish is higher. This produces a decrease in productivity of redfish and hence higher probability of being below B_{lim}. In any case, the differences are relatively minor in comparison with the risk assessment without considering the error in the assessment.

  • *Risk assessment of two stage multispecies HCRs*

The results indicate that a two stage HCR advising a higher catch when cod SSB is above 45000 tons would result in a clear reduction of the risk of being below B_{lim} for redfish, due to the lower predation from cod (Table 6.3-22). There is also a lower risk of being below B_{lim} for cod, although the difference is not as important as for redfish. For shrimp, there is also a slight benefit in some HCRs combinations, although it is minor in comparison with the high risk of collapse.

<div align="center">

CONCLUSIONS

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The results of this work allow concluding that:

- Combinations of HCRs designed under a single species approach were not precautionary for cod and shrimp in a framework where species interactions are directly modelled and simulated.

- The risk analysis of HCRs combinations defined with multispecies criteria indicated that it is not possible maintaining the 3 stocks above B_{lim} at the same time. The reasons are the strong trophic interactions between the assessed stocks. Trying to maintain shrimp above Blim requires excessive fishing pressure on cod and redfish in order to reduce predation mortality, and this involves high risk of collapse on cod. On the contrary, maintaining cod above Blim involves high predation and high risk of collapse on shrimp and redfish.

- Disregarding one stock may allow finding precautionary multispecies reference points for the other stocks. Disregarding cod would result on fishing redfish within precautionary levels. Disregarding redfish would allow fishing cod without collapsing the stock. However, this was not possible for shrimp. It is probable that the uncertainty in the recruitment process, taken randomly in this study have been determinant on this.

- Precautionary HCRs for two stocks at once were only found when shrimp SSB in relation to B_{lim} was disregarded. Although there were not a high number of possibilities, there were a few combinations of HCRs that allowed fishing cod and redfish without collapsing the stocks. The estimated yield in the long term indicates that this strategies are in the line of the yields obtained for both stocks since the reopening of the cod fishery in 2010.

- The results showed that the two stages HCRs for cod reduces predation and increases probability of cod and redfish being above B_{lim}. This result supports that alternative two stage HCRs, or some other HCRs with other shapes, may increase the possible combinations of fishing pressure for these three stocks.

- The risk assessment indicated that the selected combinations of HCRs were still precautionary when the assessment error was included in the MSE. The assessment usually underestimates the real abundance at age, and, accordingly, the catch advice will always be below the real catch that the stock could support.

ACKNOWLEDGMENTS

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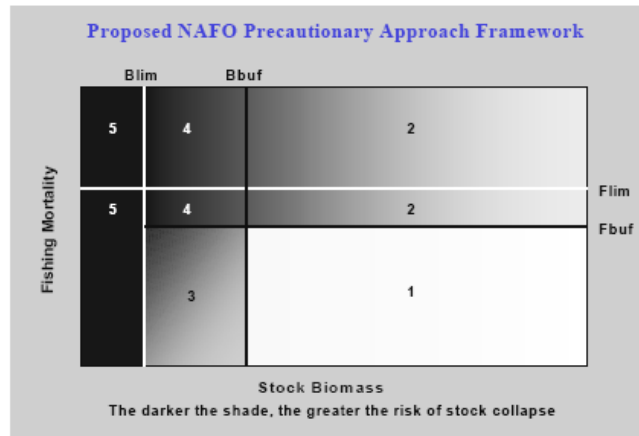
FIGURES

Figure 1.- Schematic depicting a revision to the proposed NAFO PA framework adopted by the Scientific Council in September 2003 (Taken from NAFO (2004)).
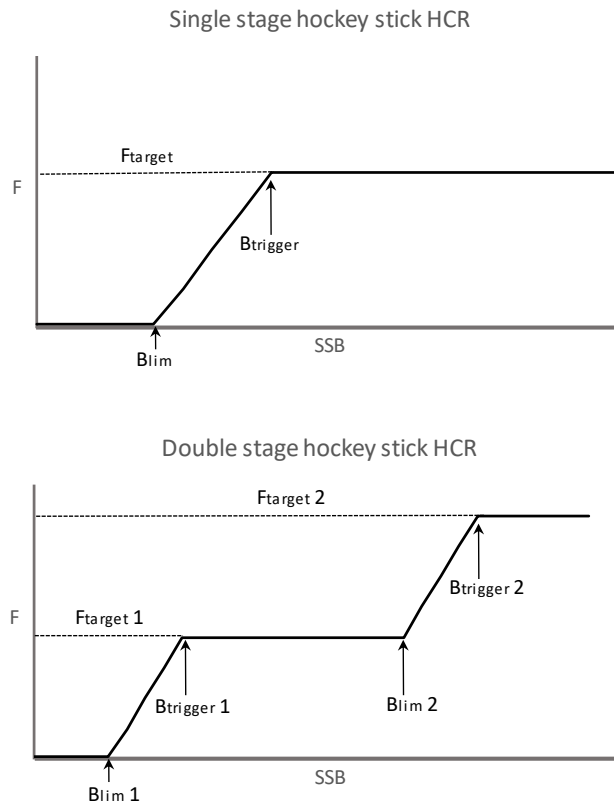
Figure 2.- One stage (upper pannel) and two stage hockey stick HCR (lower pannel), showing the reference points and the set up considered in this project.
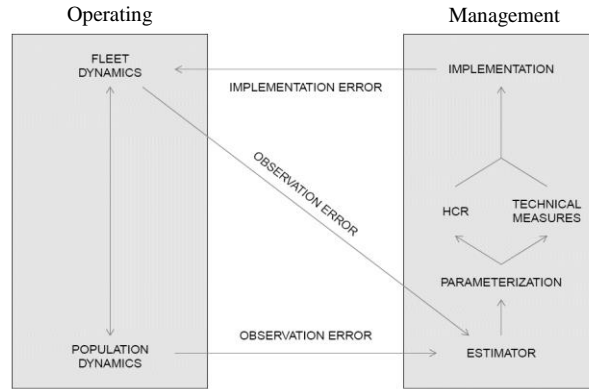
Figure 3.- The a4a-MSE algorithm showing all the different modules that simulates the management cycle.
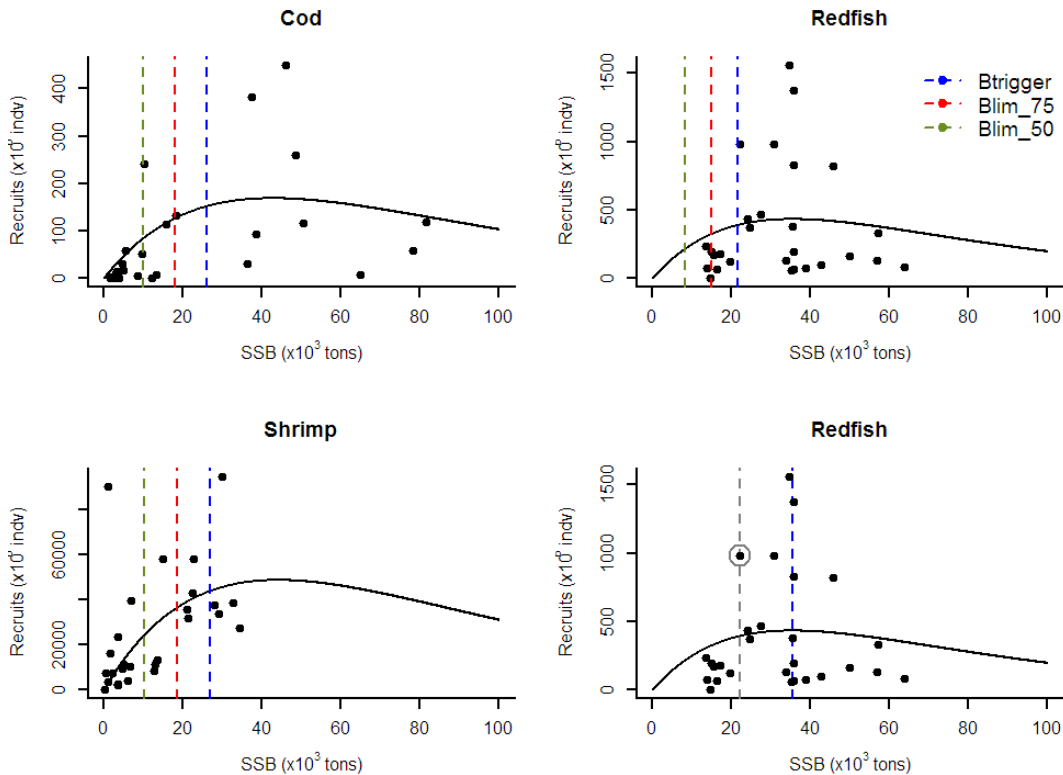
Figure 4.- SSB and recruitment values result of GadCap over the historic period (black points) and fitted Ricker SSB-Recruitment model (black line). The Vertical lines represent the B_{lim_50} (green dashed line), B_{lim_75} (red dashed line) and $B_{trigger}$ (blue dashed line), defined as the SSB at which the recruitment is, respectively, 50%, 75% and 90% of maximum predicted recruitment. The right-bottom panel shows the special criteria followed to define the precautionary reference points in redifhs. The grey line an the grey circle indicates the B_{lim}, as the SSB at which it was observed the first recruitment value above the average in the historic period. The Blue dotted line in this case is $B_{trigger}$, defined as the SSB at maximum recruitment.

Figure 5.- Mean SSB (upper panel) and Yield (lower panel) for the cod stock at the end of the forecast simulation period (2035-2050). The figures show the SSB and Yield values for the combination of 20 different F values of cod, 20 F values of redfish and 3 values of F for Shrimp. In this figures, the remaining 17 fishing mortality values for shrimp have been ommited for clarity and simplicity of the figures.
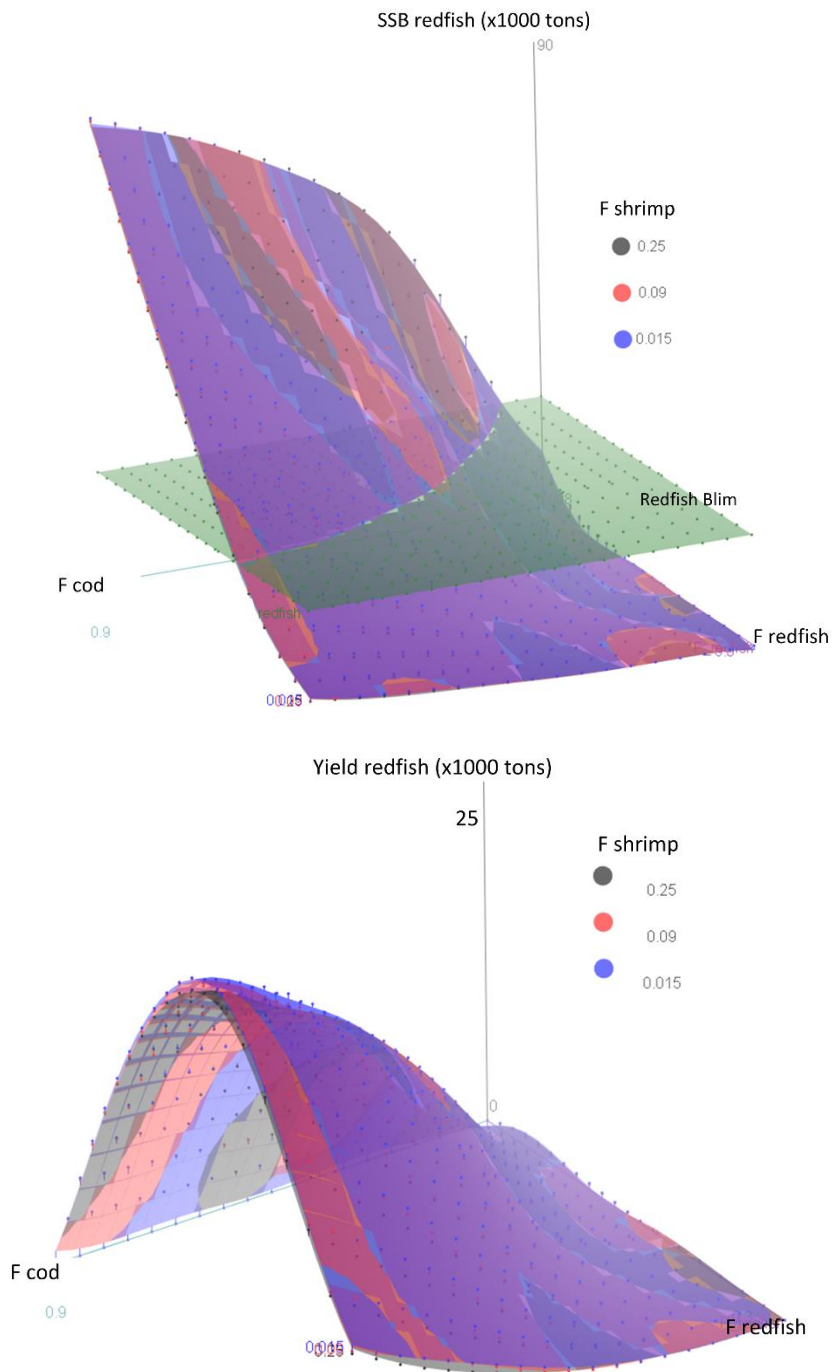
Figure 6.- Mean SSB (upper panel) and Yield (lower panel) for the redfish stock at the end of the forecast simulation period (2035-2050). The figures show the SSB and Yield values for the combination of 20 different F values of cod, 20 F values of redfish and 3 values of F for Shrimp. In this figures, the remaining 17 fishing mortality values for shrimp have been ommited for clarity and simplicity of the figures.

