The identification of measures to protect by-catch species in mixed-fisheries management plans (ProByFish)

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Final Report

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Term	Description
MSY $B_{trigger}$	The biomass above which MSY can be attained
B_{lim}	The biomass below which the recruitment of new fish is impaired
Fishing mortality, F	An indicator reflecting (but not equal to) the proportion of fish dying from fishing
F_{MSY}	The fishing mortality predicted to result in maximum sustainable yield on average in the long term
F_{PA}	The highest fishing mortality consistent with no more than a 5% risk of impairing recruitment
TAC	Total Allowable Catches in a year
Harvest control rule, HCR	A fixed rule to obtain TAC advice based on the stock status (biomass and fishing mortality) and biological reference points (target fishing mortality and biomass reference point).

EXECUTIVE SUMMARY

The ProByFish study was initiated to assist in the development of methods to evaluate the impact of different fisheries management options on the objectives of the Common Fisheries Policy (CFP). The study developed robust methods to a) define target and bycatch species and b) to divide the bycatch species into valuable and collateral bycatch species, the first generally retained on board and landed and the latter generally discarded. The classification of a species depended on the fleet and area in which the fleet operates. The study also identified species which can only sustain low levers of fishing and proceeded to include examples of these in mixed fisheries models. After the development of stock assessments, reference points and mixed fisheries management strategy evaluation models for a variety of stocks, the study identified the species for which annual catch limits of target species would be sufficient to ensure sustainable exploitation even in the absence of species specific management actions. Then it proceeded to identify measures that will lead to the sustainable development of the bycatch stocks and agreed reference levels to safeguard stocks. The measures included various combinations of single species annual catch limits and annual catch limits afor groups of species on target and valuable bycatch species, gear modifications and spatial management under different implementations of the landing obligation. The management strategy evaluations showed major differences in the results between different implementations of the landing obligation. Under the current implementation, fisheries remained relatively unchanged but a variety of stocks, with cod as the most prevalent example in the Celtic Sea and greater North Sea, remained fished at levels above the level consistent with the maximum long term yield and with a risk of impairing recruitment that exceeded 5%. In contrast, the study found that enforcing the landing obligation fully would safeguard the stocks, but would lead to so-called ‘choke species’ effects. A ‘choke species’ is a species for which the catch opportunity restricts the catches of one or more other species caught together with this species beyond what is compatible with fishing at the levels that provides the maximum sustainable yield of these other species. The ‘choke species’ issue leads to prolonged closures of most demersal fisheries with subsequent socio-economic impacts. The predicted effect of various measures targeted at reducing catches of choke species was mitigated by associated increases in effort as fishing became less effective for several species at the same time. A possible exception to this was gear changes applied to the nephrops fishery. In general, no scenarios predicted stock recovery of all stocks without an associated reduction in fishing effort.

RÉSUMÉ

L´étude ProByFish a pour objectif d´aider au développement de méthodes d´évaluation de différentes options pour la gestion des pêches et d´évaluer l´impact relatif de celles-ci sur les objectifs de la Politique Commune des Pêches européenne (PCP). L´étude a contribué à développer des méthodes robustes pour a) distinguer les espèces ciblées des prises accessoires, b) distinguer les prises accessoires à valeur commerciales des prises collatérales, les premières étant retenues à bord et débarquées, quand les autres sont rejetées. La catégorisation d´une espèce particulière est propre à la flottille et à la zone dans laquelle cette flottille opère. L'étude a également identifié les espèces incapables de supporter une pression de pêche élevée, avant d´inclure ces espèces dans les modèles de pêcheries mixtes déployés ici. Après le développement de méthode d´évaluation des stocks, des niveaux biologiques de référence et des modèles d´évaluation des stratégies de pêches alternatives pour une variété d´espèces, l´étude a pu identifier les espèces pour lesquelles les limites de capture annuelles de l´ espèce cible seraient suffisantes pour assurer une exploitation durable, même en l´absence de mesures spécifiques à ces espèces. Dans un second temps l´étude a pu identifier les mesures de gestion qui permettent la persistance des espèces accessoires et à déterminer les niveaux de références pour leur préservation. Les mesures de gestion explorées ont inclus des combinaisons variées de limites de capture annuelles (appliquées soit individuellement par espèce, soit par groupes d´espèces mélangées), des modifications techniques des engins de pêche, et des mesures de gestion spatiales, ajoutées à différents niveaux de mise en œuvre de l´obligation de débarquement. L´évaluation des stratégies de gestion révèlent un effet déterminant quant-aux différents degrés de mise en œuvre de l´obligation de débarquement. Avec la mise en œuvre actuelle, les pêcheries restent relativement stables, mais certains stocks, en particulier le stock de morue en Mer Celtique et en Mer du Nord, restent pêchés à un niveau supérieur au niveau requis par le rendement durable maximal, outrepassant le risque à 5% d´un affaiblissement du recrutement pour ces stocks. Au contraire, l'étude montre qu'une mise en œuvre complète de l´obligation de débarquement serait le gage pour une exploitation durable des stocks, au risque d´induire des situations ou des espèces pourraient se trouver en position de « choquer » la pêcherie. Des conséquences socioéconomiques sont à attendre dès que ces espèces (« choke species ») conduisent à la fermeture prolongée de certaines pêcheries démersales. L´étude montre en outre que l´effet prédit des mesures de gestion cherchant à réduire les captures des espèces pouvant « choquer » la pêcherie est la plupart du temps atténué par l´augmentation de l´effort induite par ces mesures. Cette augmentation est induite par la réduction simultanée de l´efficacité d´une unité d´effort de pêche sur la capture de plusieurs espèces. Cet effet non souhaité n'a néanmoins pas été mesuré lors du changement d´engin testé sur la pêcherie de langoustine. De manière générale, aucun scenario étudié ici n´a prédit la reconstitution des stocks sans qu´une réduction de l´effort de pêche total n´y ait été associé.

1. PROBYFISH OVERVIEW AND OBJECTIVE

The overall objective of PROBYFISH was to develop a modelling framework and a support tool to assess whether proposals for regionalised management measures are in accordance with the objectives of the CFP. The study addressed this objective through the development of agreed and robust methods to define target and bycatch species, identification of the species for which TAC management of target species would be sufficient, identification of measures that will lead to the sustainable development of the bycatch stocks, production of agreed reference levels to safeguard stocks and combination of the results of all activities in a user-friendly and flexible tool.

The study was structured in seven tasks:

Task 1: Identification of target and bycatch species.

Task 2: Effect of management through TACs of target species on protection of bycatch species.

Task 3: Identification of bycatch species where target stock TAC management is insufficient.

Task 4: Identification of appropriate management measures for bycatch stocks.

Task 5: Identification of candidate indicators and appropriate trigger values.

Task 6: Development of a management tool.

Task 7: Project management and dissemination.

The tasks were interlinked and repeatedly shared results.

2. TASK 1: DEFINING TARGET AND BYCATCH SPECIES

The objective of task one was to develop a method to define target and bycatch species. To reach this aim, task 1 delivered the following products:

D1.1 Agreed format of input data on catch composition in weight and value and fishing effort of all fleets and métiers within an area and most recent data delivered in the agreed format (month 10, completed)

D1.2 Agreed methods by which fishing métiers can be defined and updated when necessary to accommodate changes in catch composition over time (month 10, completed)

D1.3 Agreed methods to classify species as either "target", "valued bycatch" and "collateral bycatch" (month 10, completed)

D1.4 List of "target", "hybrid", "valued bycatch" and "collateral bycatch" stocks for each of the areas Bay of Biscay, Celtic Sea, English Channel and North Sea and the degree to which these stocks are concentrated across fleets, métier's, subareas and seasons (month 10, completed in tool)

"Target" and "bycatch" species are common denominations in fisheries. However, while these concepts make qualitative sense for describing mixed fisheries, they are difficult to define quantitatively and the allocation of one species into one or another category remain largely subjective, and may vary from fisheries to fisheries, or even from trip to trip. At the onset of Probyfish, there was no established and standardized method to define these concepts objectively. The objective of the task 1 was to provide a scientifically based categorization of the different species in the catch according to the degree to which they are targeted by the fishery (”target”, “valuable bycatch” and “collateral bycatch”) and to provide a tool which can be used to provide a quick overview of the importance of a given species as target, valued bycatch and collateral bycatch in different fleets. The analyses were based on catch data (including wanted and unwanted catches i.e. former landings and discards) as most of the collateral bycatch does not appear in the landings statistics. The analyses are performed at the finest possible scale (i.e. haul based observer data) to avoid any false technical interaction created by data aggregation. The analyses grouped species in homogenous groups based on their characteristics (mostly landed/discarded, representing a large/small proportion of the catch/landings/discards) for a set of countries and métiers (Table 1). The tool is available at https://probyfish.shinyapps.io/GlobalAnalysis/. Further details are available in ICES WKTARGET 2020.

3. TASK 2: EFFECT OF MANAGEMENT THROUGH TACS OF TARGET SPECIES ON PROTECTION OF BYCATCH SPECIES

3.1. Task 2.1. Development, conditioning and expansion of mixed fisheries models to include data-limited stocks

The most appropriate models to address mixed-fisheries scenarios were derived using Tab. S3 from Nielsen et al. (2017) as a template for all relevant criteria for our model selection. Four additional criteria were added based on the specific requirements of the appropriate models to be used within Probyfish:

1. Compatibility with the programming platforms R and the R-package DLMtool (Data-limited Methods Toolkit.

2. Individual parameterization: The appropriate model should have the ability to set essential stock-specific parameters.

3. Appropriate area: The selected model should be applicable to areas appropriate for Probyfish (e.g. the EU, rather than North America or Australia).

4. Appropriate species: The selected model should be applicable to fish species.

A specific scoring (weighting) system was used to emphasize the most essential criteria and distinguish between different levels of priority. This included applicability to mixed fisheries (3 points); level of implementation: high (3 points), medium (2 points) and low (1 point) and appropriate area and species (2 points each). All other criteria were scored 1 point (criterion fulfilled) or 0 points (criterion not fulfilled). The list of all models, relevant criteria and all scores can be found in Deliverable 2.1. According to this analysis, the most appropriate models were FLBEIA (Garcia et al. 2017a), SS-DBEM-IOT, FCUBE and ISIS-FISH. FLBEIA and FCUBE use the same input data (individual stock assessments and associated catches by fleet) and are hence easily comparable. FLBEIA differs from FCUBE in its ability to provide the long term forecasts necessary to evaluate management strategies and was therefore the preferred choice in Probyfish. The state of development of the various FCube (Ulrich et al., 2011, 2016) and FLBEIA (Garcia et al., 2017a, b) models in the various areas was assessed and future possible additions and challenges identified. The regions differed in the degree of implementation of species into mixed fisheries models prior to the Probyfish study. In the greater North Sea, all species defined as target species in the multiannual plan except northern prawn were included together with a few bycatch species. In the other areas, not all target species were included. Detailed descriptions can be found in Deliverable 2.2.