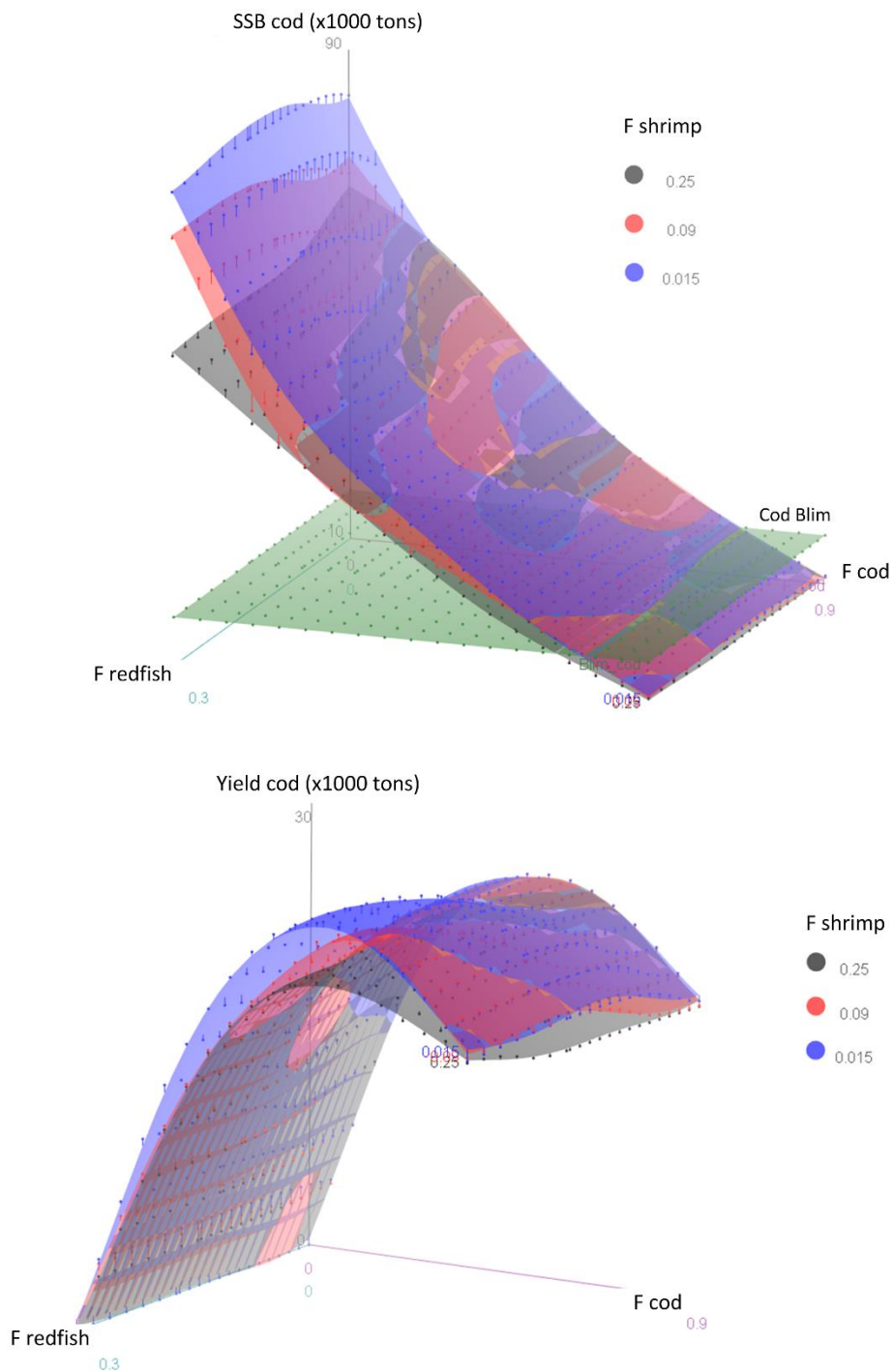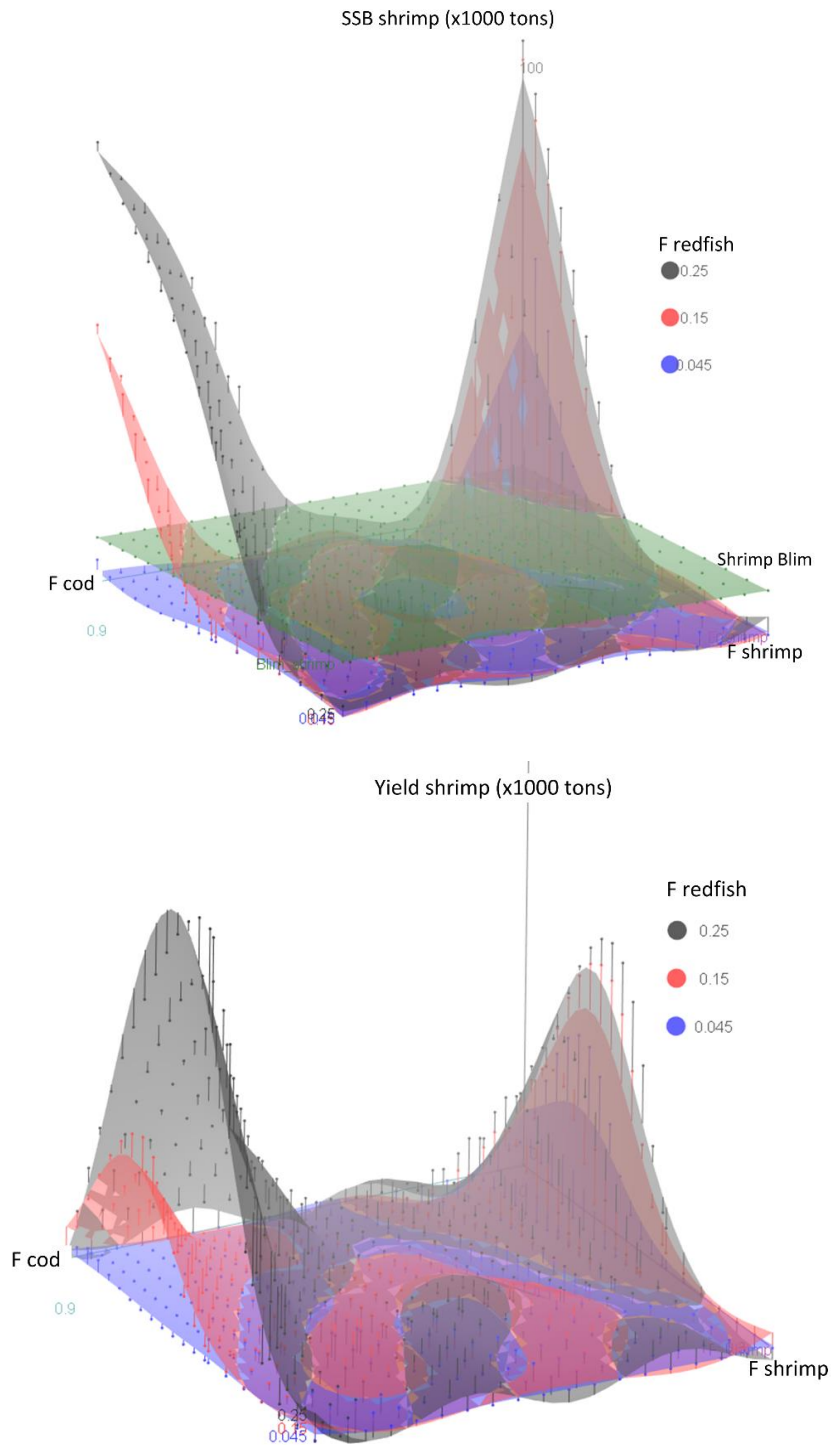*Figure 7.- Mean SSB (upper panel) and Yield (lower panel) for the shrimp stock at the end of the forecast simulation period (2035-2050). The figures show the SSB and Yield values for the combination of 20 different F values of cod, 20 F values of shrimp and 3 values of F for redfish. In this figures, the remaining 17 fishing mortality values for redfish have been ommited for clarity and simplicity of the figures.*
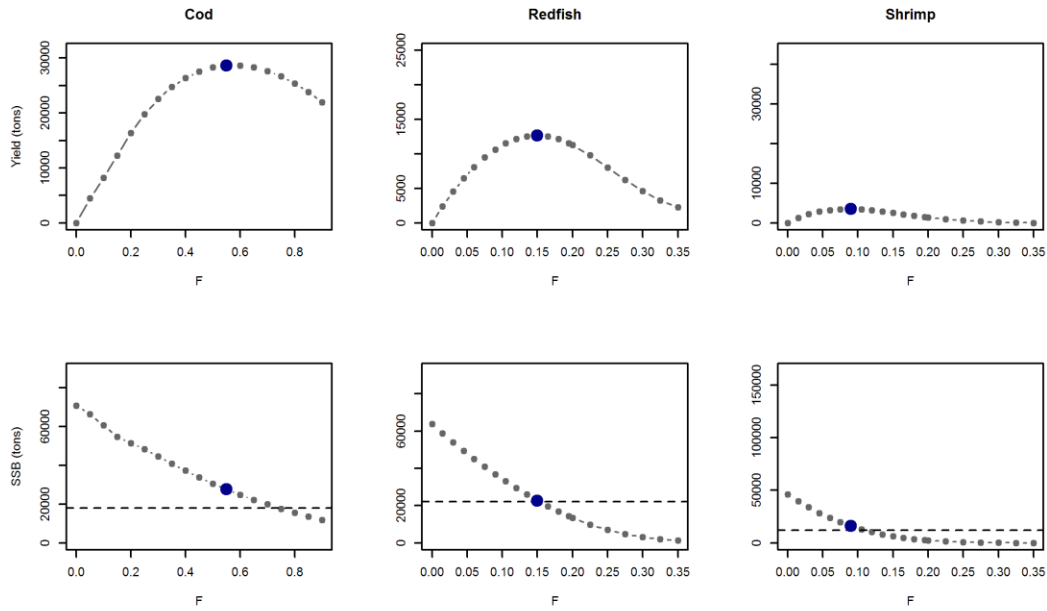
Figure 8.- Average SSB and Yield in the equilibrium (years 2035-2050) by F level tested during the long forecast simulations.

Figure 9.- Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F values selected following the criteria 1 and presented in table 4.
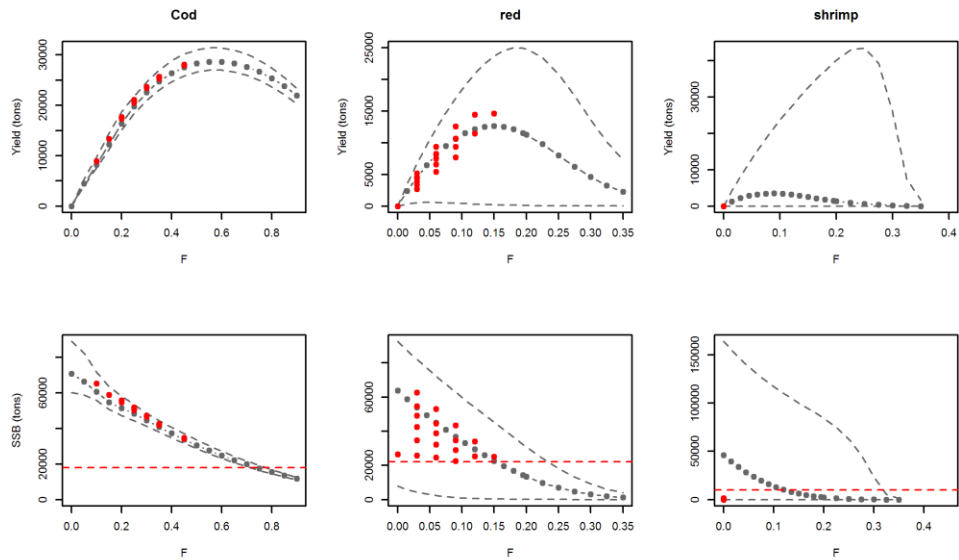
Figure 10.- Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F values selected following the criteria 2 and presented in table 5.
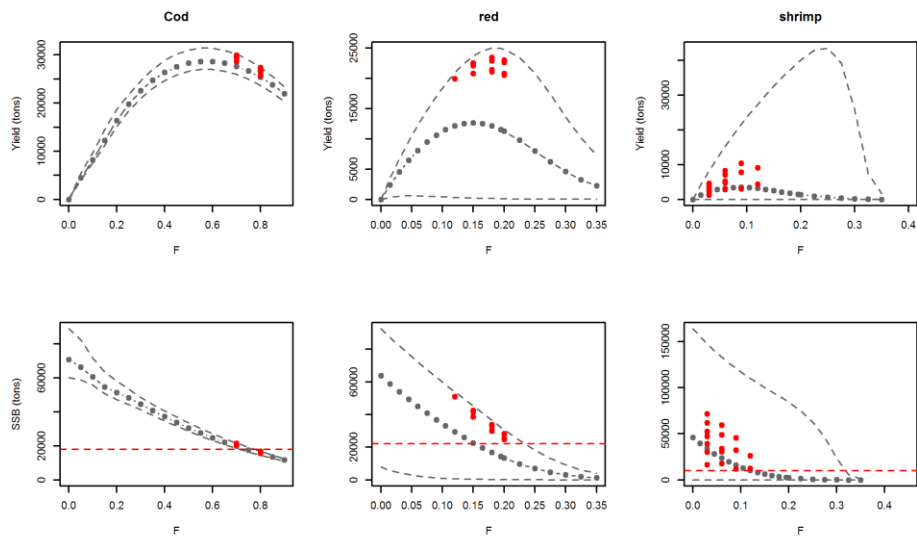
Figure 11.- Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F selected following the criteria 3 and presented in table 6Table 6.3-10.
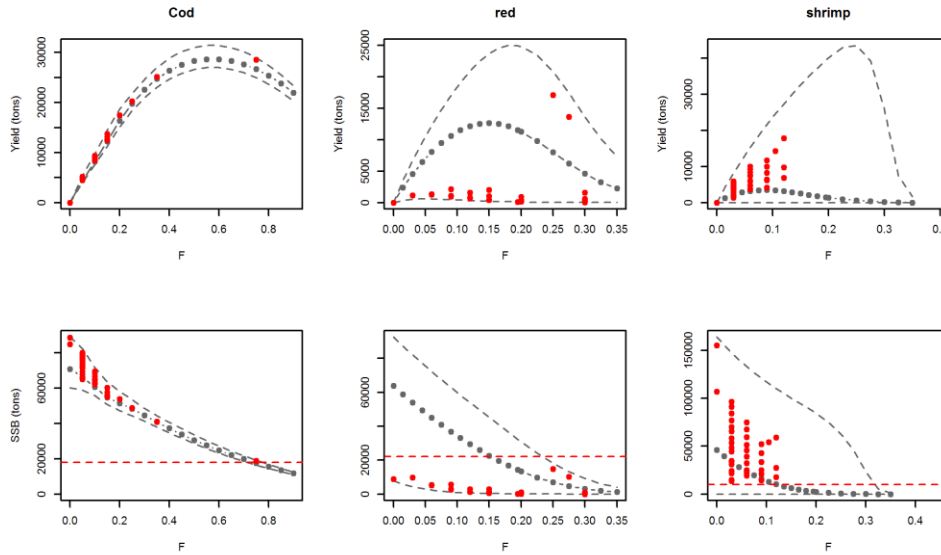
Figure 12.- Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F selected following the criteria 4 and presented in table 7.
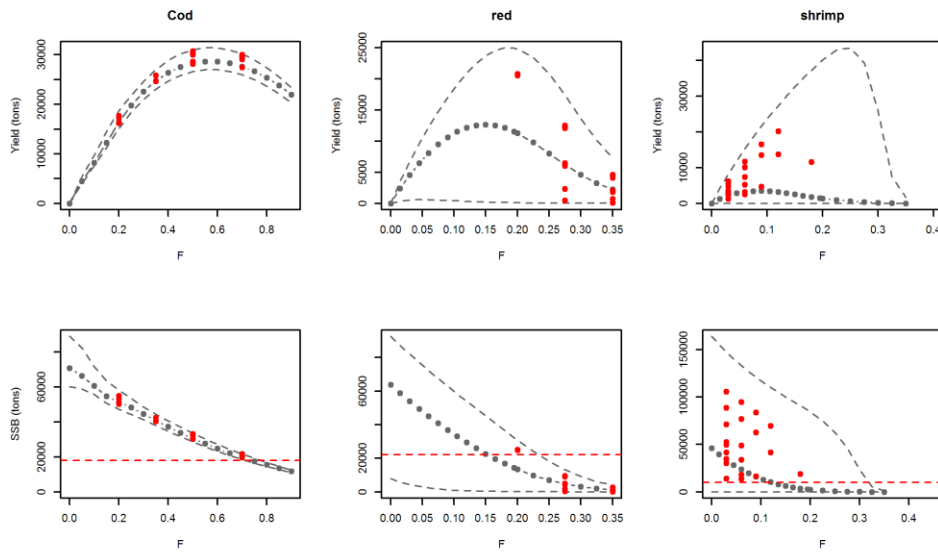
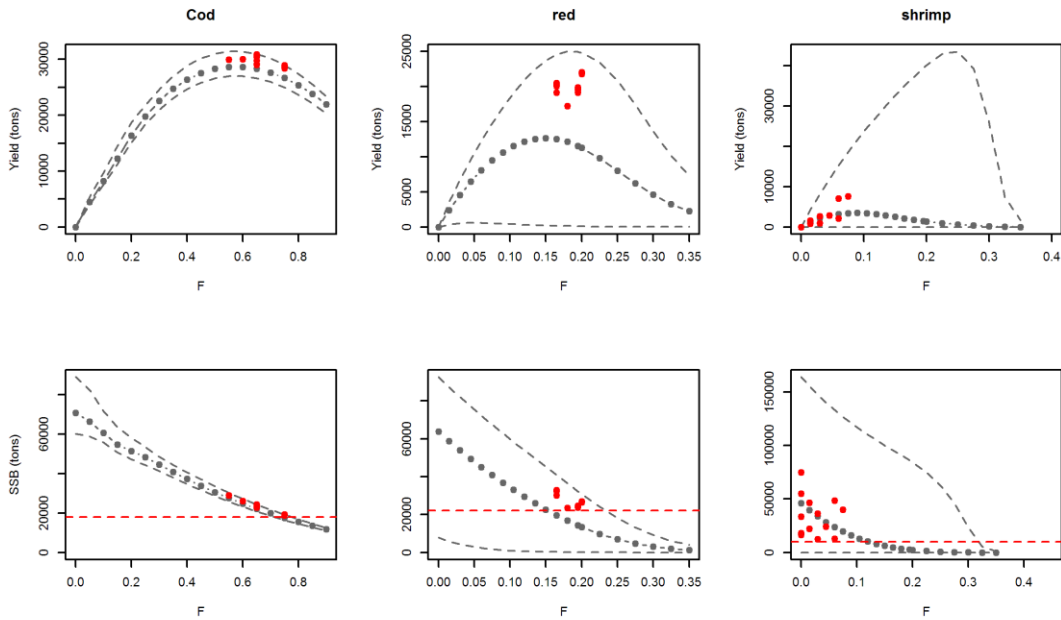*Figure 13.- Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F selected following the criteria 5 and presented in table 8.*
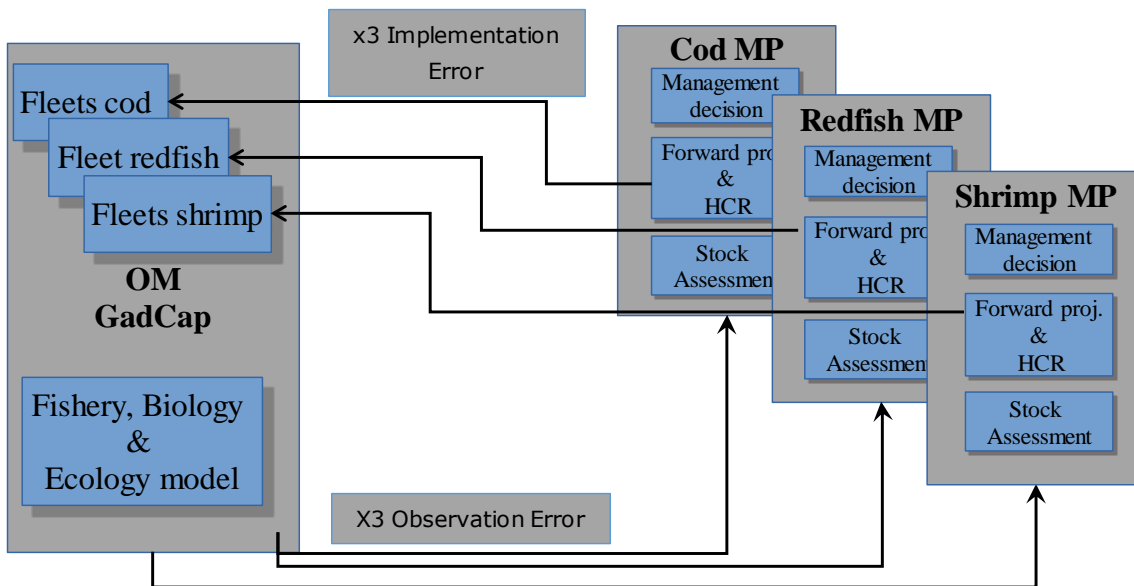
Figure 14.- Multispecies gadget-a4a-MSE framework. The multispecies model GadCap developed as part of task 2 was used as OM. Uncertainty on the knowledge of the system was expressed as SSB-Recruitment uncertainty in the OM. Uncertainty in the MP
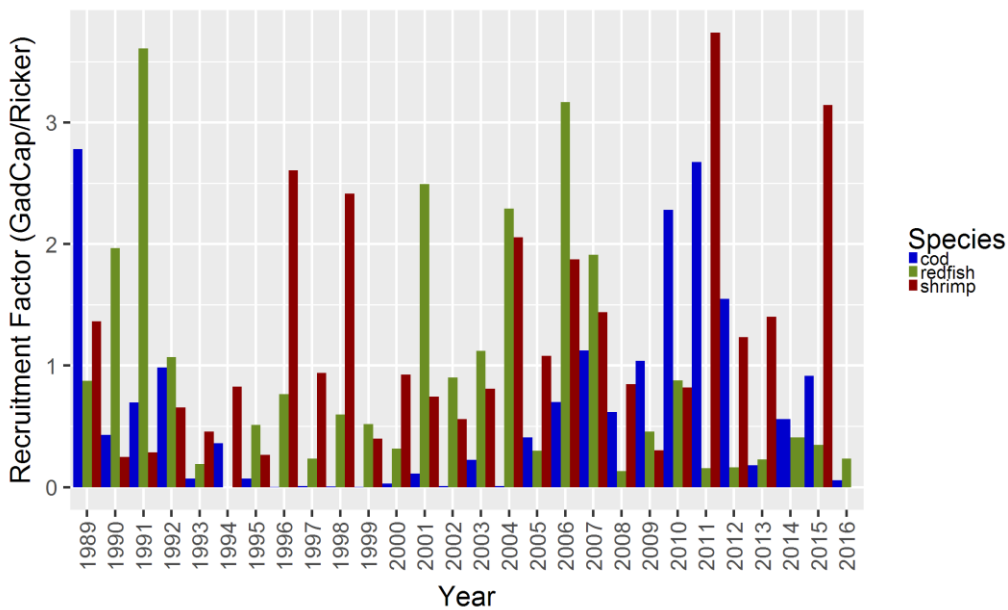
Figure 15.- Estimated annual factor for SSB-Recruitment relationship. These values result of dividing the recruitment estimated with GadCap in section 3.2 by the predicted recruitment with the fitted Ricker model. These annual factors are assumed to reflect the environmental conditions affecting recruitment and were used to change annually the Richer SSB-Recruitment curve.
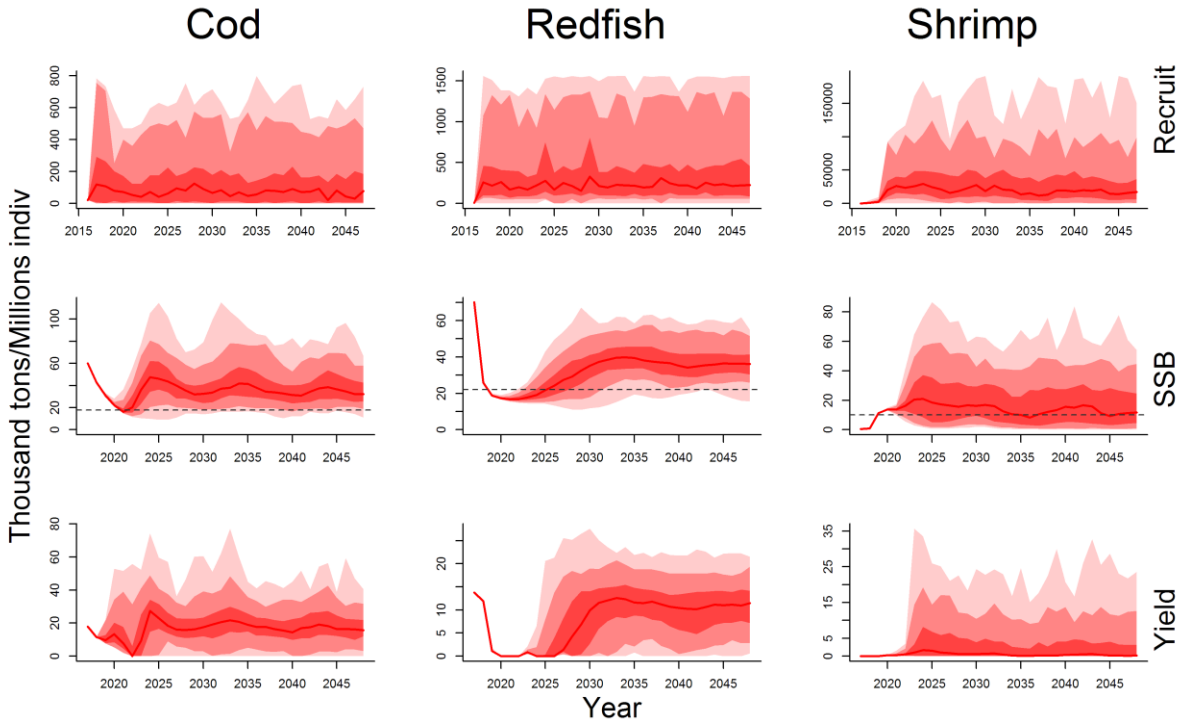
Figure 16.- Long term simulations using the multispecies MSE framework with GadCap as an OM, while in the MP, the HCRs defined with single species considerations are used to define the fishing quota annualy. The red line defines the median Recruit, SSB and yield. From darker to clearer, the coloured areas define the 25-75, the 5-95 and the 0-100 percentiles. These ranges of uncertainty were produced by running 100 simulations, each of them with a different time series of year effects in the SSB-Recruitment relationship.

- **TABLES**

Table 1- List of F values (20 values) tested for each of the three stocks considered in this study. All the possible combinations (8000 in total) were implemented in GadCap when running long term simulations over the period 2017-2050. The resulting estimates of yield and SSB were used to produce yield and SSB curves as a function of F, and serve to find MSY related F reference points.

F_{cod}	F_{red}	F_{shrimp}
0	0	0
0.05	0.015	0.015
0.1	0.03	0.03
0.15	0.045	0.045
0.2	0.06	0.06
0.25	0.075	0.075
0.3	0.09	0.09
0.35	0.105	0.105
0.4	0.12	0.12
0.45	0.135	0.135
0.5	0.15	0.15
0.55	0.165	0.165
0.6	0.18	0.18
0.65	0.195	0.195
0.7	0.2	0.2
0.75	0.225	0.225
0.8	0.25	0.25
0.85	0.275	0.275
0.9	0.3	0.3
0.95	0.325	0.325

Table 2.- B_{lim} and $B_{trigger}$ finally selected for each of the three stocks following the criteria described in the text.

Stock	B_{lim}	$B_{trigger}$
cod	17906	25943
redfish	22027	35361
shrimp	11864	31114

Table 3.- F$_{MSY}$, F$_{target}$, mean long term yield and mean long term SSB (both in tons) for the Flemish Cap cod, redfish and shrimp and estimated with a single species approach.

Stock	F$_{MSY}$	F$_{target}$	Yield	SSB
cod	0.55	0.367	28652	27605
redfish	0.15	0.1	12669	22689
shrimp	0.09	0.06	3463	16050

Table 4.- Reduced selection of F combinations from all those that resulted in SSB higher than Blim in the equilibrium for all the three stocks, cod, redfish and shrimp (criteria 1).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
1	3 stocks above B$_{lim}$	0.55	0.18	0
1	3 stocks above B$_{lim}$	0.6	0.165	0
1	3 stocks above B$_{lim}$	0.65	0.165	0
1	3 stocks above B$_{lim}$	0.65	0.165	0.015
1	3 stocks above B$_{lim}$	0.65	0.165	0.03
1	3 stocks above B$_{lim}$	0.65	0.195	0
1	3 stocks above B$_{lim}$	0.65	0.195	0.015
1	3 stocks above B$_{lim}$	0.65	0.195	0.03
1	3 stocks above B$_{lim}$	0.65	0.195	0.045
1	3 stocks above B$_{lim}$	0.65	0.195	0.06
1	3 stocks above B$_{lim}$	0.75	0.2	0
1	3 stocks above B$_{lim}$	0.75	0.2	0.06
1	3 stocks above B$_{lim}$	0.75	0.2	0.075

Table 5.- Reduced selection of F combinations from all those that resulted in SSB higher than B_{lim} in the equilibrium for cod and redfish, but disregarded the state of the SSB for shrimp (criteria 2).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
2	Disregard shrimp SSB	0.1	0	0
2	Disregard shrimp SSB	0.15	0.03	0
2	Disregard shrimp SSB	0.2	0.03	0
2	Disregard shrimp SSB	0.2	0.06	0
2	Disregard shrimp SSB	0.25	0.03	0
2	Disregard shrimp SSB	0.25	0.06	0
2	Disregard shrimp SSB	0.25	0.09	0
2	Disregard shrimp SSB	0.3	0.03	0
2	Disregard shrimp SSB	0.3	0.06	0
2	Disregard shrimp SSB	0.3	0.09	0
2	Disregard shrimp SSB	0.35	0.03	0
2	Disregard shrimp SSB	0.35	0.06	0
2	Disregard shrimp SSB	0.35	0.09	0
2	Disregard shrimp SSB	0.35	0.12	0
2	Disregard shrimp SSB	0.45	0.03	0
2	Disregard shrimp SSB	0.45	0.06	0
2	Disregard shrimp SSB	0.45	0.09	0
2	Disregard shrimp SSB	0.45	0.12	0
2	Disregard shrimp SSB	0.45	0.15	0

Table 6.- Reduced selection of F combinations from all those that resulted in SSB higher than Blim in the equilibrium for shrimp and redfish, but disregarded the state of the SSB for cod (criteria 3).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
3	Disregard cod SSB	0.7	0.15	0.03
3	Disregard cod SSB	0.7	0.18	0.03
3	Disregard cod SSB	0.7	0.18	0.06
3	Disregard cod SSB	0.7	0.2	0.03
3	Disregard cod SSB	0.7	0.2	0.06
3	Disregard cod SSB	0.8	0.12	0.03
3	Disregard cod SSB	0.8	0.15	0.03
3	Disregard cod SSB	0.8	0.15	0.06
3	Disregard cod SSB	0.8	0.15	0.09
3	Disregard cod SSB	0.8	0.18	0.03
3	Disregard cod SSB	0.8	0.18	0.06
3	Disregard cod SSB	0.8	0.18	0.09
3	Disregard cod SSB	0.8	0.18	0.12
3	Disregard cod SSB	0.8	0.2	0.03
3	Disregard cod SSB	0.8	0.2	0.06
3	Disregard cod SSB	0.8	0.2	0.09
3	Disregard cod SSB	0.8	0.2	0.12

Table 7.- Reduced selection of F combinations from all those that resulted in SSB higher than Blim in the equilibrium for shrimp and cod, but disregarded the state of the SSB for redfish (criteria 4).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
4	Disregard redfish SSB	0	0	0
4	Disregard redfish SSB	0	0.195	0
4	Disregard redfish SSB	0.05	0.03	0.03
4	Disregard redfish SSB	0.05	0.06	0.03
4	Disregard redfish SSB	0.05	0.06	0.06
4	Disregard redfish SSB	0.05	0.09	0.03
4	Disregard redfish SSB	0.05	0.09	0.06
4	Disregard redfish SSB	0.05	0.09	0.09
4	Disregard redfish SSB	0.05	0.12	0.03
4	Disregard redfish SSB	0.05	0.12	0.06
4	Disregard redfish SSB	0.05	0.12	0.09
4	Disregard redfish SSB	0.05	0.15	0.03
4	Disregard redfish SSB	0.05	0.15	0.06
4	Disregard redfish SSB	0.05	0.15	0.09
4	Disregard redfish SSB	0.05	0.2	0.03
4	Disregard redfish SSB	0.05	0.2	0.06
4	Disregard redfish SSB	0.05	0.2	0.09
4	Disregard redfish SSB	0.05	0.2	0.12
4	Disregard redfish SSB	0.05	0.3	0.03
4	Disregard redfish SSB	0.05	0.3	0.06
4	Disregard redfish SSB	0.05	0.3	0.09
4	Disregard redfish SSB	0.05	0.3	0.12
4	Disregard redfish SSB	0.1	0.09	0.03
4	Disregard redfish SSB	0.1	0.12	0.03
4	Disregard redfish SSB	0.1	0.15	0.03
4	Disregard redfish SSB	0.1	0.15	0.06
4	Disregard redfish SSB	0.1	0.2	0.03
4	Disregard redfish SSB	0.1	0.2	0.06
4	Disregard redfish SSB	0.1	0.3	0.03
4	Disregard redfish SSB	0.1	0.3	0.06
4	Disregard redfish SSB	0.1	0.3	0.09
4	Disregard redfish SSB	0.15	0.15	0.03
4	Disregard redfish SSB	0.15	0.2	0.03
4	Disregard redfish SSB	0.15	0.3	0.03
4	Disregard redfish SSB	0.15	0.3	0.06
4	Disregard redfish SSB	0.2	0.3	0.03
4	Disregard redfish SSB	0.25	0.3	0.03
4	Disregard redfish SSB	0.35	0.3	0.03
4	Disregard redfish SSB	0.75	0.25	0.105
4	Disregard redfish SSB	0.75	0.275	0.12

Table 8.- Reduced selection of F combinations from all those that resulted in SSB higher than Blim in the equilibrium for shrimp, but disregarded the state of the SSB for cod and redfish (criteria 5).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
5	Disregard cod and redfish SSB	0.2	0.275	0.03
5	Disregard cod and redfish SSB	0.2	0.35	0.03
5	Disregard cod and redfish SSB	0.2	0.35	0.06
5	Disregard cod and redfish SSB	0.35	0.275	0.03
5	Disregard cod and redfish SSB	0.35	0.35	0.03
5	Disregard cod and redfish SSB	0.5	0.275	0.03
5	Disregard cod and redfish SSB	0.5	0.275	0.06
5	Disregard cod and redfish SSB	0.5	0.35	0.03
5	Disregard cod and redfish SSB	0.5	0.35	0.06
5	Disregard cod and redfish SSB	0.5	0.35	0.09
5	Disregard cod and redfish SSB	0.7	0.2	0.03
5	Disregard cod and redfish SSB	0.7	0.2	0.06
5	Disregard cod and redfish SSB	0.7	0.275	0.03
5	Disregard cod and redfish SSB	0.7	0.275	0.06
5	Disregard cod and redfish SSB	0.7	0.275	0.09
5	Disregard cod and redfish SSB	0.7	0.275	0.12
5	Disregard cod and redfish SSB	0.7	0.35	0.03
5	Disregard cod and redfish SSB	0.7	0.35	0.06
5	Disregard cod and redfish SSB	0.7	0.35	0.09
5	Disregard cod and redfish SSB	0.7	0.35	0.12
5	Disregard cod and redfish SSB	0.7	0.35	0.18

Table 9.- Mean ratio of the difference between the estimated abundance at age for cod in the last aproved assessment for each of the three stocks, and the abundance at age estimated in the retrospective pattern.

age	meanratio
1	0.920441
2	1.160129
3	1.133066
4	1.02969
5	0.955309
6	0.951849
7	0.940828
8	0.944203
9	0.944203
10	0.944203
11	0.944203
12	0.944203

Table 10.- Mean ratio of the difference between the estimated abundance at age for redfish in the last aproved assessment for each of the three stocks, and the abundance at age estimated in the retrospective pattern.

age	meanratio
1	0.972452
2	0.972452
3	0.972452
4	0.788327
5	0.823222
6	0.842748
7	0.972452
8	0.942793
9	0.921678
10	0.910833
11	1.017579
12	1.050842
13	1.003778
14	1.007053
15	1.019722
16	0.893988
17	0.821866
18	0.932904
19	0.932904
20	0.932904
21	0.932904
22	0.932904
23	0.932904
24	0.932904
25	0.932904

Table 11.- Results of the risk analysis on the HCRs defined with single species criteria candidate to maintain the three stocks above Blim when the recruitment uncertainty is included in the long term simulations. The second column shows the F_{target} for each of the stocks in the selected combinations. The third column shows the probability (proportion of the 100 simulation runs) of being below Blim in the long term (period 2035-2050). The forth column shows the median yield and the last column the interannual variability in the catch, as percentage of difference in relation to the median yield.