The stocks included were derived from the top 95% of the landings from mixed fisheries. Where all species could not be added due to time constraints in developing new assessments and procuring data, species were selected to represent high value target species and sensitive bycatch species. This choice was based on the expectation that the species of less value or sensitivity are likely to be less impacted by fishing and hence, the information on choke species issues and bycatch stock sustainability that can be derived from including the remaining species is likely to be minor.

Species likely to be sensitive to the pressure from mixed fisheries were identified by estimating the fishing mortality required to reduce SSB by 75% for species occurring in trawl surveys in Europe was estimated using a combination of life history models (Le Qesne and Jennings 2012, Rindorf et al 2020) and catchability models (Walker et al. 2017, Rindorf et al 2020). The methods was presented at WGECO and used together with criteria from the International Union for Conservation of Nature (IUCN) to list sensitive species in the Northeast Atlantic. The species that can sustain less fishing mortality than the major commercial species saithe (Rindorf et al 2020), that are susceptible based on a Productivity-Susceptibility analysis (Altuna-Etxabe et al., 2019) or that is ranked by IUCN as Critically Endangered, Endangered or Vulnerable was characterised as sensitive.

A major task was to incorporate category 3-5 stocks (stocks without an agreed age or length based or biomass model but instead using a combination of catch data and survey time series where available) in FLBEIA/FCUBE. Work was conducted under Task 5 to produce a framework which can produce biomass models for species with assessments in categories 3-5. These biomass models were included in FLBEIA/FCUBE, making it possible to include category 3-5 stocks in the long term forecasts. For long lived species, the stocks are generally predicted to develop rather slowly in the absence of excessive fishing, meaning that the difference in a short term forecast between using the biomass model and assuming constant stock size is likely to be minor unless the species is exhibiting pronounced productivity changes. Additionally, the DLMToolkit was used to condition the data limited stocks in some cases. This tool provides historical time series of abundance and exploitation at age levels, including uncertainty, based on life history parameters and different levels of catch and effort data.

In addition to the biomass model, it is a requirement that reliable fleet based data on catch and landings exist, and this is a particular challenge for skates and rays, which are often not identified to species in catches. There are species for which the data are currently insufficient, including a number of skates and ray species. Most notable are the species which are to be released promptly but where survival is unkown or species that may be landed under other species codes. Among the top 15 sensitive species, the species white skate, common skate complex, Norwegian skate, longnosed skate, sail ray, smalleyed ray and blonde ray are likely to have species identification issues whereas Greenland shark, conger eel, tope, halibut, ling, anglerfish and blackbellied angler and probably common stingray and thornback ray are likely to be well identified. There are several efforts ongoing outside Probyfish to address the challenge of species identification – genetics, identification courses etc. and hence this may not remain a problem in the future, especially not if the legislation is harmonised for similar looking species (e.g. common skate complex, longnosed skate and Norwegian skate) so as not to incentivise misidentification.

These considerations led to definition of two criteria which must be fulfilled for species included in FLBEIA:

1. Species sensitivity: High sensitivity and high catch species are given priority.

2. Data availability: Full implementation in FLBEIA/FCUBE requires a reasonably accurate population model to link fishing effort to changes in stock biomass. There needs to be a link between fishing effort and stock development where a category 3 stock is used.

If catch data are not available or a reasonable model cannot be fitted, the fishing mortality of a bycatch species can be derived by correlation with another species and by combining species distribution, effort distribution, species sensitivity and species catchability as demonstrated by Walker et al 2019 to derived current fishing level relative to the reference level (see task 3).

The above criteria 1 and 2 were applied to the list of species identified as target or bycatch in task 1, excluding species which contribute less than 5% of the total catches in total. Using this approach, the species in Table 1 were chosen to cover different catch categories and sensitivities by area. Under Probyfish, a total of 38 stocks were added to the FLBEIA models and a further 13 were attempted but failed to converge appropriately. Details of the mdoels are found in reports of ICES WGMIXFISH-Advice (2020) and WGMIXFISH-METHODS (2019, 2020).

Table 1. Categorisation of species according to target/valuable bycatch/colateral bycatch, species sensitivity and wheter a TAC is defined in each of the three areas.

Area	Common name	Scientific name	Sensitive*	Target**	TAC
Bay of Biscay	Hake	*Merluccius merluccius*	NO	V	YES
	Megrim	*Lepidorhombus whiffiagonis*	NO	V	YES
	Monkfish	*Lophius piscatorius*	YES	V	YES
	Horse mackerel	*Trachurus trachurus*	NO	C	YES
	Mackerel	*Scomber scombrus*	NO	V	YES
	Sole	*Solea solea*	NO	T	YES
	Blue whiting	*Micromesistius poutassou*	NO	C	YES
	Spiny dogfish	*Scyliorhinus canicula*	YES	C	YES
	Thornback ray	*Raja clavata*	YES	C	YES
	Black-bellied angler	*Lophius budegassa*	YES	V	YES
	Bass	*Dicentrarchus labrax*	NO	V	NO
	Red mullet	*Mullus surmuletus*	NO	V	NO
	Starry smooth-hound	*Mustelus spp*	YES	V	YES
	Cuckoo ray	*Leucoraja naevus*	YES	V	YES
Celtic Sea	Atlantic cod	*Gadus morhua*	NO	V	YES
	Haddock	*Melanogrammus aeglefinus*	NO	C	YES
	Whiting	*Merlangius merlangus*	NO	V	YES
	Monkfish	*Lophius piscatorius*	YES	V	YES
	Hake	*Merluccius merluccius*	NO	V	YES
	Megrim	*Lepidorhombus whiffiagonis*	YES	V	YES
	Sole	*Solea solea*	NO	V	YES
Greater North Sea	Cod	*Gadus morhua*	NO	V	YES
	Haddock	*Melanogrammus aeglefinus*	NO	V	YES
	Saithe	*Pollachius virens*	NO	T	YES
	Sole	*Solea solea*	NO	T	YES
	Plaice	*Pleuronectes platessa*	NO	V	YES
	Whiting	*Merlangius merlangus*	NO	C	YES
	Norway lobster	*Nephrops norvegicus*	NO	T	YES
	Turbot	*Scophthalmus maximus*	YES	T	YES
	Witch flounder	*Glyptocephalus cynoglossus*	NO	V	YES
	Brill	*Scophthalmus rhombus*	YES	T	YES
	Dab	*Limanda limanda*	NO	V	NO
	Anglerfish	*Lophius budegassa, L. piscatorius*	YES	V	YES
	Ling	*Molva molva*	YES	V	YES
	Lemon sole	*Microstomus kitt*	NO	V	YES

**Sensitive (YES/NO) is defined as the IUCN categories Endangered, Vulnerable or as being defined by ProByFish as sensitive due to their life history characteristics.*

***Target categories: T (Target), V (valuable bycatch), C (Collateral bycatch) using a minimum requirement of 50% for the proportion of trips that classifies a species in a specific category before it is assigned to the category (target or valuable bycatch).*

3.2. Task 2.2. Classification of robustness of assessment, reference points and fleet based data for all stocks

Probyfish proceeded to investigate how robust the FLBEIA parameterisations using the following criteria to evaluate assessment robustness:

Robustness of assessment used to condition FLBEIA:

- Have gone through benchmark (QA)
- Assessment catch data quality
- Mohn's ro SSB (bias)
- Mohn's ro F (bias)
- Mohn's ro Rec (bias)
- CV in SSB in terminal year (precision)
- CV in F in terminal year (precision)

Thresholds related to biomass and fishing mortality:

- Method ranks as identified in deliverable 5.1
- Fleet catch data quality
- Available by metier in updated database (e.g. ICES intercatch or RDB)
- Concerns about species id
- Discard information available
- Effort data available by majority of fleets

This categorization was used to provide robustness indications for the results derived from FLBEIA.

3.3. Task 2.3. Effect of TACs for target species on bycatch species

Analyses of the effect of TACs for target species on fishing mortalities of hybrid, valued and collateral bycatch species were conducted assuming different management strategies to define TACs for the target species, while no management applies on the bycatch species. The analyses were conducted in a mixed fisheries Management Strategy Evaluation (MSE) framework in FLBEIA to examine the probability that single stock TACs are sufficient under natural variability, mixed fishery dynamics and management strategies. A stock status was identified as 'healthy' if the median biomass exceeded levels which may impair recruitment given that the knowledge of stock status is not perfect, MSY $B_{trigger}$, and the stocks was fished at levels consistent with attaining the maximum sustainable yield in the longterm (F_{MSY}) or less. Further, the proportion of years where biomass was below the limit for which recruitment of new fish to the stock becomes impaired (B_{lim}) was also investigated. For stocks where these reference levels were not defined by ICES, ProByFish used proxy reference levels. Stocks were considered at risk if the proportion of years with a biomass below B_{lim} or the equivalent proxy was greater than 5%. The result shows that the effect of changing the species on which to define a TAC are minor compared to the effects concerning the uncertainty around the implementation of the landing obligation. If the landing obligation is implemented in the same way as done to date, there are several species which will be at risk, even among the MAP TAC species. In contrast, a full implementation of the landing obligation would lead to these species choking the fishery but will safeguard all modelled species in the greater North Sea and Celtic Sea, whereas a number of species still require additional protection in the Bay of Biscay.

Scenarios investigated

In each area, two scenarios were run reflecting the species managed:

'Target' scenario: only the target stocks as defined in the relevant Multiannual Plan were managed by TACs. In general, there are more target stocks in the MAP than are identified in the method used in task 1 (e.g. cod is not identified as a target under task 1). However, when inspecting species classified as either vulnerable bycatch or target, the number of species exceeds that in the MAP.

'Current' scenario: all the stocks in the current TAC and quota system were managed by TACs

A further three scenarios were used to reflect the implementation of the TACs under each of the species:

'Fixed' scenario: the effort remains the same as in the initial year

'Min' scenario: the fishery ends once the most restrictive TAC is reached

'Previous' scenario: effort is restricted by the effort corresponding to all the quotas and the previous years' effort. This is the scenario that resembles the status quo most closely.

The management procedure consisted of setting a TAC for each of the stocks annually. The TACs were obtained using the harvest control rule used by ICES to generate the management advice annually.

Definitions of healthy stocks

Indicators of healthy stock status differed between age-based (i.e. quantitatively assessed stocks) and biomass-based stocks. The following indicators were used:

- age-based: Median biomass greater than MSY Btrigger, Bpa and Blim (B/Btrigger > 1.0, B/Bpa > 1.0, B/Blim > 1.0). Median fishing mortality less than Fmsy and Fpa (F/Fmsy < 1.0, F/Fpa < 1.0).

- biomass-based *with* SPiCT models presented in advice: Median biomass greater than Bmsy and MSY Btrigger (B/Bmsy > 1.0, B/Btrigger > 1.0). For these stocks, a proxy Btrigger = 0.5*Bmsy was used. This should be approximately equivalent to B/B0 > 0.25, used for other SPiCT stocks. Median fishing mortality less than Fmsy (F/Fmsy < 1.0).