Species	F_{target}	Perc_below_B_{lim}	Median_Yield	Interannual_variance
cod	0.353	26	16719	23
redfish	0.1	4	11021	12
shrimp	0.067	77	2730	81

Table 12.- Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain the three stocks above Blim when the recruitment uncertainty is considered in the simulations. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

HCR_co	F_{target} co	redfi	shri	Risk_below_B_{lim} co	redfi	shri	Median_yield cod	redfi	shri	Interannual_vari co	redfi	shri
1	0.5	0.18	0	81	3	40	171	155	0	62	11	0
2	0.6	0.16	0	92	2	38	167	157	0	10	11	0
3	0.6	0.16	0	92	1	39	176	148	0	48	12	0
4	0.6	0.16	0.01	93	1	40	168	156	0	99	13	0
5	0.6	0.16	0.03	93	1	43	143	158	0	13	13	0
6	0.6	0.19	0	92	1	36	167	157	152	10	11	55
7	0.6	0.19	0.01	92	1	37	167	156	167	10	13	58
8	0.6	0.19	0.03	92	1	41	166	156	281	10	11	54
9	0.6	0.19	0.04	93	1	44	166	155	306	10	13	47
10	0.6	0.19	0.06	92	1	49	165	155	418	10	13	52
11	0.7	0.2	0	99	1	35	165	154	514	99	13	63
12	0.7	0.2	0.06	10	1	51	138	156	561	16	13	69
13	0.7	0.2	0.07	10	1	53	138	155	641	17	13	257

Table 13.- Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain cod and redfish above Blim while disregarding shrimp when the recruitment uncertainty is considered in the simulations. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

HCR_combi	F_{target}			Risk_below_B_{lim}			Median_yield			Interannual_variance		
	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0.1	0	0	9	66	75	752	0	0	1	0	0
2	0.1	0.03	0	9	53	76	104	245	0	1	38	0
3	0.2	0.03	0	11	22	78	127	332	0	1	22	0
4	0.2	0.06	0	9	30	73	127	524	0	1	27	0
5	0.2	0.03	0	13	6	82	147	402	0	1	10	0
6	0.2	0.06	0	14	15	73	147	652	0	1	13	0
7	0.2	0.09	0	14	23	67	147	775	0	1	22	0
8	0.3	0.03	0	18	3	79	160	458	0	2	8	0
9	0.3	0.06	0	18	5	72	161	768	0	2	11	0
10	0.3	0.09	0	17	10	66	161	941	0	2	13	0
11	0.3	0.03	0	25	1	78	168	506	0	2	5	0
12	0.3	0.06	0	25	1	72	170	860	0	2	6	0
13	0.3	0.09	0	27	4	65	170	106	0	2	9	0
14	0.3	0.12	0	27	6	58	171	115	0	2	12	0
15	0.4	0.03	0	51	0	77	174	561	0	3	4	0
16	0.4	0.06	0	51	0	69	175	962	0	3	5	0
17	0.4	0.09	0	51	0	58	176	122	0	3	6	0
18	0.4	0.12	0	51	2	54	178	135	0	3	9	0
19	0.4	0.15	0	50	2	48	179	137	0	3	12	0

Table 14.- Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain cod and shrimp above Blim while disregarding redfish when the recruitment uncertainty is considered in the simulations. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

HCR_combi	F_{target}			Risk_below_B_{lim}			Median_yield			Interannual_variance		
	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0	0	0	5	96	54	0	0	0	0	0	0
2	0	0.19	0	4	99	39	0	287	0	0	153	0
3	0.0	0.03	0.03	9	90	63	410	798	306	16	768	113
4	0.0	0.06	0.03	7	92	58	411	113	335	16	88	69
5	0.0	0.06	0.06	8	93	64	404	110	561	16	209	80
6	0.0	0.09	0.03	7	95	55	412	125	351	16	220	82
7	0.0	0.09	0.06	8	95	62	405	122	600	16	183	76
8	0.0	0.09	0.09	8	94	66	399	119	771	16	170	90
9	0.0	0.12	0.03	7	98	52	413	129	365	16	112	69
10	0.0	0.12	0.06	8	97	61	405	125	626	16	116	81
11	0.0	0.12	0.09	8	97	65	399	122	808	16	103	94
12	0.0	0.15	0.03	7	99	49	414	122	382	16	148	71
13	0.0	0.15	0.06	7	99	61	406	117	646	16	167	70
14	0.0	0.15	0.09	8	99	62	399	116	836	16	130	88
15	0.0	0.2	0.03	8	99	48	415	977	398	16	131	58
16	0.0	0.2	0.06	9	100	55	407	974	672	16	129	71
17	0.0	0.2	0.09	10	100	63	400	950	861	16	133	92
18	0.0	0.2	0.12	10	100	68	394	948	100	16	125	92
19	0.0	0.3	0.03	9	100	46	417	676	427	16	329	56
20	0.0	0.3	0.06	9	100	52	409	647	709	16	255	72
21	0.0	0.3	0.09	10	100	57	401	657	907	16	127	75
22	0.0	0.3	0.12	10	100	63	395	663	106	16	126	89
23	0.1	0.09	0.03	9	85	64	754	279	236	16	86	89
24	0.1	0.12	0.03	9	90	61	754	281	252	17	102	78
25	0.1	0.15	0.03	10	91	61	755	279	266	17	193	79
26	0.1	0.15	0.06	10	91	66	745	274	446	17	189	94
27	0.1	0.2	0.03	11	91	58	757	247	283	17	197	163
28	0.1	0.2	0.06	11	91	63	746	244	471	17	125	87
29	0.1	0.3	0.03	11	96	54	759	175	305	17	261	69
30	0.1	0.3	0.06	11	96	62	748	171	518	17	148	98
31	0.1	0.3	0.09	11	96	66	737	166	652	17	170	109
32	0.1	0.15	0.03	8	78	63	104	479	201	17	118	86
33	0.1	0.2	0.03	8	82	62	104	446	220	17	82	81
34	0.1	0.3	0.03	8	87	57	104	380	242	17	237	66
35	0.1	0.3	0.06	9	88	60	103	378	402	17	93	77
36	0.2	0.3	0.03	10	67	58	128	616	219	17	74	78
37	0.2	0.3	0.03	14	50	59	148	800	212	19	64	73
38	0.3	0.3	0.03	27	18	53	171	111	247	23	32	98

| 39 | 0.7 | 0.25 | 0.10 | 10 | 1 | 55 | 139 | 154 | 799 | 17 | 16 | 170 |
| 40 | 0.7 | 0.27 | 0.12 | 10 | 1 | 57 | 138 | 154 | 848 | 17 | 19 | 83 |

Table 15.- Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain redfish and shrimp above Blim while disregarding cod when the recruitment uncertainty is considered in the simulations. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

HCR_combi	F_{target}			Risk_below_B_{lim}			Median_yield			Interannual_vari		
	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0.	0.15	0.03	97	1	49	126	155	243	24	7	47
2	0.	0.18	0.03	97	1	44	161	157	279	12	10	52
3	0.	0.18	0.06	97	1	51	124	161	297	27	9	65
4	0.	0.2	0.03	97	1	44	161	156	309	18	12	53
5	0.	0.2	0.06	97	1	50	125	161	329	26	12	53
6	0.	0.12	0.03	10	0	55	161	156	326	10	14	50
7	0.	0.15	0.03	10	0	46	126	161	343	25	13	52
8	0.	0.15	0.06	10	0	55	124	160	495	25	9	48
9	0.	0.15	0.09	10	0	63	158	155	520	99	12	67
10	0.	0.18	0.03	10	0	40	125	160	553	24	12	50
11	0.	0.18	0.06	10	0	48	158	155	548	98	14	56
12	0.	0.18	0.09	10	0	58	127	159	576	24	13	54
13	0.	0.18	0.12	10	0	64	122	159	605	24	10	79
14	0.	0.2	0.03	10	0	41	123	159	683	24	12	56
15	0.	0.2	0.06	10	0	47	125	158	718	23	13	79
16	0.	0.2	0.09	10	0	54	121	157	744	24	12	97
17	0.	0.2	0.12	10	0	63	123	156	783	24	13	128

Table 16.- Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain shrimp above Blim while disregarding cod and redfish. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

HCR_combi	F_{target}			Risk_below_B_{lim}			Median_yield			Interannual_variance		
	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0.2	0.27	0.03	10	65	58	128	626	215	17	63	70
2	0.2	0.35	0.03	10	75	57	128	580	228	17	85	77
3	0.2	0.35	0.06	11	75	62	127	579	384	18	81	140
4	0.3	0.27	0.03	27	17	53	171	112	241	23	30	106
5	0.3	0.35	0.03	27	22	52	172	110	256	23	42	85
6	0.5	0.27	0.03	71	4	42	177	142	289	39	19	63
7	0.5	0.27	0.06	72	4	49	177	141	483	40	19	79
8	0.5	0.35	0.03	71	8	38	178	142	312	38	27	47
9	0.5	0.35	0.06	72	10	44	177	140	520	40	27	61
10	0.5	0.35	0.09	72	10	55	176	139	655	40	28	110
11	0.7	0.2	0.03	97	1	44	161	156	326	10	14	50
12	0.7	0.2	0.06	97	1	50	158	155	548	98	14	56
13	0.7	0.27	0.03	97	2	38	161	156	360	98	20	38
14	0.7	0.27	0.06	97	2	45	158	154	592	99	20	43
15	0.7	0.27	0.09	97	2	52	156	153	737	99	20	54
16	0.7	0.27	0.12	97	2	56	154	152	809	10	20	79
17	0.7	0.35	0.03	97	12	34	162	154	379	98	32	39
18	0.7	0.35	0.06	97	13	44	159	153	634	99	32	45
19	0.7	0.35	0.09	97	14	52	156	152	781	99	33	53
20	0.7	0.35	0.12	97	14	55	154	151	858	99	33	111
21	0.7	0.35	0.18	98	16	64	152	149	933	11	33	106
22	0.4	0.5	0.03	36	90	39	180	103	302	25	129	57
23	0.4	0.5	0.06	35	91	47	178	102	502	25	120	76
24	0.4	0.5	0.09	38	91	56	176	102	632	25	116	145

Table 17.- Selection of HCRs for comparison of risk analysis results when the assessment error is considered in the shortcut assesment ('truth plus noise shortcut') in relation to when the error is disregarded ('no error shortcut').

HCR combi	Type	F_{target} cod	F_{target} red	F_{target} shrimp	Risk_below_B_{lim} cod	Risk_below_B_{lim} red	Risk_below_B_{lim} shrimp
1	disregard redfish	0.2	0.3	0.03	7	60	63
2	disregard redfish	0.35	0.3	0.03	22	14	51
3	disregard shrimp	0.25	0.03	0	12	8	83
4	disregard shrimp	0.3	0.03	0	17	2	82
5	disregard shrimp	0.3	0.09	0	18	7	67
6	B_{lim} 3 sp	0.65	0.195	0	99	1	33
7	disregard cod	0.8	0.2	0.03	100	3	38
8	disregard cod and redfish	0.7	0.35	0.03	97	6	28

Table 18.- Comparison of probability, for the three stocks, of SSB being below their respectives Blim when a single versus a two stage HCRs is used for cod.

comb. N	F_{target} cod	F_{target} redfish	F_{target} shrimp	Perc_B_{lim}_cod one-stage	Perc_B_{lim}_cod two-stage	Perc_B_{lim}_redfish one-stage	Perc_B_{lim}_redfish two-stage	Perc_B_{lim}_shrimp one-stage	Perc_B_{lim}_shrimp two-stage
1	0.25	0.03	0	13	10	6	0	82	82
2	0.25	0.06	0	14	11	15	0	73	75
3	0.25	0.09	0	14	12	23	2	67	65

4	0.35	0.12	0	27	28	6	2	58	54

ANNEX IX: MINUTES ON THE 10TH MEETING OF THE WORKING GROUP ON ECOSYSTEM STUDIES AND ASSESSMENT NAFO-WGESA

Framework contract – Provision of Scientific Advice for fisheries beyond EU waters

EASME/EMFF/2016/008

European Commission

SC05 Multispecies Fisheries Assessment for NAFO

NAFO-WGESA Minutes

Halifax, 7th-16th November 2017

From 7th to 16th November 2017, the 10th meeting of the NAFO Working Group on Ecosystem Studies and Assessment (WGESA) took place in Halifax (Canada). Dr. Alfonso Pérez Rodríguez attended this meeting as EU Delegate. His attendance aimed to present the main objectives and outcomes of the Specific Contract nº 5 "Multispecies Fisheries Assessment for NAFO" EASME/EMFF/2016/1.3.2.3/05/SI2.760000 of the FRAMEWORK CONTRACT – EASME/EMFF/2016/008 – "Scientific advice for fisheries beyond EU waters".

This minutes report aims to summarize the main discussions that took place in relation to the Specific Contract nº 5 during this NAFO WGESA meeting.

More information on this meeting can be found at https://www.nafo.int/Portals/0/PDFs/sc/2017/scs17-21.pdf.

2. Specific Contract 05 (Consortium)

Dr. Alfonso Pérez Rodríguez on behalf of all the partners presented the main objectives and expected outcomes of the Specific Contract nº 5 (see presentation in Annex 2). This Specific Contract N0 5 was very relevant under this agenda (Annex 1) since ultimately it aims to address some of the current impediments on implementing a multispecies approach in NAFO and will be providing solutions that shall support the implementation through collaboration and consultation in NAFO.

Some of the approaches for the integration of the SC05 project into the roadmap for the EAF in NAFO were presented:

1.- The connection between tiers 2 and 3, i.e. the multispecies and single species tiers, is programmed to be developed by using the GadCap multispecies model in two essential aspects of scientific advice: the stock assessment and the determination of reference points and HCRs. In terms of stock assessment, the SC05 project is design to contribute through the estimates of predation mortality M2 and residual natural mortality M1. M2 and M1 values will be estimated using the GadCap multispecies model once it has been updated and improved in Tasks 2 and 3 and will be tested during the benchmark of 3M cod in March-April 2018. A second contribution to the connection between tiers 1 and 2 will be by estimating alternative reference points and design of HCRs that meet the objectives of the NAFO precautionary approach, but from a multispecies approach.

2.- The connection between tiers 2 and 3 is an aspect that will be developed throughout the project. One of the potential connections will be the use of estimated potential fishery production for the demersal stocks as a reference value to define general values around which limiting the productivity of the modelled stocks, or at least values to which compare the productivity estimated in GadCap.

The project was very well received by the members of WGESA. After the presentation there were some comments, which were mostly in the line of supporting this type of work as some of the steps to follow in order to develop and integrate the EAF into the NAFO management framework. There was also some concern about the amount of work that will be needed to achieve the different objectives of the project. However, it was clarified that this project is not intended to provide definitive answers. Instead, as the project's objectives state, this project is intended to shed light on the way in which the multispecies approach fits within the NAFO EAF roadmap, using the Flemish Cap as a case study, and defining the future lines of work necessary to continue with the development of the multi-species approach in NAFO. Another important goal of the project is starting the discussions with stakeholders and creating awareness of the meaning of the multispecies approach and the implications in the management approach that this will imply. Regarding this aspect, some WGESA members

stressed that it would be very positive if interaction with stakeholders could be started at the beginning of the project, and continued at different stages of the project development, so that when the results are presented to them they feel part of the process. Although it was recognized as a positive and desirable appreciation, however, it was highlighted that it is important to keep in mind that this project is really only the beginning of a work that will need further development in the future. As such, the results of the work developed in Tasks 3 and 4 will be presented to the stakeholders in Task 5, not as a definitive result but as a first approximation for which their inputs in terms of socioeconomic and fisheries technical aspects will be very necessary in order to improve HCRs and multispecies management strategies in the future. Finally it was also stressed the convenience of attending the scientific council in person in June 2018 to present the project and the up-to-date results. Attending to this meeting would facilitate the interaction and transmission of the analyses and results to the scientific council in a more effective manner.

3. Annex 1. Agenda

WGESA 2017 - DETAILED AGENDA

<table>
<tr><td colspan="6" align="center">TUESDAY 7/11/17</td></tr>
<tr>
<th>Start Time</th>
<th>End Time</th>
<th>ToR</th>
<th>Activity[75]</th>
<th>Lead, key presenters or contributors</th>
<th>Duration (hr:min)</th>
</tr>
<tr>
<td>10:00</td>
<td>11:00</td>
<td></td>
<td>Opening, appointment of rapporteur, discussion of ToRs and approval of agenda</td>
<td>Andy, Pierre</td>
<td>1:00</td>
</tr>
<tr>
<td>11:00</td>
<td>11:30</td>
<td></td>
<td>Coffee BREAK</td>
<td></td>
<td>0:30</td>
</tr>
<tr>
<td>11:30</td>
<td>12:30</td>
<td></td>
<td>Summary of meetings SC June, WGEAFFM July, SC September</td>
<td>Andy. Pierre</td>
<td>1:00</td>
</tr>
<tr>
<td>12:30</td>
<td>14:00</td>
<td></td>
<td>Lunch BREAK</td>
<td></td>
<td>1:30</td>
</tr>
<tr>
<td>14:00</td>
<td>14:30</td>
<td>1.1</td>
<td>Update on VME indicator species data (RV trawl surveys)</td>
<td>Mar</td>
<td>0:30</td>
</tr>
<tr>
<td>14:30</td>
<td>15:30</td>
<td>1.1</td>
<td>Update on VME indicator species data (Canadian surveys)</td>
<td>Ellen</td>
<td>1:00</td>
</tr>
<tr>
<td>15:30</td>
<td>16:00</td>
<td></td>
<td>Coffee BREAK</td>
<td></td>
<td>0:30</td>
</tr>
<tr>
<td>16:00</td>
<td>17:00</td>
<td>1.3</td>
<td>Workplan - non-sponge and coral VMEs (for example bryozoan and sea squirts), preparation for next assessment 2020 – discussion</td>
<td>Ellen + Others</td>
<td>1:00</td>
</tr>
</table>

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[75] Activities may consist of either one or several of the following: plenary discussions, analysis and/or planning; presentations of latest results/findings on a regular topic, presentation of new but related R&D work.

WEDNESDAY 8/11/17					
Start Time	End Time	ToR	Activity	Lead, key presenters or contributors	Duration (hr:min)
9:00	10:30	1.2	KDE up-dated sea pen analysis – presentation & discussion	Ellen, Cam	1:30
10:30	11:00		Discussion, advice sea pen Closure Area 14 assessment for 2018.	Ellen + All	0.30
11:00	11:30		Coffee BREAK		0:30
11:30	12:30	2.1 FC10	Sea pen VME ecology, resilience, presentation & discussion	Sarah, Anna	1:00
12:30	14:00		Lunch BREAK		1:30
14:00	15:30	2.2 FC10	Up-date analysis undertaken by EU NEREIDA research – Sea pen resilience, presentation & discussion	Andy	1:30
15:30	16:00		Coffee BREAK		0:30
16:00	17:00	1.4	Workplan and timetable for reassessment of VME fishery closures including seamount closures for 2020.	Andy, Ellen + Others	1:00
THURSDAY 9/11/17					
Start Time	End Time	ToR	Activity	Lead, key presenters or contributors	Duration (hr:min)
9:00	10:00	2.2 FC10	Tabulated review of VME functions, resilience - discussion	Vonda + Others	1:00

11:00	11:30		Coffee BREAK		0:30
11:30	12:30	3.4 FC10	Workplan - Improvements to assess overlap of NAFO fisheries with VME to evaluate fishery specific impacts in addition to the cumulative impacts - discussion	Corinna, Neil, Don, Tom, Andy	1:00
12:30	13:30		Lunch BREAK		1:30
13:30	*17:00*		*Planning Group – VME Function Analysis*	*Vonda, Corinna, Neil, Lindsay, Javier, Barbara*	
13:30	15:30	FC9	Flemish Cap Red fish stock differentiation	Adriana	0:30
		3.3 FC9	Consideration of stock recruitment patterns through the application of EAFM – SC request	Pierre	1:00
15:30	16:00		Coffee BREAK		0:30
16:00	17:00		EU Atlas Project Presentation	Mar, Pablo	1:00

FRIDAY 10/11/17					
Start Time	End Time	ToR	Activity	Lead, key presenters or contributors	Duration (hr:min)
9:00	10:00	3.1 FC9	Development and application of the EAF Roadmap – presentation on EAF roadmap	Pierre, Mariano	1:00
10:00	11:00	3.3 FC9	Using Ecopath with Ecosim to support ecosystem-based fisheries management	Alida	1:00

11:00	11:30		Coffee BREAK		0:30
11:30	12:30	2.3 FC9	Flemish Cap multispecies fisheries ecosystem modelling – presentation	Alfonso	1:00
12:30	14:00		Lunch BREAK		1:30
14:00	15:00	FC9	Empirical Dynamic Modelling applied to interacting species	Mariano	1:00
15:00	15:30		Coffee BREAK		0:30
15:30	16:30	2.3 FC9	North Sea multi-species fisheries ecosystem modelling - presentation	Robert	1:00
16:30	17:30	2.3 FC9	Preliminary Multi-species modelling discussion – way forward – agree workplan	Alfonso, Robert, Pierre	1:00
17:30			NAFO Reception		

SATURDAY 11/11/17					
Start Time	End Time	ToR	Activity	Lead, key presenters or contributors	Duration (hr:min)
9:00	10:00		Summary of actions (who's doing what)	Andy, All	1:00
			Reporting on new VME analyses	Ellen, Cam	
			A Primer on KDE analysis applied to the NRA	Ellen	
10:00	11:00	2.4 FC9	Overview of oceanographic and ecosystem state in the NRA	Mariano, Diana, Pierre	1:00

Start Time	End Time	ToR	Activity	Lead, key presenters or contributors	Duration (hr:min)
		&10			
11:00	11:30		Coffee BREAK		0:30
11:30	12:30	FC9	Use of Ecosystem Indicators on the Grand Banks	Danielle Dempsey	1:00
12:30	14:00		Lunch BREAK		1:30
14:00	15:30	FC9	Development of draft ecosystem summary sheets	Pierre, Mariano	1:30
15:30	16:00		Coffee BREAK		0:30
19:00	late		Ice Hockey Social Event (TBA)	All	

MONDAY 13/11/17					
Start Time	End Time	ToR	Activity	Lead, key presenters or contributors	Duration (hr:min)
9:00	10:00		Feedback - data analysis/report drafting	Andy, Pierre	1:00
10:00	11:00	FC9	Ecosystem production potential modelling	Mike, Pierre, Mariano	1:00
11:00	11:30		Coffee BREAK		0:30
11:30	12:30	3.5	Update of WGNARS activities and plans	Geret DePiper	1:00
12:30	14:00		Lunch BREAK		1:30
14:00	15:00	2.3 FC9	An Ecosystem-based Management Procedure for Interacting Species	Mike	1:00

15:00		FC6	Up-date on plan to continue work on the risk assessment of scientific trawl surveys impact on VME in closed areas, and the effect of excluding surveys from these areas on stock assessments.	All – Brian Healey to present results from June SC Diana for EU	1:30
15:30	16:00		Coffee BREAK		0:30
16:00		FC6	Up-date on plan to continue work on the risk assessment of scientific trawl surveys impact on VME in closed areas, and the effect of excluding surveys from these areas on stock assessments.	All – Brian Healey to present results from June SC Diana for EU	continued
			Up-date development in the use of non-destructive sampling techniques to monitor VMEs and options for integrating with existing survey trawl data.	All	1:00

TUESDAY 14/11/17					
Start Time	End Time	ToR	Activity	Lead, key presenters or contributors	Duration (hr:min)
9:00	10:00		Feedback - data analysis/report drafting Preliminary report of haul-by-haul analyses Report *Planning Group – VME Function Analysis*	Andy, Pierre, All	1:00
10:00	11:00	2.2 FC10	Workplan to maintain efforts to assess all six FAO criteria - discussion	All	1:00
11:00	11:30		Coffee BREAK		0:30
11:30	12:30	3.7	Workplan - consider clearer objective ranking processes and options for objective	All	1:00

Start Time	End Time	ToR	Activity	Lead, key presenters or contributors	Duration (hr:min)
		FC10	weighting criteria for the overall assessment of SAI and risk of SAI - discussion		
12:30	14:00		Lunch BREAK		1:30
14:00	17:00		Breakout Group draft ecosystem summary sheets		
			To be agreed		
	17:00		To be agreed		

WEDNESDAY 15/11/17 to THURSDAY 16/11/17					
Start Time	End Time	ToR	Activity	Lead, key presenters or contributors	Duration (hr:min)
9:00	10:00			Andy, Pierre	1:00
			To be agreed		
			To be agreed		
			To be agreed		
			To be agreed		
			To be agreed		
			To be agreed		
	17:00		To be agreed		

4. Annex 2. Presentation SC05

Slide 1

Slide 2

Slide 3

Objectives of SC 05

- Providing a **comprehensive overview** on how multispecies assessments would fit into the scientific and decision-making processes within NAFO

- Develop **specific analyses and techniques** on a case study, the Flemish Cap, that result in potential practical implementations for the multispecies approach.

- Identifying **future steps and research activities** to progress in the implementation of the multispecies assessment in the Flemish Cap, and extensively in the area NAFO.

Slide 4

Geographical scope

Slide 5

Slide 6

Slide 7

Slide 8

Slide 9

Slide 10

Slide 11

Task 1 – Setting the Context
Methods & Activities

Tasks content, milestones and deliverables	2017						2018	
	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
	M1	M2	M3	M4	M5	M6	M7	M8
Task 1 - Setting the context								
1.1 The multispecies approach in other management organizations							M1.1	
1.2 Revision of the case study: Flemish Cap and NAFO								M1.2

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Task 2 – Update and Improvement of Gadcap Multispecies Model
Methods & Activities

Subtask 2.1 Updating model input databases
- Updating commercial, survey and oceanographic input data and revision of the input data from 1988 to 2012.

Subtask 2.2 Improving of GadCap model

- The structure and different parameters and submodels of GadCap will be checked for potential improvement.

Subtask 2.3 Model assemblage

- The model will be assembled with all the new information and model parameters will be optimized. All the necessary sensitivity analysis and diagnostics will be conducted.

It is expected that these three subtasks will be developed almost in parallel.

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Task 2 – Update and Improvement of Gadcap Multispecies Model
Methods & Activities

Tasks content, milestones and deliverables	2017						2018				
	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
Task 2 - Update and improvement of GadCap multispecies model											
2.1 Updating model input databases							M2.1				
2.2 Improving of GadCap model											M2.2
2.3 Model assemblage											D2.1

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Task 3 – Application of Multispecies Model in Stock Assessment in the Flemish Cap
Methods & Activities

Subtask 3.1 Estimates of natural mortality (M1+M2) and use in single species short term forecast
- Estimates of natural mortality for cod, redfish and shrimp will be delivered.
- Complimentary effort to connect SC05 with SC03

Subtask 3.2 Explore multispecies reference points and HCRs

- Define MSY reference points considering the trade-offs and interdependency between cod, redfish and shrimp in the Flemish Cap.

- Alternative HCRs containing multispecies considerations and reference points

- Close communication with the NAFO Designated Experts in charge of the Flemish Cap stock assessments.

Subtask 3.2 Multispecies Management Strategy Evaluation

- Assemblage of a Multispecies MSE (msMSE)

- Assessment of ecological implications: explore different management objectives.

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Task 3 – Application of Multispecies Model in Stock Assessment in the Flemish Cap
Methods & Activities

Tasks content, milestones and deliverables	2018											2019
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec		Jan
	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18		M19
Task 3 – Application of multispecies model in stock assessment in the Flemish Cap												
3.1 Estimates of natural mortality (M1+M2) and use in single species short term forecast		D3.1										
3.2 Explore multispecies reference points and HCRs						D3.2						
3.3 Multispecies Management Strategy Evaluation								D3.3				

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Task 4 – Evaluation Of Economic Implications Of Trade-offs
Methods & Activities

Subtask 4.1 Identification and description of the existing economic data and the ecological-economic models suitable to be applied on multispecies assessment

- Review all up-to-date economic fisheries models
- Define the best modelling approach to cope with the economic evaluation, based in the HCRs and the availability of economic related data.
- An analysis of the challenges to use a full coupled model.

Subtask 4.2 Trade-offs between different fisheries derived from a multispecies approach

- Based in the possibilities defined in previous step an economic evaluation of the arising trade-offs of the multi-species HCRs will be executed.
- Results including uncertainty estimates derived from the modelling output coming from tasks 2 and 3.

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Task 4 – Evaluation Of Economic Implications
Of Trade-offs
Methods & Activities

Tasks content, milestones and deliverables	2018				2019
	Sep	Oct	Nov	Dec	Jan
	M15	M16	M17	M18	M19
Task 4 - Evaluation of economic implications of trade-offs					
4.1 Identification and description of the existing economic data and the ecological-economic models suitable to be applied on multispecies assessment			D4.1		
4.2 Trade-offs between different fisheries derived from a multispecies approach.					M4.1 D4.2

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Task 5 – Discussion and Interaction between
Scientists and other Stakeholders
Methods & Activities

Subtask 5.1 Organization of a workshop to present the results of the study to main stakeholders and administrations in the EU
- A two day workshop with the main stakeholders from the fishing industry, EU administrations and leaders of Tasks 3, 4 and 5
- Promote a constructive discussion around the topic
- Create awareness of this relatively new approach
- Optimize the quality and quantity of feedback from stakeholders. Use previous experiences in the presentation and discussion with stakeholders (Kempf et al, 2016)

Subtask 5.2 Integration of results on the NAFO Roadmap for the development of an ecosystem approach to fisheries management

- Integrate the results of this project into the roadmap for the EAFM in NAFO.

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Task 5 – Discussion and Interaction between Scientists and other Stakeholders
Methods & Activities

Tasks content, milestones and deliverables	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18
Task 5 - Discussion and interaction between scientists and other stakeholders														
5.1 Organization of a workshop to present the results of the study to main stakeholders and administrations in the EU														M5.4 D5.3
5.2 Integration of results on the WGESA Roadmap for the development of an ecosystem approach to fisheries management (EAFM) for NAFO during the WGESA meetings in 2017 and 2018, and the Scientific Council in 2018.	M5.1						D5.1	M5.2				D5.2	M5.3	

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Task 6 – Future Research Directions and Needs
Methods & Activities

Subtask 6.1 Analyses about the progress and implementation of multispecies assessment
- Review the progress made by this study and identify the challenges and limitations encountered (ecological, economic, methodology, data, etc) and how they could be addressed in the future.
- Lessons learned

Subtask 6.2 Research activities to strengthen the multispecies assessment implementation within the NAFO roadmap for an EAF

- Propose activities to address the limitations within the NAFO case study.

- Description of research activities, their potential contribution to the multispecies implementation, and best way to be taken forward as part of the NAFO roadmap for EAF

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Task 6 – Future Research Directions and Needs
Methods & Activities

Tasks content, milestones and deliverables	2018 Dec M18	2019 Jan M19
Task 6 - Future research directions and needs		
6.1 Analyses about the progress and implementation of multispecies assessment		
6.2 Research activities to strengthen the multispecies assessment implementation within the NAFO roadmap for an EAF		M6.1

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Specific Contract no. 5

"Multispecies Fisheries Assessment for NAFO"

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Framework contract – Provision of Scientific Advice for fisheries beyond EU waters

EASME/EMFF/2016/008

SC05 Multispecies Fisheries Assessment for NAFO

NAFO-WGESA Minutes

Halifax, 13th-22nd November 2018

Participants

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Minutes on the 11th Meeting of the Working Group on Ecosystem Studies and Assessment NAFO-WGESA.

From 13th to 22nd November 2018, the 11th meeting of the NAFO Working Group on Ecosystem Studies and Assessment (WGESA) took place in Halifax (Canada). Dr. Alfonso Pérez Rodríguez attended this meeting as EU Delegate. His attendance aimed to present the main results of the work developed as part of the Specific Contract nº 5 "Multispecies Fisheries Assessment for NAFO" EASME/EMFF/2016/1.3.2.3/05/SI2.760000 of the FRAMEWORK CONTRACT – EASME/EMFF/2016/008 – "Scientific advice for fisheries beyond EU waters". Specifically, the work that was planned going to be presented was mostly related with Tasks 1 to 4. However, due to the limitation set by the IIM-CSIC in relation to the use of the historical Flemish Cap summer survey database (1988-2001), two days before the start of the meeting DG-MARE indicated that the results of the project should not make public before this data permission issue had been solved. Accordingly, the communication of results to the WGESA was reduced to a superficial presentation of the work done in Tasks 1 to 4, without showing any numeric result (Attached in annex 2). However, contribution of SC05 to SC03 *"Support to a robust model assessment, benchmark and development of a management strategy evaluation for cod in NAFO division 3M"*, Task 3.1, was presented since these results were made public before the problem with the use of the data was raised by the IIM-CSIC.

It was originally planned, as part of the deliverables of the project, presenting during the meeting a working document compiling the results of SC05 presented to the WGESA. However, since no results were presented, as well as the guidelines from DG-MARE in relation to cancelling spreading the results of SC05 project, precluded of releasing this document. Accordingly, this is a deliverable that has not been accomplished.

This minutes report aims to summarize the main discussions that took place in relation to the Specific Contract nº 5 during this NAFO WGESA meeting.

More information on this meeting can be found at https://www.nafo.int/Portals/0/PDFs/sc/2018/scs18-23.pdf.

1. Specific Contract 05 (Consortium)

Dr. Alfonso Pérez Rodríguez, on behalf of all the partners contributing to the SC05 project, presented a broad summary about the work that has been conducted so far as part of the project SC05 in the Tasks 1, 2, 3 and 4. However due to the limitations set by the IIM-CSIC for the use of the historical period database (years 1988-2001 and 2014-2017), no any specific result was presented (see presentation in annex 3) , with the exception of the contribution of the SC05 project to the Task 2 of the EU SC03 project "Support to a robust model assessment, benchmark and development of a management strategy evaluation for cod in NAFO division 3M". Instead, a very shallow presentation of the work done along this year within the project SC05 was done.

This Specific Contract N0 5 was originally very relevant in the 11th WGESA meeting this agenda (Annex 1) and Tors (Annex 2), since there is an aim to address some of the current impediments on implementing a multispecies approach in NAFO. Next a brief summary of the presentation and the main questions or comments raised are presented.

The communication to the group of the impossibility of presenting the results of the project SC05 due to the limitation set by IIM-CSIC to the use of the data and spreading of results created deeply disappointed the members of the group. This project was expected to contribute very importantly this year to the work of the group in relation to the multispecies approach, and would trigger the discussion in the scientific council in June about the importance of considering interactions between the components of a managed system. For this reason, the chairs decided to write a formal letter to the Scientific Council communicating this problems and the limitations that this will involve in relation to the development of the roadmap for an EAF in the NAFO area. In addition, some members of the WGESA also asked about the impact that this data use ban may have in other projects that are running at this moment, like NEREIDA.

As a first step in the SC05 presentation, the tasks of the project were introduced:

- Task 1: Setting the context
- Task 2: Updating GadCap
- Task 3: First approach to implement multispecies assessment
- Task 4: Economy trade-offs
- Task 5: Dissemination to scientists and stakeholders
- Task 6: Further research

It was indicated that currently, Tasks 1 to 4 have already been accomplished. In Task 2, the multispecies model GadCap (Pérez-Rodríguez et al. 2017) was extended to cover and assess the dynamic of cod, redfish and shrimp over the period 1988-2016. For this, all the survey and commercial databases were updated and revised, in order to ensure that the data used in GadCap was, as much as possible, the same data used in the single species stock assessment of these stocks. In addition to the databases, some very important sub-models

defining the productivity and interactions between the three stocks were reviewed and improved.

In relation to the natural mortality, different approaches were used to estimate the residual natural mortality (M1), that together with the predation mortality (M2) estimated within GadCap would produce values of total natural mortality (M=M1+M2) at age every year (Pérez-Rodríguez and González-Costas 2018). This matrix of natural mortalities were used (as part of the Task 3) as an alternative estimate of natural mortality during the 3M cod benchmark exercise in the EU SC03 project "Support to a robust model assessment, benchmark and development of a management strategy evaluation for cod in NAFO division 3M" (González Troncoso et al. 2018).

In relation to the Task 3, the steps to develop and a multispecies MSE framework were described, highlighting the contribution with the EU Joint Research Centre of Ispra (Italy). This multispecies MSE framework (Figure X) included the updated multispecies model GadCap as an operating model, that provided information about the commercial fishery, survey and the stock to three different management procedures (one for each of the three stocks), where two possible options for the stock assessment were available (shortcut and an a4a SCAA stock assessment model).

The approaches to estimate the reference points and define different management strategies were described. HCRs were designed by defining the precautionary reference points (Blim and Btrigger) and F reference points defined with single and multispecies considerations.

Finally, it was communicated that, as part of the Task 4, the ecological and economic trade-offs result of the implementation of a number of different HCRs with single and multispecies foundations have been assessed.

There was a general recognition of the large amount and the relevance of the work that have been accomplished, and it was regretted the imposibility of presenting those results, that would have allowed very productive discussions during the meeting. The WG members showed their desires that this situation is reversed, since this kind of studies are absolutely necessary to continue progressing in the EAF in NAFO.

2. Annex 1. Agenda

WG-ESA Detailed Agenda

Detailed Terms of Reference and Summary of Commission Requests appear in Appendix 1.