- biomass-based *without* SPiCT models presented in advice: Median biomass greater than Bmsy and MSY Btrigger. For these stocks, a proxy Btrigger = 0.25*B0 was used. (B/Bmsy > 1.0, B/B0 > 0.25). Median fishing mortality less than Fmsy (F/Fmsy < 1.0).

- fixed biomass: Median fishing mortality less than Fmsy (F/Fmsy > 1.0) as only fishing mortality reference points exist

Bay of Biscay demersal fishing

The Bay of Biscay model covers ICES divisions 8abd. In Probyfish, the number of stocks included was extended from the original 12 stocks of which only 2 were modelled with full dynamics to 28 species. The selection was based on a species prioritization approach proposed by Altuna-Etxabe, Ibaibarriaga et al. (2019) and the analysis carried out in Task 1 of the ProbyFish study to identify target and valuable bycatch species. Of these 28 species, 14 had an assessment that allowed the full dynamics to be modelled: hake, megrim, white anglerfish, black anglerfish, horse mackerel, mackerel, sole, bass, blue whiting, dogfish, smooth-hounds, cuckoo ray, thornback ray and red mullet. The scenario 'Current' and 'Target' differed for the species thornback ray, smooth-hounds, cuckoo ray and undulate ray.

The difference between SSB levels was bigger between implementation scenarios than between the species scenarios. Continuing the Previous scenario leads to stable or declining SSB of most of the stocks. However, under the Min scenario where fishing is stopped when the first TAC is exhausted, the SSB increased in most of the cases. Furthermore, the increase was bigger when the current management was maintained, i.e when the TAC was maintained for the current TAC stocks. The probability of SSB being below B_{lim} for data-rich stocks was low with the exception of white anglerfish. For data-limited stocks, thornback ray and smoothhound, the probability of being below 25% of the biomass in absence of fishing ($0.25B_0$) was around 20% and 35% respectively, but there were not big differences between scenarios. For black-bellied anglerfish and red mullet, the probability was close to 100%. Furthermore, the probability was lower under the current management configuration than when there were TACs on only target species. For cuckoo ray, under current TAC species, the probability of SSB being below $0.25B_0$ was around 13% and when the TAC was removed for non-target stocks it increased to 20%.

Celtic Sea demersal fishing

The Celtic Sea model cover ICES divisions 7f,g,h,j,k. The stocks included in the Probyfish model were cod, haddock, whiting, anglerfish, hake, megrim, sole, plaice, Nephrops, dogfish, red gurnard and thornback ray. In addition to these species, black-bellied angler, spurdog, black Scabbard fish, European conger and common mora were considered but had insufficient information. The TAC species were identical to the target species in the multiannual plan in this area, and hence, only two scenarios were estimated.

The median SSB for all the stocks except whiting show a strong increasing biomass trend under the Min scenario. As the cod stock is below Blim, this scenario operates with a TAC of zero for several years, substantially reducing fishing pressure. In the Previous scenario, fishing effort is much higher and stock biomasses increases are lower. The cod biomass continues to fluctuate around Blim and whiting falls below Blim after 5 years. Haddock and anglerfish show declining biomass trends but remain above their Blim reference points.

Greater North Sea demersal fishing

The greater North Sea model covers demersal fisheries ICES areas 4a-c, 7d, 3a20 and 6a. In Probyfish, the number of stocks included was extended to a total of 14 species selected based on important commercial species and the evaluation of species sensitivity. The scenarios of current management include a larger number of TAC managed stocks than the target (map) scenario (brill, lemon sole, ling, turbot and witch).

The biomasses were slightly lower under the target scenario, but the differences were small compared to the difference between implementing the Min and Previous management scenario. Under the Min fleet effort control setting, all stocks were in good status by the terminal year. Only witch was found to be fished above Fmsy in median, but Fpa was not exceeded. Under the Previous fleet effort control scenario, several age-based stocks show above 5% risk to B_{lim} (cod and witch) and Fpa (cod, eastern channel plaice and witch). For biomass-based stocks, anglerfish was below $0.25B_0$ in 28% of the iterations. Cod, anglerfish, English Channel plaice, haddock, sole, turbot, whiting and witch median fishing mortality exceeded F_{MSY} under the previous effort scenario.

3.4. Task 2.4 Sensitivity of mixed fisheries models to changes in key productivity parameters on whether single species TACs are sufficient

The performance of the Bay of Biscay system was highly influenced by the slope of the stock-recruitment relationship near the origin. In contrast, the estimated unfished biomass did not have any impact on the biomass of the stocks in the projection period. In general, the impact of productivity parameters on the biomass of the stocks was stock dependent and the biomass in the final year was mostly independent of the initial condition of the stock. In all bycatch stocks except red mullet, the productivity parameters were more important for the biomass level in the last projection year than the management strategy. For the one exception to this, the landing obligation and harvest control rules explained most of the variance, indicating that management strategy is an important factor in stock status. In target stocks limiting the fishing activity of a fleet (choke stocks), the landing obligation explained a large proportion of the variance. In general, the impact of the harvest control rules depended on the indicators of stock recruitment productivity.

4. TASK 3 IDENTIFICATION OF BYCATCH SPECIES WHERE TARGET STOCK TAC MANAGEMENT IS INSUFFICIENT

The objective of task 3 was to identify bycatch stocks, which are not protected by TAC management of the target species and to investigate correlations between fishing mortalities of different species over time, as well as the consistency and potential causes of these correlations.

To reach this aim, task 3 delivered the following products:

D3.1 Report on the extent and consistency of correlation between identified target and bycatch species at different fleet and métier scales

D3.2 Report on the possible causes of consistent correlations

D3.3 Identify fleet units in future management strategy evaluation context

D3.4 Report on bycatch species not protected by TAC management of target species

The work conducted to derive each of these deliverables is summarised below.

4.1. Task 3.1. Extent and consistency of correlation between identified target and bycatch species

Under task 3.1, clustering analyses using the same observer data in task 1 was developed to determine the degree of association (i.e. correlation) between target and bycatch species. A tool was developed to visualise the results of these analyses, thereby making it possible to assess the consistency of these correlations with respect to time and the level of detail use of fleet definition. The tool requires raw observer data and it may be possible to identify individual vessels in the data. The identification of individual vessels is in conflict with the General Data Protection Regulation and hence the tool cannot be publically available outside WGMIXFISH. The tool also displays maps showing the spatial distribution of the clusters identified, which is used to describe the spatial extent of the correlations. Further details can be found in ICES WGMIXFISH-METHODS 2019.

4.2. Task 3.2. Analyses of the possible causes of consistent correlations

Under task 3.2, Probyfish evaluated the causes of spatio-temporal patterns in catch composition. First, spatial models were applied to survey and observer data to provide species distribution maps which can be used as a basis for decisions on spatial management measures in task 4. The maps are of species and overlayed with stock boundaries they become stock maps. They are not maps of commercial catches but commercial catch rates are used to inform the species distribution. Both survey and observers' data were included in the analysis of overlap in the catches for pairs of species. The technical approach to identifying target and bycatch species in fishing trips of a given métier was supplemented with information from interviews of Dutch fishers on which species they consider bycatch, how important they are to their landings, how stable they consider the assignment of a species to 'bycatch' or 'target' to be and whether they would be able to avoid bycatch of a particular species. The interviews provided five overarching conclusions:

1**.** Bycatch definition varied from fisher to fisher. Some made clear distinctions, while others found it a difficult question to answer. Fishers often paused when asked what the difference was between bycatch and target species, somewhat confused about the question. Some responded that such a distinction was not relevant to them.

2. The importance of bycatch species to the fishers varies depending on their gear and their business model. Some are very targeted and specialised, therefore bycatch is not a large part of their operation. For others, who are more seasonal and sensitive to fluctuations in market price, bycatch can be more profitable per kilo than their target species.

3. Even fishers with very effective targeting gear consider other species as important to their operation. Valuable bycatches supplement the income from the target species, as well as allowing fishers to have a profitable operation year-round while staying within their annual quota.

4: Many of the decisions that determine catch composition happen at sea, according to what each haul contains. A skipper can consider the current price of various species in different seasons and use that to determine whether to target 'bycatch' species. Therefore a species does not have a fixed status as 'bycatch' or 'target'.

5: Some species, particularly those that school like sea bass, can be very difficult to avoid as bycatch. If a fisher does not have quota for this species then it has to be discarded, and in the case of cod or sea bass the survival rate is effectively zero, which fishers see as wasteful.

4.3. Task 3.3. Identification of optimal fleet units for a proper management strategy evaluation

Using the tools for visualization of the results of task 3.1 and 3.2, the optimal fleet and métier units, that corresponds best to the technical interactions (correlations), were identified. When considering the fishing activity aggregation level that is used for mixed fisheries models, métier level 6, two situations were encountered: cases where correlations between species reflect a fine scale technical interaction, and cases where they arise from the existence of different sub–metiers (level 7), with differences in species composition. No significant correlations were observed at the level 7 where these did not also occur at level 6, indicating that it was not necessary to use the finer métier level 7 as the basic fleet unit in the models. Using métier level 5 as the basic fisheries unit in mixed fisheries models would mean in some instances combining métiers level 6 with different technical interactions, and therefore did not seem appropriate.

4.4. Task 3.4. Identification of bycatch species not protected by TAC management of target species

The simulations conducted using FLBEIA for the three areas of interest in PROBYFISH indicated that a number of bycatch species were not protected by a TAC management of the target species in each of the areas. The distribution of the landings of these bycatch species across fishing fleets, quarter of the year and in space was investigated to provide an indication of the likely effect of fleet, spatial and temporal management measures. This information forms the basis of work in task 4 on possible management measures to protect those stocks.

In the greater North Sea, witch was the only bycatch species not protected. This species occurred frequently in a variety of fleets and was evenly distributed across quarters. There were only minor differences between quarters in catches of dogfish in the Celtic Sea, and hence total catch measures are likely to be most efficient followed by spatial measures. For Celtic Sea red gurnard and thornback ray, temporal measures and measure regulating total catch were likely to be most efficient. Only a small proportion of stripped red mullet and smooth-hound catches were taken in the Bay of Biscay, and hence measures regulating total catch are likely to be most efficient. The cuckoo and thornback ray catches showed diverging patterns between data sources and as a result, the analyses was not considered reliable. For Bay of Biscay dogfish, catches are widespread and fleet, temporally or spatially specific measures are likely to be less efficient than total catch measures. The model applications have been reviewed by WGMIXFISH-METHOD and can be used in future evaluations of the effects of removing single species TACs for species fully modelled provided that the input data is updated to reflect recent conditions (for example, as specified in https://doi.org/10.17895/ices.pub.4531).

5. TASK 4. IDENTIFICATION OF APPROPRIATE MANAGEMENT MEASURES FOR BYCATCH STOCKS

The objective of task 4 was to determine measures that will ensure that any bycatch species identified as not managed in accordance with the CFP under target TACs can be protected by other specified measures.