Start time	End time	ToR (CR)	Activity	Leads	Duration
			Tuesday 13-November-2018		
9:30	10:00		Opening, appointment of rapporteur, discussion of ToRs and approval of agenda	Andy, Pierre	0:30
10:00	11:00		Summary of meetings SC June 2018, WGEAFFM August, 2018 AGM September, 2018 and other relevant activities	Pierre, Andy	1:00
11:00	11:30		Coffee BREAK		0:30
11:30	12:30	1.1	New preliminary data on VMEs from bottom trawl groundfish surveys in NAFO Regulatory Area (Divs. 3LMNO): 2018 surveys	Mar Tor_1_1_CR_ [filename]_[Author]	1:00
12:30	14:00		Lunch BREAK		1:30
14:00	15:00	1	*Vazella pourtalesi* SDM and biodiversity (Lindsay) Ecological diversity and interaction with fishing on Flemish Cap (Javier) Physical connectivity between NRA closure areas (Ellen)	Ellen, Lindsay, Javier	1:00
15:00	15:30	1.4 (11)	Sea pen SDM modelling under ATLAS project (update): Species Distribution models for two deep-water pennatulacean coral	Mar	0.30
15:30	16:00		Coffee BREAK		0:30
16:00	17:00	1.2 1.3 (11)	VME closure review workplan & discussion on updating KDA and SDM models for reassessment Non-coral and non-sponge VMEs	Ellen, Andy (All) Javier	1:00

Start time	End time	ToR (CR)	Activity	Leads	Duration

			Wednesday 14-November-2018		
09:00	10:00	1 (13)	Impacts of sediment plumes from fishing trawls and mining muds on sponges	Erik Wurz (WebEx) Ellen	1:00
10:00	11:00	1 (13)	Ecosystem impacts of sponge biomass removals	Christopher Pham (WebEx) Ellen	1:00
11:00	11:30		Coffee BREAK		0:30
11:30	12:30	2.1 (9)	Up-date on NEREIDA analysis. Part 1. Sea pen modelling	Anna, Andy	1:00
12:30	14:00		Lunch BREAK		1:30
14:00	15:00	2.1 (9)	Up-date on NEREIDA analysis. Part 2. VMS Swept Area Ratios: Overlap of NAFO fisheries with VME to evaluate fishery specific impacts in addition to the cumulative impacts	Mar	1:00
15:00	15:30	2.3 (9)	VME Biological Traits Analysis and assessment of functions	Andy Barbara, Neil, Vonda, Javier, Corina Ellen Javier Pablo	0.30
15:30	16:00		Coffee BREAK		0:30
16:00	17:00	2.3 (9)	VME Biological Traits Analysis and assessment of functions. Cont….	Barbara, Neil, Vonda, Javier, Corina, Andy	1:00

Start time	End time	ToR (CR)	Activity	Leads	Duration
			Thursday 15-November-2018		
09:00	10:00	2,6	Update of Ecosystem Status Reports	Pierre, Mariano, Mar, Andrew, Alfonso	1:00
10:00	11:00	3.2	Review of Ecosystem Summary Sheet (ESS) Design	Pierre, Mariano	1:00
11:00	11:30		Coffee BREAK		0:30

11:30	12:30	3.2	WG-EAFFM August and October Reports	Elizabethann, Pierre	1:00
12:30	14:00		Lunch BREAK		1:30
14:00	15:00	3.1 (8)	Ecosystem Production Potential (EPP) Review – Research Work plan	Pierre, Mariano	1:00
15:00	15:30	3.1 3.2 (8)	Breakout Groups – Preliminary Outline of Commission Response to Changes in EPP and Ecosystem Status / Revisions to ESS	Pierre Mariano Andy	0:30
15:30	16:00		Coffee BREAK		0:30
16:00	17:00		Breakout Groups – Preliminary Outline of Commission Response to Changes in EPP and Ecosystem Status / Revisions to ESS - continued		1:00
17:30			NAFO Reception		

Start time	End time	ToR (CR)	Activity	Leads	Duration
			Friday 16-November-2018		
09:00	10:00	2.5 (8)	EwE modelling of the Grand Banks Ecosystem	Jamie Tam	1:00
10:00	11:00	2.5 3.1 (8)	Results of EU SC05 project "Multispecies Assessment for NAFO"	Alfonso Perez Rodriguez	1:00
11:00	11:30		Coffee BREAK		0:30
11:30	12:30	2.5 2.6 3.1 (8)	Ecosystem Reports, Modelling and Management procedures in GoM/Georges Bank	Robert Gamble	1:00
12:30	14:00		Lunch BREAK		1:30
14:00	14:30	2.6	Neural Networks in the analysis of indicators	Danielle Dempsey	0:30
14:30	15:30	2.5	Update of modelling activities on the Newfoundland Shelf	Mariano	1:00
15:30	15:45		Coffee BREAK		0:15
15:45	17:00	2.5 3.1 (8)	An Economics Lens – Understanding NAFO Fishing Conceptual Bio-Economic model	Fred Phelan Mariano Koen-Alonso	1:15

Start time	End time	ToR (CR)	Activity	Leads	Duration
19:00			Mooseheads Friday Night Hockey		

Start time	End time	ToR (CR)	Activity	Leads	Duration
			Saturday 17-November-2018		
09:00	10:00	2.3	1) Soft coral functional roles, as potential components of VMEs and 2) Preliminary results CCGS *Amundsen* mission to SW Greenland (*Lophelia* gardens).	Barbara – send reminder	1:00
10:00	11:00		Traits and ESS breakout groups		1:00
11:00	11:30		Coffee BREAK		0:30
11:30	12:30		Breakout groups continue		1:00
12:30	14:00		Lunch BREAK		1:30
14:00	15:00	3.5 (9)	Objective ranking and weighting of SAI criteria	Andy – with traits	1:00
15:00	15:30	3.4	Options for non-destructive regular monitoring of VMEs, develop plans	Andy	0.30
15:30			End of day		

Start time	End time	ToR (CR)	Activity	Leads	Duration
			Monday 19-November-2018		
09:00	10:00		Breakout Groups Report		1:00
10:00	11:00			Kaboom	
11:00	11:30				0:30
11:30	12:00				
12:00	12:30				
12:30	14:00		Lunch BREAK		1:30

Start time	End time	ToR (CR)	Activity	Leads	Duration
14:00	14:45	2.2	VME modelling – layer development	Corina – reminder	0:30
14:45	15:30	2.2	VME modelling	Mariano, Neil	1:00
15:30	16:00		Coffee BREAK		0:30
16:00		3.6 (13)	ATLAS: map the pressures and impacts in Flemish Cap and proximity	Pablo Durán Muñoz	0:30
		3.6 (13)	Up-date on research on impacts of non-fishing activities in the NRA	All	0.20
	17:00	3.3 (5)	Impacts of scientific trawl surveys on VMEs	Andy – one sentence, maybe two	0.10

Start time	End time	ToR (CR)	Activity	Leads	Duration
			Tuesday 20-November-2018		
09:00	09:30		Relevant external meeting feedback (CBD, BBNJ, GESAMP, ATLAS, Montreal Conference)	Fred, Andy, Pierre	0:30
09:30	10:30	3.5 3.6	"Economic valuation and risk assessment of deep-sea sponge ecosystems"	Hassan Moustafhid	1:00
10:30	10:45	3.8, 3.9 (10)	Up-date of NCEM VME indicator species list and provide FAO codes	Andy, Ellen, Lindsay (others)	0:15
11:00	11:30		Coffee BREAK		0:30
11:30	12:30				1:00
12:30	14:00		Lunch BREAK		1:30
15:30	16:00		Coffee BREAK		0:30
16:00	17:00	2.5 (14)	Development of a 3-5 year work plan		

Start time	End time	ToR (CR)	Activity	Leads	Duration

			Wednesday 21-November-2018		
11:00	11:30		Coffee BREAK		0:30
12:30	14:00		Lunch BREAK		1:30
15:30	16:00		Coffee BREAK		0:30

Start time	End time	ToR (CR)	Activity	Leads	Duration
			Thursday 22-November-2018		
11:00	11:30		Coffee BREAK		0:30
			Date and Place of Next Meeting		
12:30			CLOSE		

3. Annex 2. 11th WGESA Meeting Agenda ToRs and specific topics to address

WG-ESA Relevant Commission Requests to SC to be addressed by the ToRs (below):

[5] The Commission requests that Scientific Council continue its evaluation of the impact of scientific trawl surveys on VME in closed areas, and the effect of excluding surveys from these areas on stock assessments.

[8] The Commission requests the Scientific Council to continue to refine its work under the Ecosystem Approach Road Map, including testing the reliability of the ecosystem production potential model and other related models, and to report on these results to both the WG –EAFFM and WG- RBMS to further develop how it may apply to management decisions.

[9] In relation to the assessment of NAFO bottom fisheries, the Commission endorsed the next re-assessment in 2021 and that the Scientific Council should:

- Assess the overlap of NAFO fisheries with VME to evaluate fishery specific impacts in addition to the cumulative impacts;

- Consider clearer objective ranking processes and options for objective weighting criteria for the overall assessment of significant adverse impacts and the risk of future adverse impacts;

- Maintain efforts to assess all of the six FAO criteria (Article 18 of the FAO International Guidelines for the Management of Deep Sea Fisheries in the High Seas) including the three FAO functional SAI criteria which could not be evaluated in the current assessment (recovery potential, ecosystem function alteration, and impact relative to habitat use duration of VME indicator species).

- Continue to work on non-sponge and coral VMEs (for example bryozoan and sea squirts) to prepare for the next assessment.

[10] Review the proposed revisions to Annex I.E, Part VI as reflected in COM/SC WG –EAFFM WP 18-01, for consistency with the taxa list annexed to the VME guide and recommend updates as necessary.

[11] The Commission requests Scientific Council to conduct a re-assessment of VME closures by 2020, including area #14 irrespective of a decision to continue or not continue this closure after 2018.

[13] The Commission requests Scientific Council to monitor and provide regular updates on relevant research related to the potential impact of activities other than fishing in the Convention Area, such as oil exploration, shipping and recreational activities, and how they may impact the stocks and fisheries as well as biodiversity in the Regulatory Area.

[14] The Commission requests Scientific Council to take the first steps to develop a 3-5 year work plan, which reflects requests arising from the 2018 Annual Meeting, other multi-year stock assessments and other scientific inquiries already planned for the near future. The work plan should identify what resources are necessary to successfully address these issues, gaps in current resources to meet those needs and proposed prioritization by the Scientific Council of upcoming work based on those gaps

Theme 1: Spatial considerations

ToR 1. Update on identification and mapping of sensitive species and habitats (VMEs) in the NAFO area.

1. *Update on VME indicator species data and VME indicator species distribution from EU and EU-Spain Groundfish Surveys in 2018. (Mar, Ellen)*
2. *Progress on implementation of workplan and timetable for reassessment of VME fishery closures including seamount closures for 2020 assessment. (Ellen, Andy + Others).* **COM Request # 11.**
3. *Discussion on up-dating Kernel Density Analysis and SDM's for VME indicator species in preparation for VME fishery closure review in 2020 (Ellen, Cam).* **COM Request # 11.**
4. *Update on the Research Activities related to EU-funded Horizon 2020 ATLAS Project, Flemish Cap Case Study: Species Distribution models for two deep-water pennatulacean coral (Mar).* **COM Request # 11.**
5. *Continue work on non-sponge and coral VMEs (for example bryozoan and sea squirts) to prepare for the next reassessment of bottom fisheries. (Ellen + Others).* **COM Request # 9**

Theme 2: Status, functioning and dynamics of NAFO marine ecosystems.

ToR 2. Update on recent and relevant research related to status, functioning and dynamics of ecosystems in the NAFO area.

4. *Progress of analysis undertaken by EU NEREIDA research – VME sea pen resilience and mapping fishing effort (Anna, Andy, Mar).* **COM Request # 9**
5. *Up-date on VME modelling (Mariano, Neil).* **COM Request # 9**
6. *Up-date on VME biological traits analysis and the assessment of VME functions (Vonda, Corrina, Ellen, Andy, Neil).* **COM Request # 9**
7. *Maintain efforts to assess all six FAO criteria (Article 18 of the FAO International Guidelines for the Management of Deep Sea Fisheries in the High Seas) including the three FAO functional SAI criteria which could not be evaluated in the current assessment (recovery potential, ecosystem function alteration, and impact relative to habitat use duration of VME indicator species). (Vonda, Anna, Ellen, Andy).* **COM Request # 9.**
8. *Up-date on fishery modelling activities and develop 5-year plan for development and expansion of single species, multispecies and ecosystem production potential modelling (Robert Thorpe, Robert Gamble, Alfonso, Pierre, Mariano).* **COM Request # 14.**
9. *Review of oceanographic and ecosystem status conditions in the NRA (Pierre, Mariano, Mar)*

Theme 3: Practical application of ecosystem knowledge to fisheries management

ToR 3. Update on recent and relevant research related to the application of ecosystem knowledge for fisheries management in the NAFO area.

1. *Refine work to progress the EAFM roadmap by testing the reliability of the ecosystem production potential model and other related models, and to report on these results to the WG-EAFFM and WG-RBMS to further develop how it may apply to*

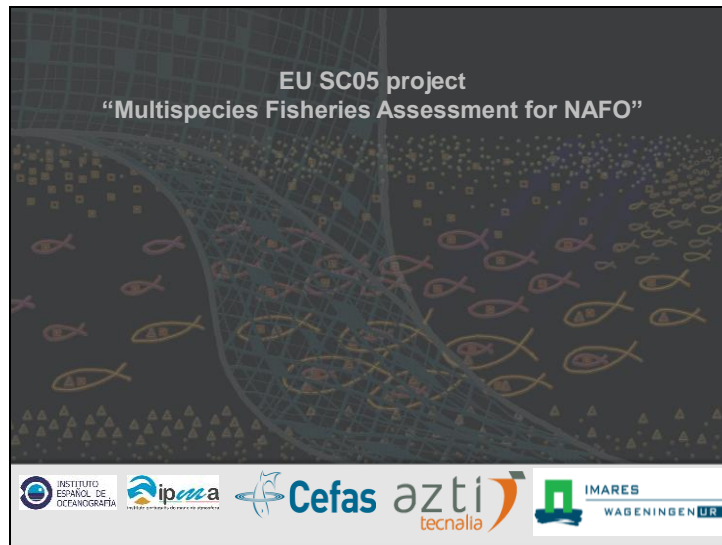*management decisions. (Pierre, Mariano, Robert Gamble, Andrew Cuff). **COM Request # 8**.*

2. *Consider the terminology used in ecosystem summary sheets in order to avoid potential confusion with standard terminology in fisheries management, review their structure to address concerns raised by WG-EAFFM, as well as considering their potential to inform management decisions and responses. (Pierre + All)*

3. *The Commission requests that Scientific Council continue its evaluation of the impact of scientific trawl surveys on VME in closed areas, and the effect of excluding surveys from these areas on stock assessments. **COM Request # 5**.*

4. *Consider possible options for the non-destructive regular monitoring within closed areas, develop preliminary plans for evaluation of new approaches and potential survey design, bearing in mind the cost implications and the utility of data collected for the provision of advice. (All).*

5. *Review progress against establishing clearer objective ranking processes and options for objective weighting criteria for the overall assessment of SAI and risk of SAI (All). **COM Request # 9**.*

6. *The Commission requests Scientific Council to monitor and provide regular updates on relevant research related to the potential impact of activities other than fishing in the Convention Area, such as oil exploration, shipping and recreational activities, and how they may impact the stocks and fisheries as well as biodiversity in the Regulatory Area. **COM Request # 13**.*

7. *Assess the overlap of NAFO fisheries with VME to evaluate fishery specific impacts in addition to the cumulative impacts. **COM Request # 9**.*

8. *In relation to FAO three letter codes for VME indicator species, the existing taxa list in Annex I.E Part IV of the NCEM should be up-dated with the FAO ASFIS codes as listed in Annex 4.*

9. *Review the proposed revisions to Annex I.E Part IV as reflected in COM-SC EAFFM-WP 18-01 and to compare the consistency of the list of taxa in that Annex to the VME species guide with a view to recommend up-dates as necessary. (Ellen). **COM Request # 10**.*

AOB.

Date and place of next meeting

10. Annex 2. Presentation SC05

Slide 1

Slide 2

Slide 3

SCO5 Project tasks
Overview

- **Task 5:** Dissemination to scientists and stakeholders
  - Discussion and interaction between scientists and other stakeholders: workshop.

- **Task 6:** Further research
  - Identify future necessary steps and research activities

Slide 4

SCO5 Project tasks
Overview

- **Task 1:** Setting the context
  - A general overview of the multispecies approach worldwide
  - Description of the biological, ecological, fishery and scientific features of the Flemish Cap.
- **Task 2:** Updating **GadCap**
  - An updated version of the multispecies model GadCap: a gadget cod, redfish an shrimp **multispecies model in the Flemish Cap**.
- **Task 3:** First approach to implement multispecies assessment
  - Explore the provision of scientific advice for a multispecies approach in the Flemish Cap
    - Use of multispecies natural mortality estimates in stock assessment
    - **Multispecies MSE framework and potential new multispecies HCRs.**
- **Task 4:** Economyc trade-offs
  - First analysis of the socio/economic implications
  - Available techniques and models needed to assess the trade-offs
- **Task 5:** Dissemination to scientists and stakeholders
  - Presentation and integration of results in the NAFO-WGESA and NAFO Scientific Council meetings

Slide 5

Task 2: An updated version of the multispecies model GadCap: a gadget cod, redfish an shrimp multispecies model in the Flemish Cap.

Slide 6

Task 2: Improvements in GadCap

- Extension to 2016
  - Survey data:
    - length and age distributions: update and corrections
    - survey indices
    - Recruitment indices
    - New estimations, different time division for growth curves
    - Diet composition
    - …
  - Commercial data:
    - Update and standardization of length distributions with single species methods
    - Update of catch by season, changes to approved data
    - New fleet: longliners

Slide 7

Task 2: Improvements in GadCap

- Extension to 2016
  - CPR data: copepods, hyperiids, chaetognats, euphausiids.
  - Estimate water temperature
  - Prey abundance estimates: demersal fishes, pelagic fishes...
- Review of trophic related parameters for the new period.
- Improvement in several small elements of the model: length-weight, different division of growth periods, maturation....

Slide 8

Task 2: Improvements in GadCap

- Other improvements tested/applied
  - Annual time steps
  - Separate redfish species
  - Exploring functional response III
  - Introduction of "Carrying capacity" proxy in long term simulations
  - Modelling of temperature and density-dependent growth on cod and shrimp

Slide 9

Task 2: Improvements in GadCap

- Residual Natural mortality
  - Catch curves
  - Longevity method
  - Gadget likelihood score

Slide 10

Task 3: Explore the provision of scientific advice for a multispecies

approach in the Flemish Cap

- Use of multispecies natural mortality estimates in stock assessment
- Multispecies MSE framework and potential new multispecies HCRs.