To reach this aim, task 4 delivered the following products:

D4.1 Report on the application of one or more additional single species bycatch TACs and the impact of this on the remaining species and the fishery (month 26, completed)

D4.2 Report on the impact of applying grouped species bycatch TACs on other stocks and yield of the fishery (month 26, completed)

D4.3 Report on the use of gear based technical measures, and/or métier management to reduce bycatch (month 26, completed)

D4.4 Report on the impact of applying specific fixed spatial and temporal closure measures to reduce bycatch (month 30, completed)

D4.5 Report on the impact of applying adaptive spatio-temporally explicit management to reduce bycatch (month 30, completed)

The work conducted to derive each of these deliverables is summarised below.

5.1. Task 4.1. Effect of single species TACs

Due to the low number of bycatch species at risk in the greater North Sea and Celtic Sea, the Bay of Biscay was the main focus in this task. Adding TACs to protect bycatch species had stock and fleet dependent effects. In some cases, severe choke issues were introduced in some fleets with expected losses greater than 50% and prolonged fishery closures. In other cases, very little impact was seen. The model-free harvest control rule used by ICES in category 3 stocks did not succeed in rebuilding depleted stocks whereas upgrading the HCR for black anglerfish resulted in biomasses well above the reference point in the whole projection. Furthermore, the loss for the fleets fishing in the Bay of Biscay was marginal and, in some cases, resulted in significant gains. Upgrading the HCR of thornback ray resulted in an increase in the biomass of the stock. However, it implied a significant loss in yield for the fleets when the landing obligation was in place. When the landing obligation was not considered both winners and losers occurred among the fleets.

The models developed can be used in future evaluations of the effects of adding single species TACs for bycatch species fully modelled provided that the input data is updated to reflect recent conditions.

5.2. Task 4.2 Effect of grouped bycatch species TAC

In the greater North Sea case, two pairings were investigated; turbot with brill, and witch with lemon sole. Joining TACs of turbot and brill in one group TAC did not have any effect on fleet choking, since these stocks are not typically choking. Joining witch and lemon sole in one group TAC allows for a higher fishing effort since witch is often a choking stock. This higher fishing effort results in the overexploitation of witch (F/Fmsy > 1.0) although the median biomassremains above B_{lim}. Dutch beam trawlers and Scottish otter trawlers are the fleets that most benefit from the witch/lemon sole grouped TAC in terms of increased catches. In the Celtic Sea, combining TACS for haddock and whiting led to the F/Fmsy ratio being improved slightly, and a concomitant slight improvement in the biomass relative to B_{lim}. There was evidence that the pairing led to a reduction in effort, principally in the Irish fleet and that the effort reduction led to improvements in F for cod, anglerfish, hake and megrim. In the Bay of Biscay, grouping TACs for anglerfishes or rays had no impact on the median stock levels. However, grouping TACs resulted in slightly higher fishing mortalities of black anglerfish and thornback ray. The activity of some fleets was more restricted when the TACs were separated. As above, the models developed can be used in future evaluations of the effects of combining single species TACs for target and bycatch species fully modelled provided that the input data is updated to reflect recent conditions.

5.3. Task 4.3 Gear and métier based approaches

The Probyfish study conducted a comprehensive review of selectivity data available for commonly used commercial gears in the greater North Sea and Western Waters followed by an analyses of effects of introducing gear modifications at a métier level to limit the catch of bycath species. The main issue in the review was the sparsity of data for non-target species. While there have been many selectivity studies carried out, in most case these focus on a very few species, and usually the most important commercial species. Data on other species in the catches have often not been recorded. As a consequence, the selectivity change from different gear modifications had to be predicted based on information from other species and expert judgement, and therefore is likely to have high and unknown uncertainty. If results are to be used for operational management, seelctivity experiments would be required for a greater variety of species than what is presently available. Hence, the present application shoul be considered proof of concept rather than a tool directly for operational management implementation. A second issue is that almost all selectivity studies analyse the results in the context of length. So the data produced were length at 50% retention and the range across the length selectivity ogive. To use these in the FLBEIA models, it is necessary to convert the lengths to ages using age to length keys. Finally, the most appropriate modifications for use in the analysis must be selected. This was principally based on having a good spread of species with selectivity data for the modification, and secondly, on it providing a significant selectivity change from the base case (unmodified net). This was to provide the greatest chance of identifying the effects within a multi-fleet model like FLBEIA. The analysis focused on gear modifications in the North and Celtic Seas, as there was insufficient data for the gears commonly deployed in the Bay of Biscay.

For the greater North Sea, the main conclusions were:

- TR1 modification results in a decrease in F/Fmsy for haddock, cod, whiting and saithe as well as for witch. Haddock benefitted the most and exhibited a faster recovery and higher SSB levels. The other stocks show minimal changes to SSB trajectories. One exception was a decrease in biomass for anglerfish, which was not affected by the selectivity changes directly, but were likely subjected to a higher fishing pressure due to less choking by haddock.

- TR2 modification had lower impacts than TR1, but decreased the F/Fmsy ratios for whiting and cod. Only small changes to SSB trajectories.

- BT2 modification mainly influenced sole, with lower F/Fmsy, and increased SSB.

- The TR1 modification had the strongest impact on catchability (i.e. CPUE), forcing fleets to fish longer (i.e. increase effort) to achieve their quotas as they were less efficient in catching fish.

- Overall catch levels were only minimally affected by modifications, as some degree of compensation in increased fishing effort occurred in order to obtain quotas.

For the Celtic Sea, the main conclusions were:

- The BT2 modifications substantially reduced the catches and catch per unit effort for most of the stocks studied except cod. At the stock level, the main effect was for the two sole stocks, where biomass increased and F decreased. At the national fleet level, there were only minor changes in catches, effort and catch per unit effort, although there was some reduction in effort from the Belgian fleet, which is predominantly a beam trawl fleet.

- The TR1 modifications led to significant reductions in catches of hake, anglerfish, sole, and whiting, and smaller reductions for cod and haddock. There was also a small increase in effort in compensation. At the stock level, the biomass of whiting and hake increased, while anglerfish biomass was reduced. Fishing mortality for both anglerfish and cod was higher with the modified gear, but was reduced for whiting, hake, and sole in VIIf&g. The likely issue with cod and anglerfish is that the selectivity improvements were not substantial, and the increased effort required to catch the stocks where selectivity did improve, resulted in negative impacts on the cod and anglerfish. At the national fleet level, catches improved for England, Spain and the Netherlands, with no change for Belgium and Ireland, and some reduction for France.

- The TR2 modifications led to significant reductions in catches of cod, haddock and whiting and possibly anglerfish. They had no impact on Nephrops catches. There was no change in effort in compensation, so catch per unit effort followed catches. At the stock level, the main effect was for the biomass of cod to increase relative to Blim, with a concomitant decrease in F. There was also a small reduction in F for the other fish stocks modelled. At the national fleet level, there were no obvious changes in overall catches or effort.

The overall findings were that the modifications to each gear worked largely as expected, and catches were reduced for that particular gear. However, in most cases these improvements onlyresulted in an improved stock status in terms of biomass or fishing mortality for the species to which the modification was tailored while catches of other species increased due to increased effort. The BT2 modification did demonstrate improvements in F and B for sole in both areas, but no additional benefits. The TR1 modification led to improved stock status for a number of stocks in both areas, mainly for gadoid stocks. However, the major improvements in selectivity identified were commonly mitigated by compensatory increases in effort. This sometimes led to the modification actually resulting in poorer stock status for some species where the selectivity improvements were minimal. Finally, the TR2 modification also had mixed results. In the greater North Sea it slightly improved the stock status for whiting and cod, while in the Celtic Sea, the main improvement was for cod, with slight improvements for a range of other species. Again, some species showed lower stock status with this improvement.

For the métier management analysis, the study focused on the greater North Sea, as there were issues in the application of the max profit scenario in the Celtic Sea. There were also issues with the model as applied in the greater North Sea, but it was possible to arrive at some tentative conclusions:

- There was no differences between Maximum Profit (i.e. Value) and Maximum Yield scenarios, indicating possible issues with the optimization procedure or conditioning of the scenario.

- TAC uptake is increased, as reflected by F/F_{MSY}, especially in anglerfish, haddock, and Channel plaice.

- Optimization produces winners and losers, since optimizations in some fleets spell increased catches for them while decreases for others.
- Some unrealistic optimizations were identified - e.g. fishing in 6a to avoid catching North Sea cod

It was concluded that the metier based approach may have merit, but that there are issues to resolve in the modelling before rigorous conclusions will be possible.

5.4. Task 4.4 Fixed spatiotemporal management measures: closed areas and closed seasons

This task investigated two model analyses of the effectiveness of spatial or spatio-temporally explicit management to reduce bycatch. The first was conducted using a DISPLACE model – a dynamic, individual-based model of fishing activity, that incorporates fishers behaviour, ecosystem components etc. (Bastardie et al 2014). This model was adapted to the Celtic Sea, with a focus on cod. The second model was an Ecopath with Ecosim model. This model develops a spatially resolved mass balance perception of the ecosystem with functional groups by species or taxa (Ecospace) (Pauly et al 2000). The Ecospace model was focused on the southern North Sea, again with an emphasis on cod.

The DISPLACE used in this study is spatio-temporally explicit. It included:

- Multi-species interactions for 23 fish species
- Simulations of individual fisher's behaviour over 4 vessel size classes and 9 different gears, with their selectivities
- Habitat maps, and ecosystem variables including depth, temperature and salinity
- Survey and landings data, plus fish prices.

A series of different scenarios were evaluated with the model. These included:

- The Landing obligation and avoiding choke
- Closed areas based on high discard abundance of cod on an annual or seasonal basis

The key finding was that closing areas predicated on high likelihood of cod discarding can be effective in reducing cod catches and mortality and increasing stock biomass. They are more effective when using seasonally variable closed areas rather than a single annual structure. However, they come at the cost of decreased catch and value per unit effort and increased fishing mortality on hake and haddock. The model application has yet to be reviewed by ICES and the underlying process models and may have issues yet to resolve before it is used in operational management advice.

The Ecospace model also illustrated how designated closures could help conserve the cod stock. The model was used to evaluate the effects of spatial management options on the cod stock. These include already designated marine protected areas (MPAs) as well as planned and operated offshore windfarms (OWFs). The model was then used to evaluate the inclusion of MPAs specifically designed to protect the cod stock. Closing MPAs specifically to protect cod increased the biomass of cod juvenile and adults substantially within the closed areas. Existing MPAs and OWFs did not have such a strong effect. The increase of cod biomass within closed areas meant that fishing effort was displaced into other areas still open to fishing. The biomass of cod in these areas consequently was reduced and in almost all scenarios, cod was only abundant in the protected areas. There was no overall increase in cod abundance across the whole of the southern North Sea, despite the increase within the protected areas. This highlights that effort displacement and habitat quality outside closed areas have to be taken into account in spatial management decisions to avoid unintended effects on the stocks and the fisheries. The model application has yet to be reviewed by ICES and the underlying process models and may have issues yet to resolve before it is used in operational management advice.