Slide 11

Task 3: Explore the provision of scientific advice for a multispecies approach in the Flemish Cap

- Use of multispecies natural mortality estimates in stock assessment

Slide 12

Connection SC03 and SC05
Estimates of natural predation and residual mortality for the Flemish Cap cod

- EU SC03 project:
"Support to a robust model assessment, benchmark and development of a management strategy evaluation for cod in NAFO division 3M"
- Task 2: 3M cod benchmark
- Testing different option for Natural mortality
  - Constant M at age and over time
  - Vector of variable M at age, but constant over time
  - Matrix of variable M at age and over time (connection with SC05)

Slide 13

First step: estimates of Residual Natural Mortality M1

- Selection of cohorts to be studied: 1996-2002
    – Low or null fishing mortality: no F
    – No cannibalism (based in diet composition): no M2

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First step: estimates of Residual Natural Mortality M1

- Catch curves:

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First step: estimates of Residual Natural Mortality M1

• Catch curves: selected range of ages 4-8
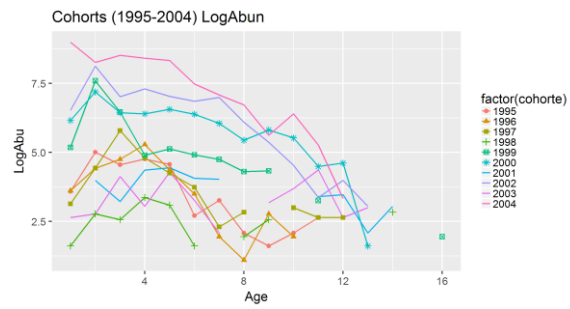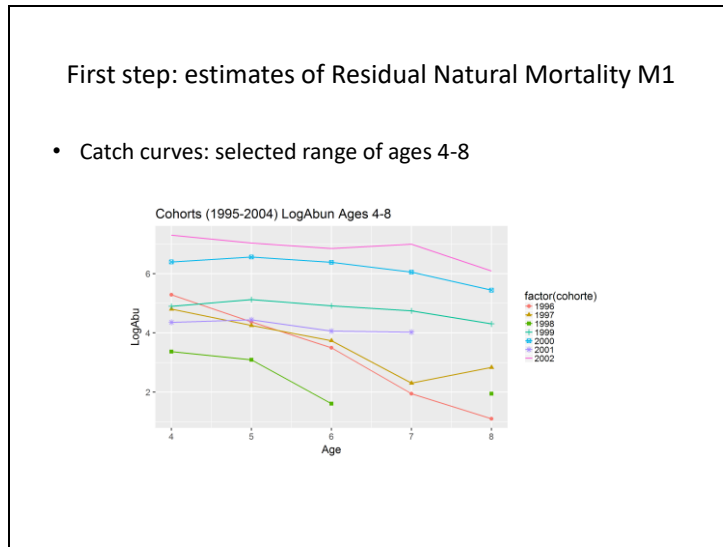
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First step: estimates of Residual Natural Mortality M1

• Catch curves: selected range of ages 4-8

Average Z for the group of cohorts 1996-2002 estimated using the different catch curve methods for the group of ages 4 to 8.

Catch curve method	Average Z
Chapman-Robson	0.644285714
Chapman-Robson CB	0.641428571
Heincke	0.484285714
Linear Regression	0.407142857
Poisson Model	0.627142857
Random-Intercept Poisson Model	1.295714286
Weighted Linear Regression	0.411428571

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First step: estimates of Residual Natural Mortality M1

- Longevity method
  - Hewitt and Hoenig, 2005. Comparison of two approaches for estimating natural mortality based on longevity. Fishery Bulletin 103(2): 433-437.
  - Look for the M value that will allow the survivorship of the 1.5% individuals at age Longevity.
  - Longevity is the barely considered the plus group in GadCap, age 12

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First step: estimates of Residual Natural Mortality M1

- Longevity method

Percentage of the recruited number of individuals at age 1 that reach age 12 (maximum longevity)

cohort	M_0.175	M_0.20	M_0.25	M_0.30	M_0.35	M_0.40	M_0.45	M_0.50
1996	9.57	7.5	4.56	2.69	1.59	0.93	0.54	0.31
1997	11.48	8.74	5.1	2.92	1.69	0.98	0.56	0.32
1998	11.24	8.58	4.98	2.86	1.64	0.95	0.55	0.31
1999	8.14	6.21	3.6	2.07	1.17	0.67	0.39	0.22
2000	6.5	4.93	2.85	1.62	0.9	0.51	0.29	0.16
2001	4.71	3.57	2.04	1.14	0.63	0.35	0.19	0.1
2002	2.61	1.96	1.12	0.6	0.31	0.17	0.09	0.04
Average	7.75	5.92714	3.46429	1.98571	1.13286	0.65143	0.37286	0.20857

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First step: estimates of Residual Natural Mortality M1
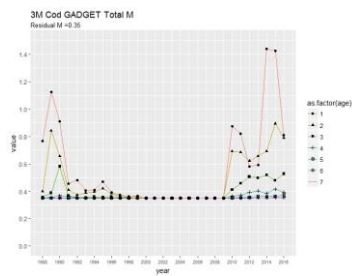
- Loglikelihood method

  Loglikelihood score resulting of applying different values of M_1 by age and year during the optimization of GadCap.
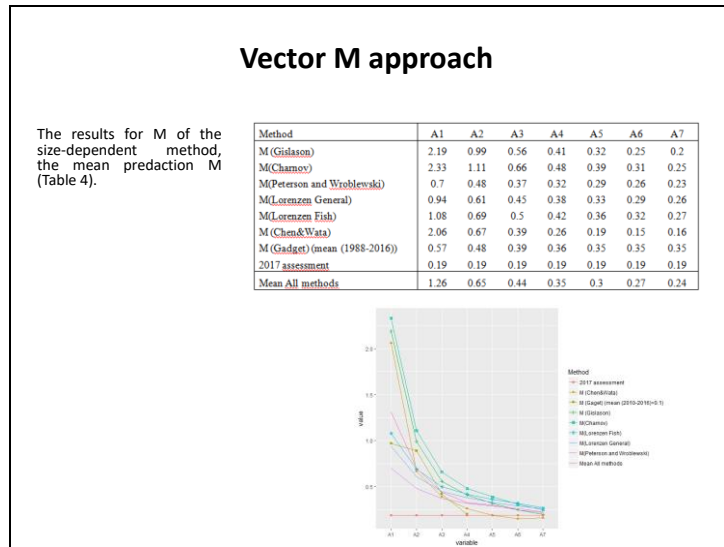
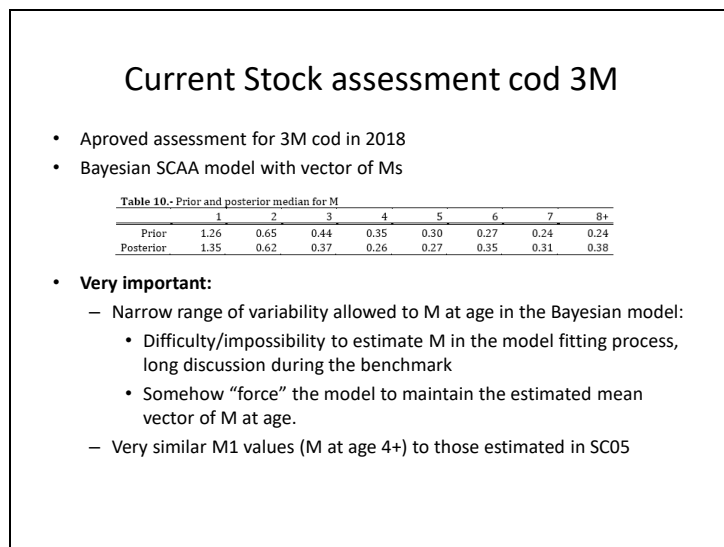

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Second step: estimates of Total Natural Mortality

- Selected M1: 0.35
- Optimize GadCap parameters with M1=0.35 and produce total M=M1+M2
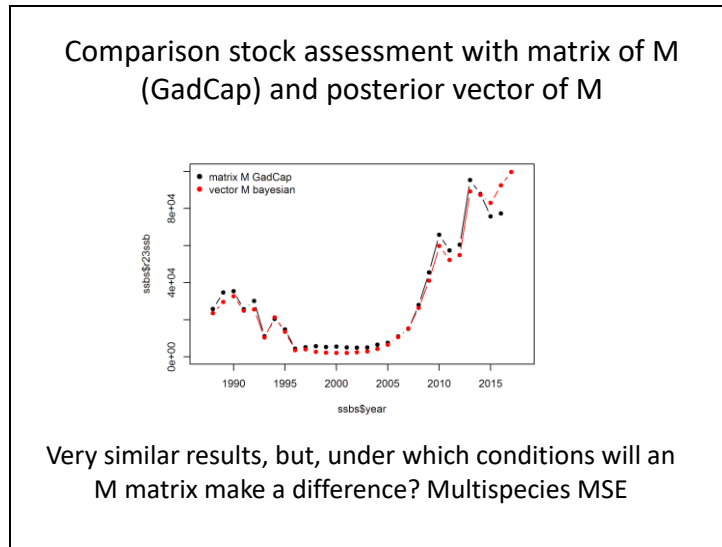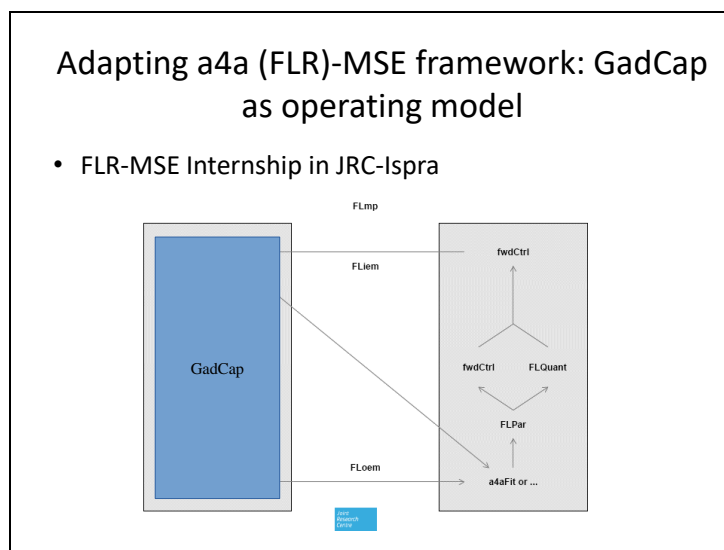-

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Vector M approach

The results for M of the size-dependent method, the mean predaction M (Table 4).

Method	A1	A2	A3	A4	A5	A6	A7
M (Gislason)	2.19	0.99	0.56	0.41	0.32	0.25	0.2
M(Charnov)	2.33	1.11	0.66	0.48	0.39	0.31	0.25
M(Peterson and Wroblewski)	0.7	0.48	0.37	0.32	0.29	0.26	0.23
M(Lorenzen General)	0.94	0.61	0.45	0.38	0.33	0.29	0.26
M(Lorenzen Fish)	1.08	0.69	0.5	0.42	0.36	0.32	0.27
M (Chen&Wata)	2.06	0.67	0.39	0.26	0.19	0.15	0.16
M (Gadget) (mean (1988-2016))	0.57	0.48	0.39	0.36	0.35	0.35	0.35
2017 assessment	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Mean All methods	1.26	0.65	0.44	0.35	0.3	0.27	0.24

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Current Stock assessment cod 3M

- Aproved assessment for 3M cod in 2018
- Bayesian SCAA model with vector of Ms

Table 10.- Prior and posterior median for M

	1	2	3	4	5	6	7	8+
Prior	1.26	0.65	0.44	0.35	0.30	0.27	0.24	0.24
Posterior	1.35	0.62	0.37	0.26	0.27	0.35	0.31	0.38

- **Very important:**
  - Narrow range of variability allowed to M at age in the Bayesian model:
    - Difficulty/impossibility to estimate M in the model fitting process, long discussion during the benchmark
    - Somehow "force" the model to maintain the estimated mean vector of M at age.
  - Very similar M1 values (M at age 4+) to those estimated in SC05

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Comparison stock assessment with matrix of M
(GadCap) and posterior vector of M

Very similar results, but, under which conditions will an
M matrix make a difference? Multispecies MSE

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Task 3: Explore the provision of scientific advice for a multispecies

approach in the Flemish Cap

- Multispecies MSE framework and potential new multispecies HCRs.
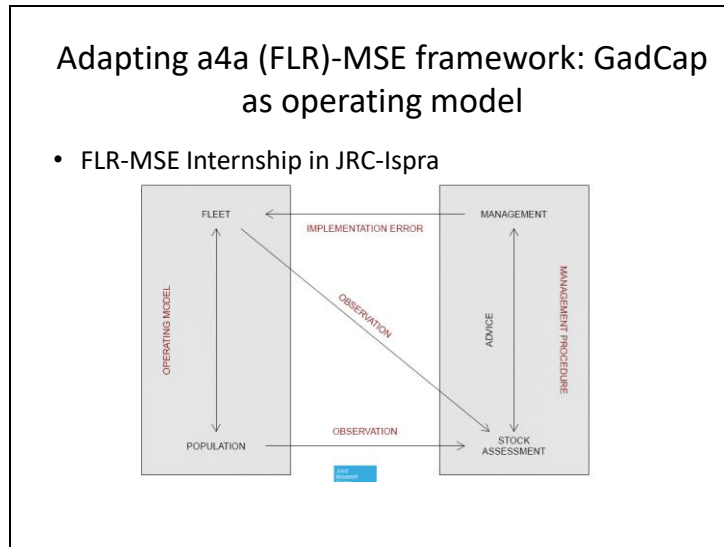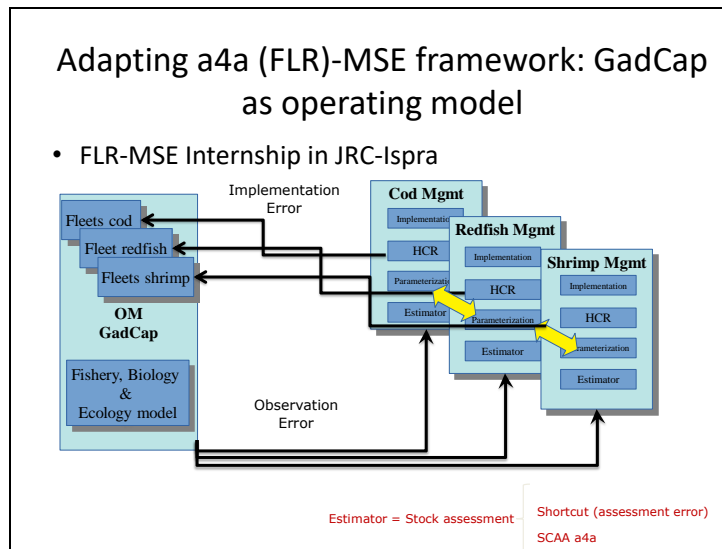
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Adapting a4a (FLR)-MSE framework: GadCap as operating model

- FLR-MSE Internship in JRC-Ispra

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Steps:

1. Multispecies model (SCO5-Task 2)
2. MSE framework (SCO5-Task 3)
3. Define HCRs:
   - Blim and Btarget
   - Estimate candidate single and multispecies F reference points deterministically

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Estimate deterministic reference points
Shortcut option without error

Operating model

Management Procedure

Implementation

TAC

GadCap
Fisheries, populations and
ecology
With **deterministic SSB-
Recruitment relationship**

Forward projection
& HCR

FLStock object

Stock assessment
**Shortcut
(without error)**

Observation
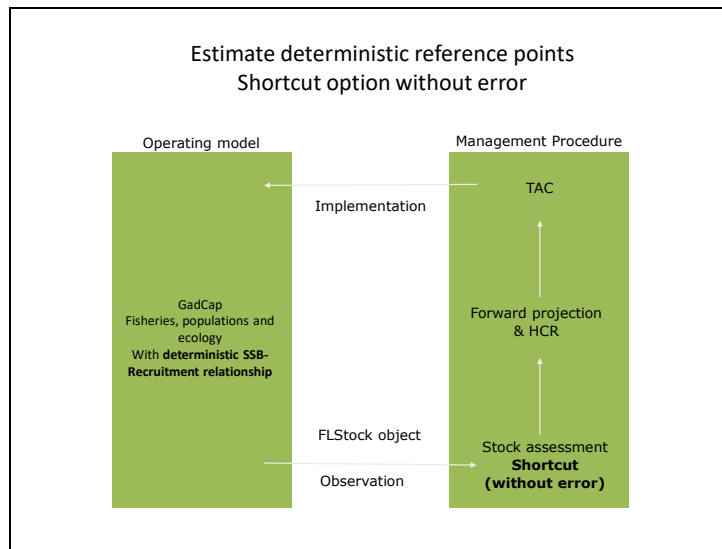
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Steps:

1. Multispecies model (SCO5-Task 2)
2. MSE framework (SCO5-Task 3)
3. Define HCRs:
   - Blim and Btarget
   - Estimate candidate single and multispecies F reference points deterministically
   - Risk assessment considering recruitment uncertainty

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Steps:

1. Multispecies model (SCO5-Task 2)
2. MSE framework (SCO5-Task 3)
3. Define HCRs:
   - Blim and Btarget
   - Estimate candidate single and multispecies F reference points deterministically
   - Risk assessment considering recruitment uncertainty
4. Evaluation of HCR considering assessment error in the shortcut option

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Estimate probabilistic reference points
Shortcut option with assessment error

Operating model   Management Procedure

                    Implementation   TAC

GadCap   Forward projection
Fisheries, populations and   & HCR
ecology
With **stochastic SSB-
Recruitment relationship**

                    FLStock object   Stock assessment
                                             **Shortcut
                    Observation   (with assessment
                                             error)**

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Assessment error in shortcut option

- Use of retrospective patterns of number at age: cod and redfish stock assessments
- Rho parameter was used as a measure of the assessment error
- The mean value of Rho at age and the variance-covariance in the rho parameter by age over time was used to introduce variability in the OM stock N at age

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Two stages HCR: avoid excessive predation?

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Alternative option for stock assessment:
a4a SCAA models with/without observation error

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Study of the importance of considering variable
age/time M in comparison to M vector or constant M

Operating model

Implementation

Management Procedure

TAC

GadCap
Fisheries, populations and
ecology
With **deterministic SSB-
Recruitment relationship**

Forward projection
& HCR

FLStock object

Observation

Stock assessment
A4a SCAA

- Assumed constant M vector
- Assumed constant M at age/year
- Real matrix of M from the OM
- Real matrix of M from the OM with error

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Task 4: Trade-offs of different management strategies

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Task 4: Trade-offs of different
management strategies

- Selections of:
  - Single HCRs
  - Multispecies HCRs
    - One stage HCR
    - Two stage HCR
- Assessment of ecological and economic trade-
  offs

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EU SC05 project
"Multispecies Fisheries Assessment for NAFO"

Task 2: Update of the multispecies model GadCap

ANNEX XI: Minutes of the Stakeholder Workshop

Workshop on implementing multispecies assessments in support of NAFO fisheries management advice (17th – 18th, January 2019)

Authors

Collated Documents

Minutes   Andrew Kenny◊, Alfonso Perez†, Raul Prellezo*, Adolfo Merino~

◊ Cefas

† WUR

* AZTI

~ EASME/EMFF

1. CONTENTS

2. INTRODUCTION

2.1. Meeting objective and scope

The objective of the stakeholder meeting was to provide the fishing industry and other fishery related associations (see list of attendees below) operating in NAFO with opportunity to find out what and how multi-species assessments are being developed and the benefits they provide in the context of implementing an ecosystem approach to fisheries management and the provision of fisheries management advice. The meeting also allowed some of the 'key' challenges associated with the operational implementation and scientific development to be identified and discussed.

2.2. List of Attendees

Name	Organisation	Position
Andrew Kenny	CEFAS	WP5 Lead
Alfonso Perez	WUR	SC05 Coordinator/ WP3 Lead
Raul Prellezo	AZTI	WP4 Lead
Irene Garrido	ARVI	Arvi/IEO research scientist
Adolfo Merino	EASME	EMFF Senior Project Adviser
Ivan Lopez	LDAC	President
Edelmiro Ulloa	ARVI	Manager
Diana González	IEO	3M cod scientist assessor
Mar Sacau	IEO	NAFO EAF specialist
Mikel Casas	IEO	3M shrimp scientist assessor
Jolanta Cesiuliené	Ministry of Agriculture of the Republic of Lithuania	Chief Specialist of the Fisheries Division

2.3. Opening of the meeting

The meeting was officially opened at 14:00 hrs at the IEO offices in Vigo (Centro Oceanográfico, Beiramar) and delegates welcomed by the co-Chairs, Dr Alfonso Perez and Dr Andrew Kenny. The meeting agenda (Annex 1) was agreed following participant introductions (Fig. 1).

Figure 5. Stakeholder workshop participants.

3.   **SUMMARY OF MEETING PROCEDINGS AND PRESENTATIONS**

3.1. Sustainable fisheries policy development - importance of multi-species assessment approaches

In an introductory presentation, Adolfo Merino, on behalf of DG-MARE, indicated that the Multispecies assessment and advice is addressed within the Northwest Atlantic Fisheries Organization (NAFO) as part of the discussion on the Precautionary Approach and the development of the Ecosystem Approach roadmap. The amended NAFO Convention binds contracting parties to apply the Precautionary Approach in accordance with Article 6 of United Nations Fish Stock Agreement. Adolfo Merino highlighted that, to be able to react properly to this obligation, DG MARE has launched a contract to provide an overview on how this multispecies assessment would fit into the decision-making processes within NAFO. This approach requires a good communication between scientist, stakeholders and decision makers, which is the main objective of this workshop. DG-MARE expects that the outcomes from this contract will feed the scientific debate and will provide the sounded basis for future management proposals.

3.2. NAFO – roadmap for developing an Ecosystem Approach to Fisheries Management

The development and plans for the implementation of the ecosystem approach to fisheries management in NAFO was presented by Dr. Andrew Kenny. Work on developing the NAFO EAFM 'roadmap' began in 2008 with the identification of Vulnerable Marine Ecosystems (VMEs) in the NAFO Regulatory Area (NRA). Since then other parts of the roadmap, notably Tier 1 and Tier2 (Fig. 2), have been the subject of R&D. Multispecies assessments (Tier 2) form an important part of the overall roadmap, as they provide a critical link between the estimates of total fisheries production and total catch indices, and the allocation of allowable catches to the different target species in mixed fisheries. A full account of the development of NAFO EAFM roadmap is given in Koen-Alonso et al. (2019).
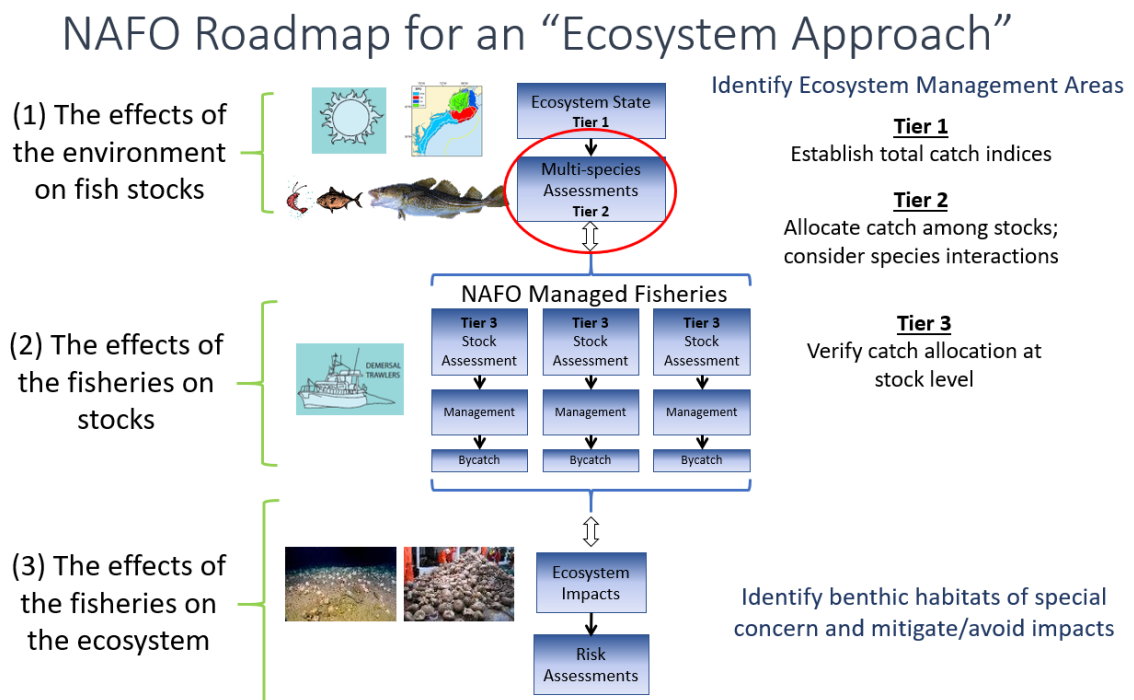

Figure 6. NAFO 'roadmap, showing the key steps and associated tiers of R&D activity – see Koen-Alonso et al. (2019) for further details.

3.3. Overview of scientific approaches for multi-species assessments

Alfonso Pérez-Rodríguez, from Wageningen Marine Research. The increase in fishing capacity since mid 20th century due to the outstanding improvements in technology and the expansion of high seas fisheries was accompanied of numerous collapses worldwide, triggering the development of international agreements for a better management of marine resources based in sounded scientific research. Ignoring species interactions was considered one of the reasons that would explain the generalized failure in the management of fishing resources in the 60s, 70s and 80s. In these decades, the first multispecies models were developed (Andersen and Ursin 1977). However, it was since the 1990s when, due to the increase in computational power and accumulation of data and knowledge, that the multispecies and ecosystem models experienced a generalized expansion worldwide. Alfonso Pérez-Rodríguez presented some examples of the approaches followed worldwide for the implementation of a multispecies approach, which were classified in two main groups:

1. Support for single species assessment models
    a. Provide more adequate natural mortality values (Example North Sea cod and haddock, and Baltic Sea cod)
    b. Provide estimates of predator consumption that will be considered when setting the TAC (example CCAMLR krill, and capelin in Barents Sea and Iceland)
2. Support to define long-term management plans, defining HCRs with multispecies foundation
    a. MyFish (accounting for technical and biological interactions)
    b. Barents sea (project REDUS and two stage HCRs for Arctic cod)

3.4. Introduction to SC05 project "multi-species fisheries assessment for NAFO

The second day of the workshop started with a presentation about the events and previous research that motivated the launch of the SC05 project by DG-MARE in 2017, as well as an introduction to the SC05 project. Alfonso Pérez-Rodríguez explained how the accumulated knowledge about the trophic interactions between cod, redfish and shrimp in the Flemish Cap (NAFO regulatory area 3M) and the influence on the dynamic of prey populations (shrimp, redfish and cod) as result of predator consumption (cod and redfish), motivated the request of the NAFO Fisheries commission (NAFO FC) to:

1. *"provide an explanation to the most recent decline of the shrimp stock, the recovery of the cod stock and the reduction of the redfish stock"*
2. *"Advise on the feasibility and the manner by which these three species are maintained at levels capable of producing a combined maximum sustainable yield, in line with the objectives of the NAFO Convention."*

In order to give answer to this request from the fisheries commission, the EU (Marie Sklodowska-Curie programme) funded the development of a Gadget multispecies model for the Flemish Cap cod, redfish and shrimp (GadCap). Alfonso Pérez-Rodríguez showed how, on reply to the first question of the NAFO FC, this model allowed concluding the interdependent dynamic of these stocks, and revealed strong synergic interactions between recruitment, fishing and predation (including cannibalism), with marked changes in their

relative importance by species-age-length over time. The multispecies model shows that disregarding the species interactions would lead to serious underestimates of natural mortality, overestimations of the exploitable biomass, and highlights the need to move beyond single-species management in this highly coupled ecosystem. On reply to the second request of the NAFO FC during the project GadCap preliminary estimates of total SSB and yield, under different combinations of fishing mortality for all the three stocks were explored.

The SC05 was next introduced in this presentation as a project promoted by DG-MARE with the intention of contributing and promoting the development of alternatives for the implementation of a multispecies approach to fisheries advice in the NAFO area. The six tasks of the SC05 project were briefly described:

- **Task 1:** Setting the context
  - A general overview of the multispecies approach worldwide
  - Description of the biological, ecological, fishery and scientific features of the Flemish Cap.
- **Task 2:** Updating GadCap
  - An updated version of the multispecies model GadCap: a gadget cod, redfish and shrimp multispecies model in the Flemish Cap.
- **Task 3:** First approach to implement multispecies assessment
  - Explore the provision of scientific advice for a multispecies approach in the Flemish Cap
    - Use of multispecies natural mortality estimates in stock assessment
    - Multispecies MSE framework and potential new multispecies HCRs.
- **Task 4:** Economic trade-offs
  - First analysis of the socio/economic implications
  - Available techniques and models needed to assess the trade-offs
- **Task 5:** Dissemination to scientists and stakeholders
  - Discussion and interaction between scientists and other stakeholders: workshop.
  - Presentation and integration of results in the NAFO-WGESA and NAFO Scientific Council meetings
- **Task 6:** Further research
  - Identify future necessary steps and research activities

3.5. Examples of assessment outputs and results from SC05, and how they can be used to achieve sustainable fisheries

In the last presentation before the plenary session, Alfonso Pérez-Rodríguez and Raúl Prellezo presented the update and improvements to the multispecies model GadCap (Task 2 in SC05), the MSE framework and new HCRs (Task 3) and the ecological-economic trade-offs result of alternative management strategies for all the three stocks cod, redfish and shrimp (Tasks 3 and 4).

Alfonso Pérez-Rodríguez presented the updated GadCap model, which included a new longline fleet for cod, improved simulation of biological and ecological processes, and updated databases up to 2016. This renovated model showed the extreme relevance of predation mortality in the dynamic of all the three stocks, comparable to the fishing pressure, or even higher in some ages and years. Next, the MSE framework developed to include GadCap as an operating model was presented. The steps needed to use this framework in the estimation of the SSB and yield in the long-term equilibrium as result of combining different fishing mortality F values for the three stocks (8000 different combinations of F) were

described. Once the precautionary reference points (B_{lim} and $B_{trigger}$), and all the candidate MSY (F_{target}) reference points were defined, a selection of all the possible combinations of HCRs was selected, for which a risk assessment exercise was carried out. This risk assessment allowed concluding that:

- HCRs defined from a single species approach were not precautionary for cod and shrimp.
- It is not possible maintaining the 3 stocks (cod, redfish and shrimp) above Blim at the same time.
- Disregarding one stock may allow finding precautionary multispecies based HCRs multispecies for the other two stocks.
- Precautionary HCRs for two stocks at once (cod and redfish) were only found when the shrimp SSB in relation to Blim was disregarded.
- The results suggest that the two stages HCRs for cod reduces predation and increases probability of cod, redfish being above Blim.

After the presentation of the multispecies model and explanations on how HCRs were designed and selected, Raúl Prellezo presented the economic trade-offs of using each HCR. These trade-offs arise from the different fleets in the fishery, from the different time perspective and therefore economic indicator selected and from the coupled overview of the biological and economic risk of using each HCR. Raúl Prellezo presented the modelling approach, focusing on how results from the multispecies HCRs and economic results of the fleets were integrated. Using this integration a series of plots were presented to show, in relative terms, the existing trade-offs. Conclusions, were focused on the difficulty of designing an HCR in where these trade-offs do not appear. Furthermore, there are also trade-offs in terms of the stability (variability) of the economic indicators, which could affect the investment decisions of the fishing firms.

4. **IDENTIFYING THE KEY CHALLENGES IN PROGRESSING TO MULTI-SPECIES ASSESSMENTS FOR FISHERIES MANAGEMENT**

At the end of the first, following the background presentations on EAFM and multi-species assessments, there was an opportunity to initiate a general discussion on identifying the 'key' challenges in progressing towards EAFM and multi-species assessments. The discussion was broadly divided into two parts, **i.** challenges associated with operational and management issues, and **ii.** Scientific and technical issues.

4.1. Operational challenges

- Ensure dialogue between scientists, industry and managers is maintained. Especially as work progresses on developing Multispecies Approach (MSA) and Ecosystem Approach to Fisheries Management (EAFM) approaches more generally, this type of event should be repeated. *Ad hoc* participation at the LDAC meeting in March, especially WG2, was suggested as a useful forum to help facilitate a better understanding of the science being developed to support EAFM and specifically MSAs.
- In this line, for further development of the MSA in the NAFO area, meetings with stakeholders will be necessary to identify the management objectives and the metrics that need to me measures to assess the performance of different HCRs that will be tested. It will also be important defining the constraints of the system, both at the economic and ecological level, defining the limit reference points. Finally, a discussion on the management tools existing options could be considered.
- It was noted by the industry that there are an increasing number of requests for different types of fisheries data (e.g. recording total catch, VME indicator species, gear dimensions etc.) to support developments emerging from the EAFM roadmap. This is not objected too, but the *ad hoc* way in which the requests are made (in time) is particularly disruptive for fishing operations – it would be much better if a minimum set of data could be identified and communicated as part of a plan say every 5 years.
- The role that other types of human activity, e.g. oil and gas exploration and production, could be contributing to reduced fishery yields needs to be considered – as such, including an additional criterion in the ecosystem summary sheet which corresponds to other human activities would be beneficial.

4.2. Science challenges

- Gear technology and advances in marine technology more generally (e.g. sonars, navigation and weather instrumentation) was highlighted as offering potential opportunities for collaboration with the industry in providing useful additional data to support the development of MSAs. For example:
  - Fish stomach and otolith samples could be collected. In addition, advances in gear technology can allow different species of fish to be targeted at the same time in a mixed fishery, resulting in clean catches of the target species that maximizes CPUE whilst minimizing the overall impact on the seabed.
  - Advances in sonar technology could be evaluated as a tool for determining different types of demersal stock assessment metrics, e.g. species biomass, abundance etc.

o It was made clear the will of the industry to contribute in collecting the necessary data to facilitate the evaluation of technical interactions (mixed fisheries). This information would hence allow the consideration of technical interactions in addition to the ecological interactions in the multispecies model.

Since more information is required for a MSA, it was highlighted that a new protocol standardized for all the fleet in the NAFO area should be designed.

- There is good disposition to provide the necessary financial information needed to achieve more representative economic models to assess the trade-offs of different management strategies. However, it is important finding the vehicle and the way to transfer that information in a manner that ensure the usefulness for scientific purposes while maintaining the confidentiality.

5. **R&D PRIORITIES FOR NEXT STEPS TOWARDS IMPLEMENTING MULTI-SPECIES ASSESSMENTS**

- There are some components of the multispecies ecological model that would benefit from improvement for which the cooperation from the industry would be very beneficial:

  o Separation of beaked and golden redfish: there is limited information that allows the separation of the commercial catches of golden and beaked redfish. During the meeting it was indicated a good disposition to collaborate by training the crew in the commercial fishing vessels to be able of separating these two stocks

  o Modelling the technical interactions. It was indicated that, in order to assess the collateral consequences of the technical interactions, it is necessary some extra information that would have to be provided by the commercial fishery.

- It was indicated that, a higher reliability in the estimation of the trade-offs associated to different management strategies will be achieved when an economic model is integrated with an ecological model within the operating model of an MSE. This is work that may be developed in the future, but this will require the collaboration from the fishing firms to nourish the model with more accurate data and necessary financial information.

- It was highlighted that, due to the constant evolution of the fleet, it will be necessary, when running scenarios to assess the performance of different HCRs, exploring scenarios where the effectiveness of the fleet (increase in CPUE) or changes in the selectivity pattern occur.

- An MSE with an improved operational model (economy-ecology-fisheries) will have to be performed to assess the performance of the selected management procedures considering uncertainty in our knowledge about the functioning of the system (operating model), the collection of data, the stock assessment and the implementation of the management decisions.

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