5.5. Task 4.5 Adaptive spatiotemporal management approaches

The DISPLACE application used under task 4.4 was subsequently used to investigate adaptive spatiotemporal management approaches such as real time incentives (RTI - Kraak et al. 2014). The scenarios evaluated included two spatio-temporally explicit management with tariff based management approaches with scenarios of avoiding or targeting high tariff areas. The spatio-temporally explicit RTI approach was more effective than the closed area approach. Of the two scenarios, the one where fishers targeted the highest tariff areas i.e. the most abundant cod areas, worked better in terms of protecting the stock. This led to a decrease in effort, and therefore impacts on other species and the wider ecosystem. The model application has yet to be reviewed by ICES and the underlying process models and may have issues yet to resolve before it is used in operational management advice.

6. TASK 5. IDENTIFICATION OF CANDIDATE INDICATORS AND APPROPRIATE TRIGGER VALUES

Task 5 aimed to determine trigger values below which protective measures need to be introduced in order to promote the protection and sustainable exploitation of by-catch species.

To reach this aim, task 5 delivered the following products:

D5.1 Review of existing indicators and trigger values for bycatch species in each case study.

D5.2 Report on the performance of indicators and methods to derive trigger values.

D5.3 Final list of indicators and trigger values for bycatch stocks by fleet/métier.

The work conducted to derive each of these deliverables is summarised below.

6.1. Task 5.1: Existing indicators and trigger values for bycatch species

Probyfish conducted a critical review of the experience gained so far with the various methods and collected information on internationally agreed indicators and trigger levels for relevant stocks. The results of the review were tabled and forwarded to ICES to consider as a format that is regularly updated. ICES will consider this opportunity in their future work. The work on identifying sensitive species has been passed from ICES WGECO and OSPAR to WGBIODIV for review and subsequent publication as an ICES approved trait database. The work on providing indices of abundance of sensitive species has passed through review in ICES WGECO and OSPAR and the method to select sensitive species was further considered by STECF in October 2020 and WKCOFIBYC November 2020 (STECF 2020, ICES WKCOFIBYC 2021).

6.2. Task 5.2 Test the performance of indicators and trigger values

Work under this task has focused on producing biomass models capable of simulating stock development under the agreed advice rules for data limited stocks. The results were presented at ICES WKLIFE. A simulation framework was developed in R (FLIBM - *Individual-based operating model for fisheries simulations*). The flexible framework allows for the development of operating models (OM) of a variety of life histories types, which will be used in the exploration of data poor stocks. OM outputs (e.g. stock and catch numbers, mean weights, mortality rates, etc.) are recorded in both age- and length-based FLR objects (Fisheries Library for R, Kell et al. 2007), allowing for easy integration into a wide array of assessment models.

Different methods to derive reference points and trigger values often give different results. Therefore, the choice of the right indicator is critical to ensure both precise and unbiased (no systematic over or underestimation) results regarding the current stock status (i.e. whether a stock is currently overexploited or not) of bycatch stocks. In deliverable 5.2 different data-limited assessment methods were tested in scenarios of varying data poverty in order to challenge the main methods currently used by ICES. Further, a Robin Hood approach for the assessment of greater North Sea flatfish stocks was tested to see whether a multi-species state-space model outperforms traditional single-species assessment methods. Based on the results a confidence rating can be determined for assessment methods under different data-poor scenarios. Further, the performance of different methods to set biomass reference points in age based stock assessments was investigated.

6.3. Task 5.3 Determine a final list of indicators and trigger values

This task provided a final set of indicator and trigger values and their associated confidence levels for all relevant stocks in the three case study areas (greater North Sea, Celtic Seas and Bay of Biscay). The information was used in task 2.3 where details on assessments and reference points (and the confidence in these values) can be found. For each relevant stock, information was provided here on landings, discards and catches by fleet and métier in absolute terms (tonnes) and as percentages (contribution of each fleet and métier to total catches, landings and discards). Based on this information, the most relevant fleets and métiers catching a certain bycatch species in a certain area were identified. The information can also be used to calculate partial fishing values and reference and trigger values for each fleet and métier by multiplying the total fishing mortality or fishing mortality reference point with the percentages each fleet and métier contributes to the total catches in a given area. As final product, the results were assembled in two Excel tables for further use within and outside the study.

7. TASK 6. DEVELOPMENT OF A MANAGEMENT TOOL

Under task 6, tools providing easy access to the results of the analyses conducted under tasks 1 to 5 together were developed.

Task 6 delivered the following products:

D6.1 Stakeholder user interface

D6.2 Tool to determine regional target and bycatch species.

D6.3 Tool to identify whether TACs for target species are sufficient.

D6.4 Tool to identify the effect of additional management measures

The work conducted to derive each of these deliverables is described below.

7.1. Task 6.1. Developing the stakeholder interface

The tool interfaces have been discussed with DGMARE and ICES and it was agreed that a modular approach using R-shinies (https://shiny.rstudio.com/) allows a flexible interface and subsequent integration into ICES web based products. A further desirable result was that the interface can be updated regularly by WGMIXFISH, making a link to RDBES data and/or FLBEIA elements essential. It was also concluded that the interface used may differ between different situations, as there is a trade-off between clarity and detail in the interface. To accommodate differences between users in the desire for different levels of detail, four different interfaces have been developed:

- A 'simple' interface showing the overall results with respect to stock status of the two scenarios for all modelled species
- A detailed interface showing the role of different species as targets, valuable bycatch or collateral bycatch in different areas and fleets
- A detailed interface showing the predictions of FLBEIA by fleet and species
- A detailed interface showing the predictions of DISPLACE of spatial management measures

7.2. Task 6.2 Developing the tool to determine regional target and bycatch species.

A prototype tool was developed for the definition of target and bycatch species. Input data (on fleet and métier scale information on catch composition in weight and value of all regional fleets and métier) as well as method to estimate "target", "valued bycatch" and "collateral bycatch", methods for updating input data and recommendations are derived directly from D1.1 and D1.2. The tool was constructed using R-shiny an interactive tool to display the results of the analyses and is available here: https://probyfish.shinyapps.io/GlobalAnalysis/.

Using the tool, information can be derived on the number of years in which a fleet receives the categorization target of different species in an area (fig. 1), the categorization of a specific species in all areas (fig. 2) and the spatial distribution of the categorization of a species (fig. 3).

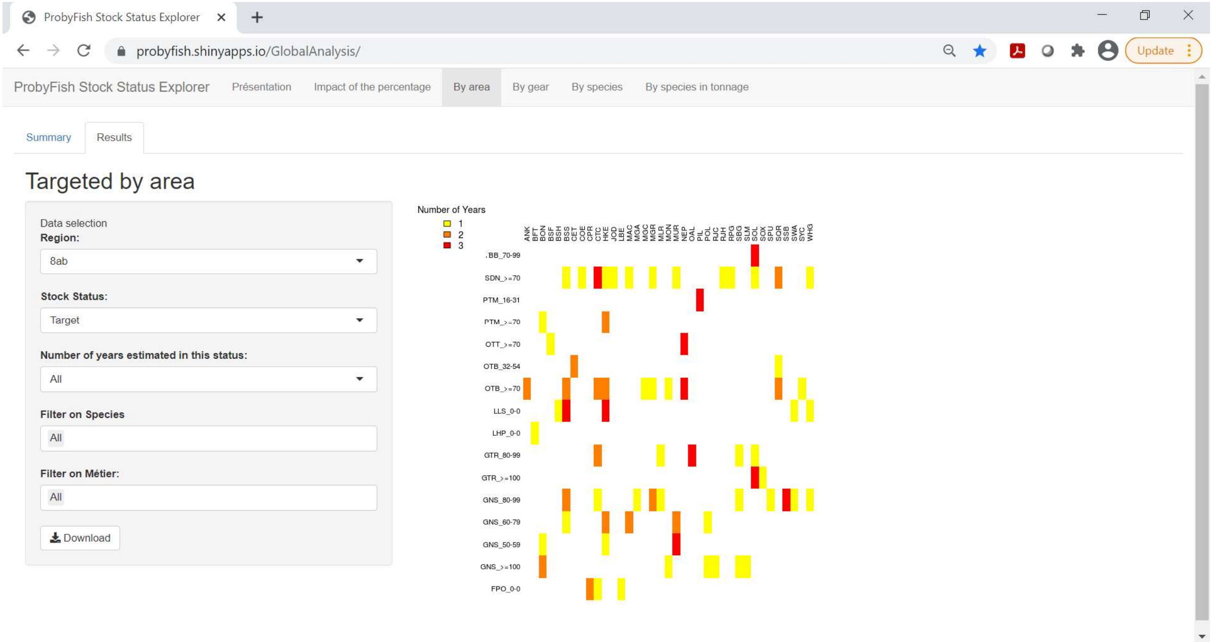

Figure 1. Number of years in which a fleet receives the categorization target of different species in an area.

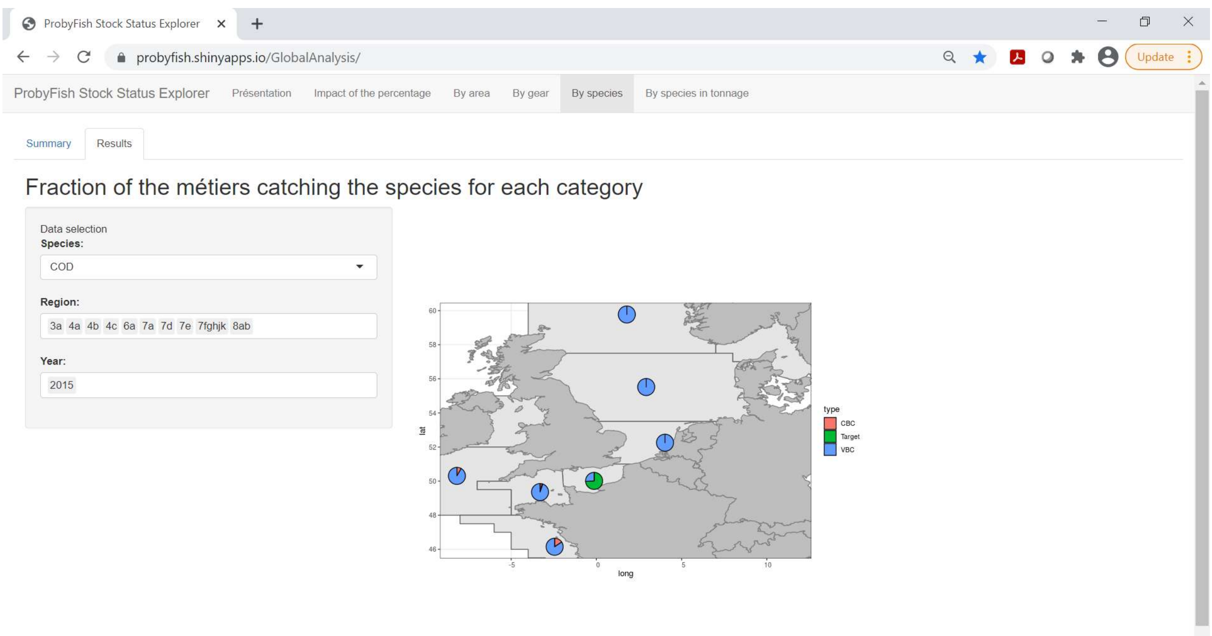

Figure 2. The categorization of a specific species (cod) in all areas.

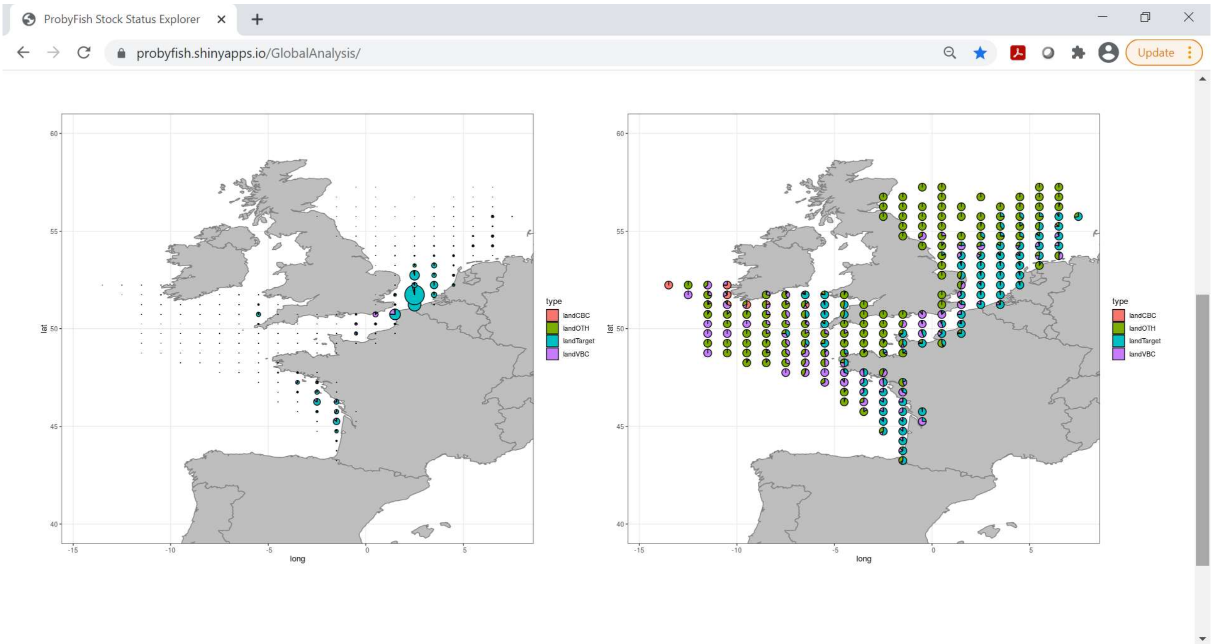

Figure 3. Spatial distribution of a specific species (sole) categorization weighted by landings.

7.3. Task 6.3 Developing the tool to identify whether TACs for target species are sufficient.

Based on results from task 6.2 and communication with DGMARE, Probyfish produced two interactive interfaces to the management strategy evaluation output: a simple interface of effects on stock status and a detailed interface including fleet-based information. Both demonstrate the effect of implementing TACs on target species on stock status and fleet specific catches. The tools are based on the decision on which stocks are to be managed by target species TAC (tasks 1 and 2), model output surfaces of target and bycatch species stock biomass (indices) as a function of target TAC and the resulting fishing pressure as well as threshold levels for biomass (indices) and confidence in these levels. The two tools are the 'simple web application' and the detailed FLBEIAshiny.

'Simple web application'

The output of multi-species and multi-fleet models can be very complex and important information that is needed by managers and stakeholders can be difficult to discern in the multitude of output graphs and tables. Therefore, a prototype web application was developed that provides a focused and simplified approach of presenting quantities and aspects of the output that are most relevant for managers and policy makers to base their decision making.

The application uses the output information of the FLBEIA model and provides overview graphs of important quantities. There are two subpages in the application. The first subpage provides the results in the final year of simulations, in terms of biomass (B), Biomass/$B_{trigger}$, fishing mortality (F), F/F_{MSY}, and probability B < B_{lim}. The user has choices on the way results are presented: by species or by scenario (Fig. 4). The second subpage presents the important quantities, catch, discards, landings and price for all scenarios. The user can select one or more species and the quantity of interest.

The web application was developed using the "*shiny*" R web application framework (https://shiny.rstudio.com) and it is found here: http://ono.dtuaqua.dk:8282/probyfish_simple_shiny.

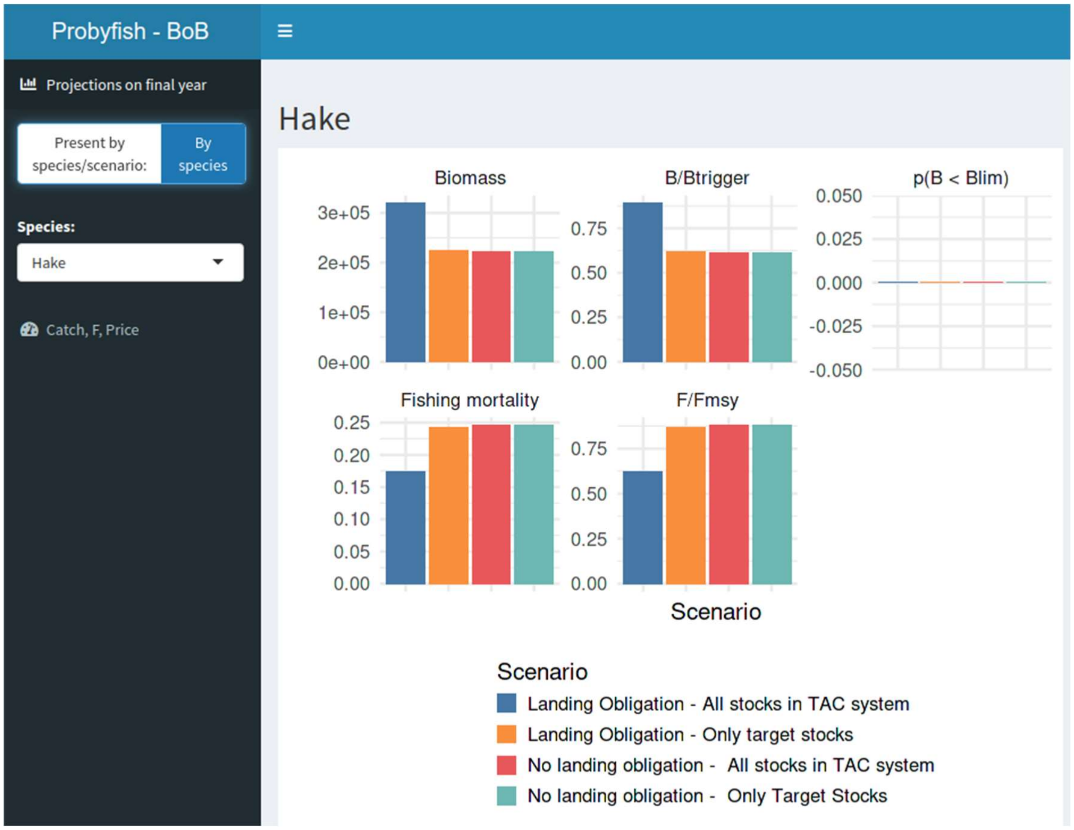

Figure 4. Final year projections for one of the species (here it is hake) in four different scenarios.

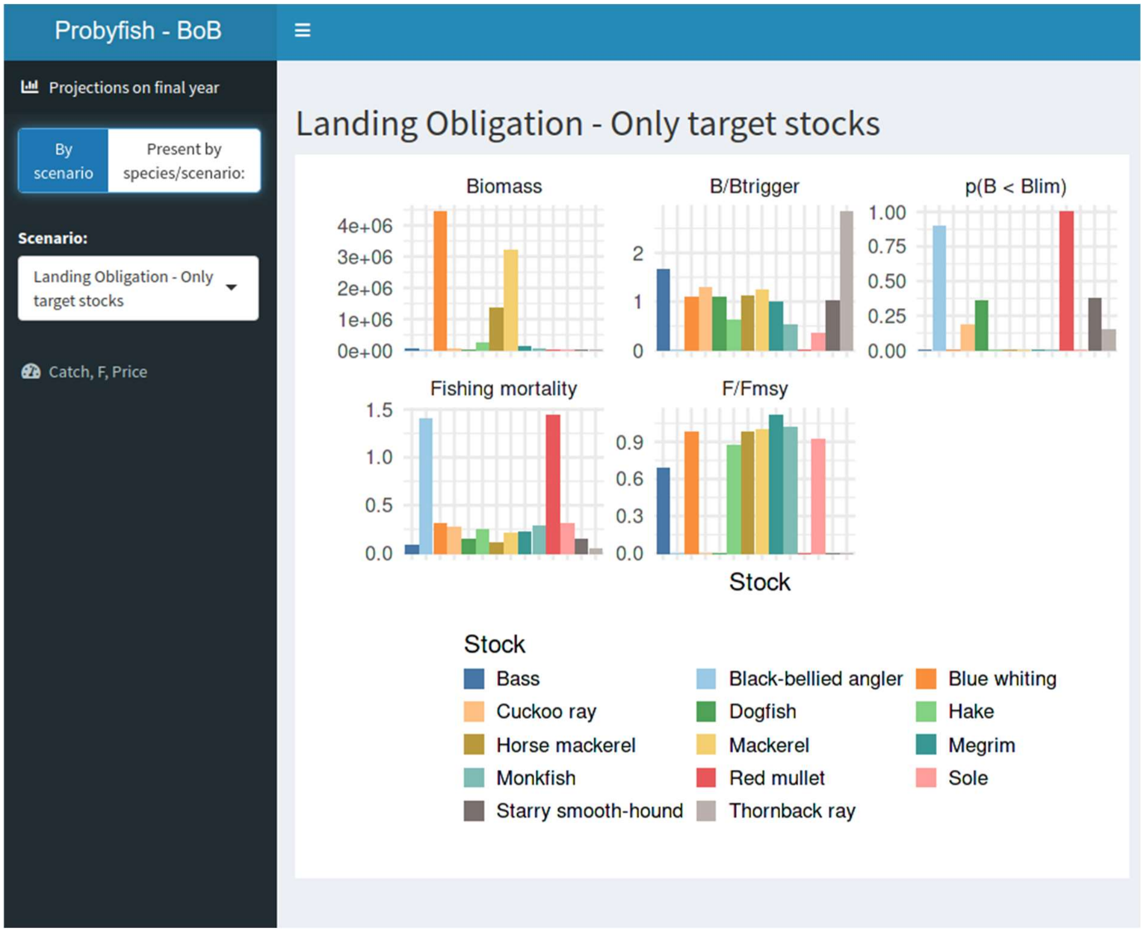

Figure 5. Final year projections for all species in one selected different scenario.

Figure 6. The second subpage of the "simple" prototype: the user selects the species. Her the catch by selected species and scenario are shown.

FLEBEIA Shiny

The FLBEIAshiny is a Shiny application to explore and present the output of FLBEIA multi-stock and multi-fleet simulation models.

FLBEIAshiny is a R package (R Core Team, 2020) with a twofold objective:

- Provide a tool that can be used by developers of multi-stock and multi-fleet simulation models to analyse and present the results of simulations,
- Provide a decision support tool that can be used by the stakeholders to analyse the trade-offs of management options.

FLBEIAshiny package is coupled with the FLBEIA model (Garcia et al., 2017a, b) and it launches a Shiny application using the output of FLBEIA directly or from a set of data frames obtained using the summary functions available in the package. However, the library can be used with the output of other models if the data is arranged in data frames with the same format as those produced by FLBEIA, but not necessarily with the same performance indicators.

When using the package from R, by default, the application opens an internet browser locally, that can not be exported elsewhere. However, there is an option to send the application to a Shiny server on the internet so the link can be shared publicly. The link https://aztigps.shinyapps.io/ProbyFish_BoB/ corresponds with the application produced by FLBEIAshiny package for the Bay of Biscay case study in ProbyFish.

The application has three main links, the '*Home'* link which opens a window with the logo of FLBEIA, the '*About'* link which leads to a window with a short description of FLBEIA and the case study presented in each particular case, and the '*Simulations'* link which is a drop-down menu to give access to the simulation results at different levels, 'Stock', 'Fleet', 'Fleet and stock', 'Fleet and metier', 'Fleet, metier and stock', 'Advice' and 'Summary' level (Fig. 7).

Figure 7. Main window of FLBEIAshiny application.

In each of these sections, different type of plots are available to provide a complete overview of the simulation results. In all the cases there is a menu in the left-hand side of the window to select the years, the stocks, the fleets, the scenarios, and the performance indicators to be plotted along with other plot depended graphical options. All the plots can be downloaded using the options in the left-hand side of the plot. The following plot types are provided for most of the levels:

- *Time series plots*: Time series of median values and confidence intervals for selected performance indicators are shown. In each panel the time series of selected scenarios are graphed and in the same layout panels for different stocks, fleets, metiers and indicators can be displayed. An example is provided in Fig. 8.

- *Stacked area plots*: Staked area plots are useful to explore the composition of some of the indicators as a function of stock, fleet, or metier. The composition can be shown in absolute value or in percentage. In each panel the time series of selected stocks, fleets or metiers are graphed and in the same layout panels for different scenarios and indicators can be displayed. An example is provided in Fig. 9.

- *Radar plots*: Radar plots facilitate the comparison of the indicators across scenarios in certain year. The edges correspond to scenarios and the lines to stocks or fleets. An example is provided in Fig. 10.

Figure 8. Time series plots of biomass and f2fmsy (ration between fishing mortality and Fmsy) for cuckoo ray (RJC) and dogfish (SYC) in different management scenarios.

Figure 9. Area plot with the catch composition in two different fleet dynamics scenarios (min = landing obligation and pre = no landing obligation).

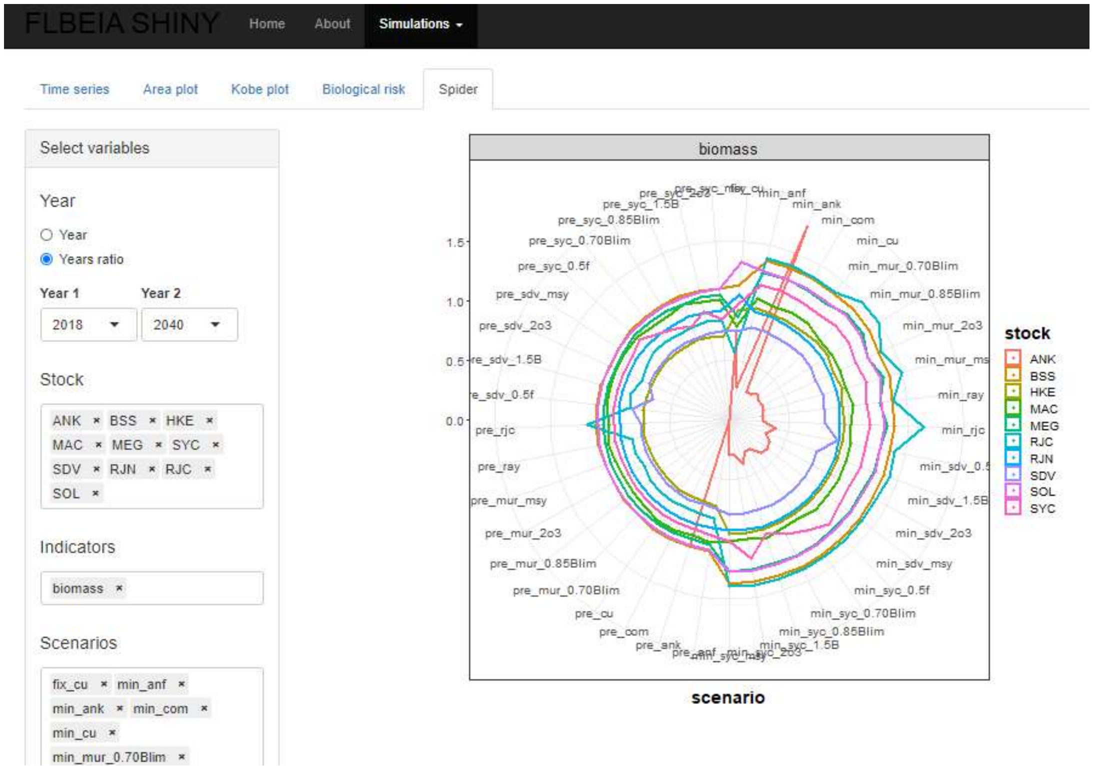

Figure 10. Radar plot of biomass for several stocks (lines) and all the management and fleet dynamics scenarios (edges) simulated in Bay of biscay case study.

A brief description of the content in each of the windows:

- *Stocks*: In this window the performance indicators at stock level are provided: `biomass`, `catch`, `discards`, `f` (fishing mortality), `landings`, `rec` (recruitment), `ssb`, `catch.iyv`, `disc.iyv`, `land.iyv` (interannual variability in catch, landings and discards), `Bpa`, `Blim`, `Bmsy`, `Fpa`, `Flim`, `Fmsy` (the probability of SSB and F being below (SSB) or above (F) the reference point), `ssb2Bmsy` and `f2Fmsy` (the ratio between SSB or fishing mortality and the MSY reference point). Apart of the plots described above, kobe plots are also provided in this section, they show the historical trajectory of the stock compared to the MSY reference points. An example of Kobe plot is provided in Fig. 11.

- *Fleets*: In this window the performance indicators at fleet level are provided: `capacity`, `catch`, `choke` (the probability that an stock will limit the activity of the fleet), `costs`, `discards`, `discRat` (ratio between discards and catch), `effort`, `fcosts` (fixed costs), `fep` (full equity profit), `grossSurplus`, `grossValue`, `gva` (gross value added), `landings`, `netProfit`, `nVessels` (number of vessels), `price`, `profitability`, `quotaUpt` (ratio between catch and quota), `salaries`, `vcosts` (variable cost) and `npv` (net present value).

- *Fleets and stocks*: This window provides performance indicators at fleet and stock level: `discRat` (ratio between discards and catch), `price`, `quotaUpt` (ration between catch and quota), `catch`, `discards`, `landings`, `tacshare` (the proportion of the TAC that corresponds to the fleet), and `quota`.

- *Metiers*: This window provides performance indicators at metier level: `effort` and `effshare` (the proportion of effort exerted in each metier).

- *Fleets, Metiers and stocks*: This window provides performance indicators at fleet, metier and stock level: `discRat` (ratio between discards and catch), `price`, `catch`, `discards` and `landings`.

- *Summary*: This window provides a summary plot for each of the scenarios using a polar plot (Fig. 12). The polar plot has four quadrants and in each of them a performance indicator is shown, SSB (top-left), fishing mortality (top-right), gross-surplus (bottom-left) and capacity (bottom-right). The performance indicators are shown for the selected stocks and fleets. The area corresponding to each performance indicator and stock or fleet represent the ratio between the value of the performance indicator in a specific year and the mean over a range of years, so it can be identified easily for which stocks or fleets the performance indicator has increased or decreased.

- *Advice*: Window that shows the performance indicators related with the advice at stock level: `catch`, `discards`, `landings`, `discRat` (ration between discards and catch), `quotaUpt` (ratio between catch and TAC), `tac`.

Figure 11. Kobe plot of the biomass trajectories for Black anglerfish (ANK), hake (HKE), Cuckoo ray (RJC) and dofish (SYC) for three different scenarios. The color of the area depend on the ratio between fishing mortality (F) and SSB and the corresponding MSY reference points.

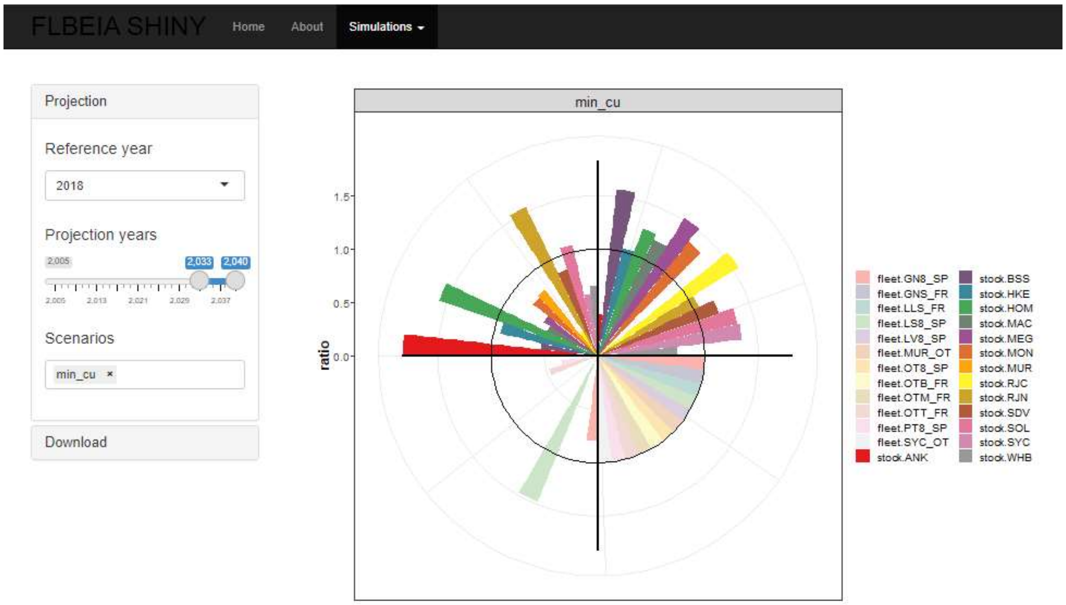

Figure 12. Polar plot to show the change in mean biomass (top-left), fishing mortality (top-right), gross surplus (bottom-left) and capacity (bottom-right) over 2033-2040 with respect to 2018 for all the fleets and stocks in 'min_cu' scenario.

7.4. Task 6.4 Developing the tool to identify the effect of additional management measures

Based on results from tasks 6.1 and 6.2, Probyfish produced an interactive visualization tool displaying DISPLACE model's simulation outcomes of spatial management measures applied to the Celtic Sea. The outcomes shown are derived directly from D4.4 and D4.5 applying spatial management (closed areas or an innovative Real-Time-Incentives system) to the Celtic Sea demersal mixed fishery. The modelling platform contributes to impact assessments on the social and economic impacts of alternative pathways to achieve environmental targets for exploited and non-exploited fish stocks and benthic habitats. The visualization tool to display outcomes was constructed using R-shiny, an interactive tool to display the results of the analyses concisely, and is available here: http://ono.dtuaqua.dk:8282/DISPLACE_CelticSea/

DISPLACE is a spatial bio-economic model for simulating individual fishing vessel agents' movement combined with an underlying spatial marine population dynamics model. The model comes with a Graphical User Interface to run simulation studies for spatial management and other default CFP management (TAC or effort regime, gear selectivity) and visualize the tracked biological, economic and social indicators as time series and corresponding spatial maps (Fig. 13). The DISPLACE software is open source and available at https://displace-project.org/blog/download/

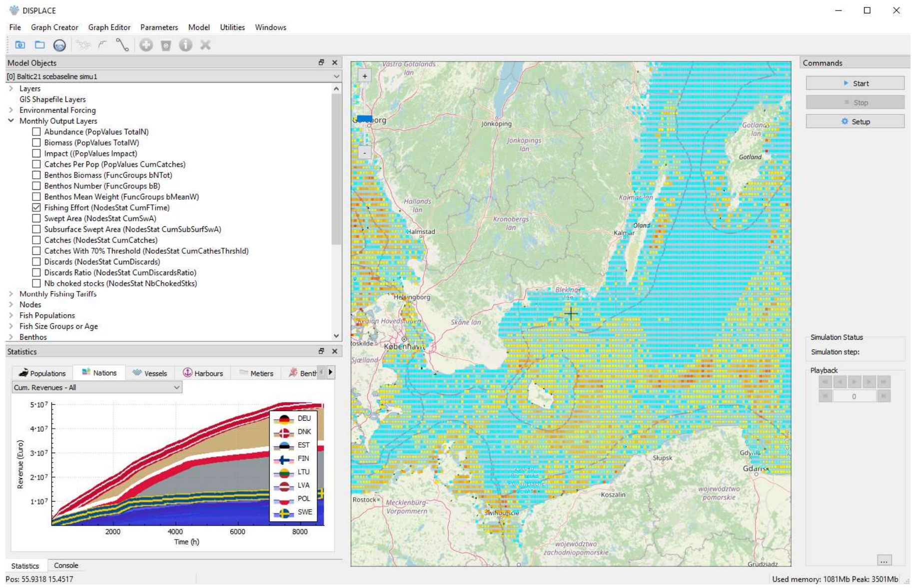

Figure 13. A snapshot of the DISPLACE graphical user interface used to run the simulation studies of fishing impacts vs economic return, here in a Baltic Sea context.

Beside the DISPLACE default graphical interface, a visualization tool was developed within the study in RShiny to display the stochastic simulation outcomes all at once. Necessary information is provided in the first panel (Fig. 14), including the geographical scope and the marine species list at work. A second panel enables the stakeholder to screen and compare the final average spatial allocation of realized catches, discards and fishing effort in the simulations (Fig. 15) visually. The last panel displays the outcomes in time series forms for biological, economic and social indicators, per management, biological, or fishery scenario, per species and aggregation of fleet-segments (Fig. 16). That said, contrary to the existing DISPLACE user interface, this shiny visualization tool is not for running simulations as such but to visualize pre-existing simulation outcomes. Running a representative row of spatial simulations is still time-consuming and demands specific computer power beyond what a single computer can provide for interactive use in a limited time.

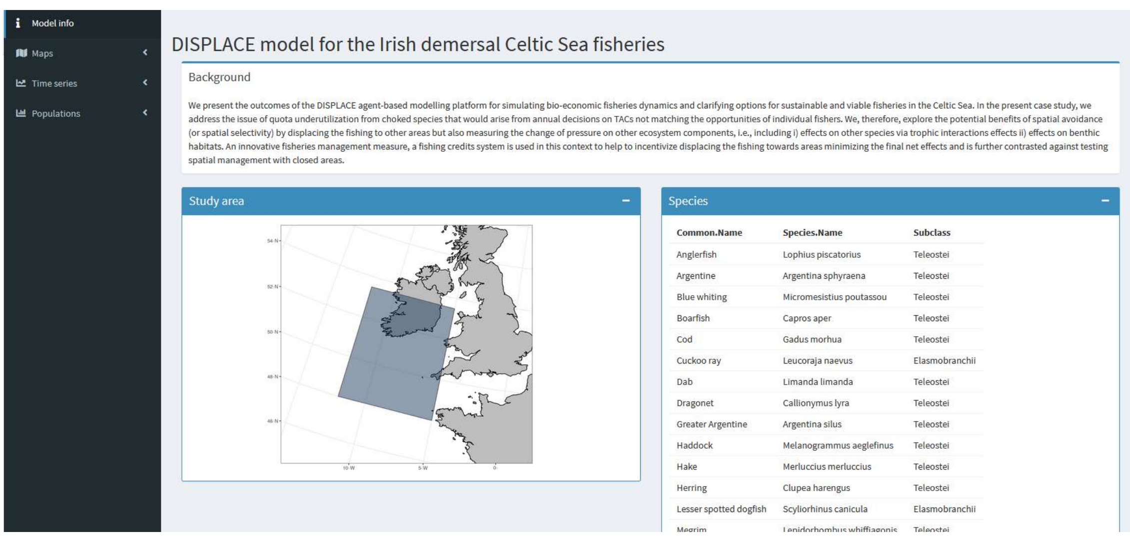

Figure 14. A snapshot of the DISPLACE shiny tool first panel that displays basic information about the application at work.

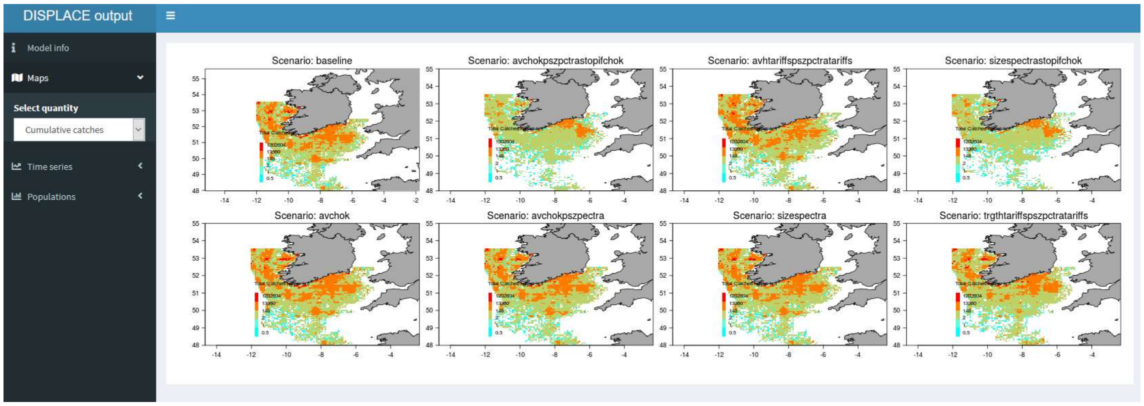

Figure 15. A snapshot of the DISPLACE shiny tool second panel, which displays final average maps of tracked indicators during the simulations for different scenarios testing.

Figure 16. A snapshot of the DISPLACE shiny tool last panel, which time series and 5-95% intervals for the tracked biological and economic indicators during the simulations for different scenarios testing, and different species and fleets' selections.

8. TASK 7. PROJECT MANAGEMENT AND DISSEMINATION

Under task 7, project management and communication was organized to ensure a smooth flow of the necessary information between tasks 1 to 6 and between the project and the outside world.

To reach this aim, task 7 delivered the following products:

D7.1 Meeting agenda and minutes from project meetings on project progress delivered to the European Commission (Progress report)

D7.2 Meetings with the European Commission

D7.3 Submission of reports to the European Commission

D7.4 Stakeholder Advisory Board meeting reports

D7.5 Financial management

Management within the project encompassed the organisation of annual physical and intermediate web based meetings internally in the project and the successful delivery of meeting reports to the partners in the project. At the meetings, focus was on ensuring smooth delivery of the necessary products both within the project (between tasks and subtasks) and from the project to the European Commission. The project ensured that all communication requirements described in the tender specifications were adhered to. To ensure that the final tool and the data and models on which it is based is relevant and acceptable to ICES, STECF and DGMARE, the project invited DGMARE staff, ICES and STECF members to represent these organs and advice the project along the way. Participation in ICES working groups and workshops was an integral part of the project. Correct financial management was also ensured and invoices submitted.

10. CONCLUSIONS

ProByFish completed all of the six tasks listed in the tender specification. The statistical analyses was able to divide the species caught in each region into target, valuable bycatch and collateral bycatch species in different métier and overall (Task 1). More species were categorized as valuable bycatch species rather than target species. The method did not account for whether the catch is above or below minimum levels for size and including this in a future analyses may lead to more species being classified as target species. The mixed fisheries management strategy evaluations demonstrated that target species TACs were sufficient to protect most bycatch species if the landing obligation is fully implemented (Task 2) and the reference level for sustainable exploitation are consistently defined (Task 5). The management strategy evaluations showed major differences in results between different implementations of the landing obligation. Under the current implementation, fisheries remained open but a variety of stocks, with cod as the most prevalent example in the Celtic Sea and greater North Sea, remained fished at levels above F_{MSY} and with a risk of impairing recruitment that exceeds 5%. In contrast, enforcing the landing obligation fully would safeguard the stocks, but would lead to a strong reduction in fishing effort and subsequent catches of most demersal fisheries, resulting in significant socio-economic impacts. The catch of most species was spread across all quarters, large areas and several fleets, rendering season, area or fleet based management measures less efficient (Task 3). The predicted effect of various measures targeted at reducing catches of choke species was mitigated by associated increases in effort as fishing became less effective for several species at the same time. While some species could be combined in grouped species TACs without loss of yield or precautionarity (turbot/brill in the North Sea, haddock/whiting in Celtic Seas) this was not the case for all groupings (witch/lemon sole in the North Sea, anglerfishes in the Bay of Biscay, rays in the Bay of Biscay)(Task 4). Gear specific, area and tariff measures were also investigated but generally led to increases in effort and resulting greater fishing mortality of other species. A possible exception to this was gear changes applied to the Nephrops fishery. In general, no scenarios predicted stock recovery of all stocks without an associated reduction in fishing effort. The results were visualized in a variety of interactive web based tools (Task 6).

A number of areas require further work:

- In relation to the classification of target and bycatch species, the method should be further developed to account for length of the fish caught.In relation to the modelling of species in FLBEIA, further work is needed to develop full assessments of bycatch species which may be candidates for TAC removal or group species TACs. Improved age and length distribution of catches at fleet level is likely to improve model accuracy.

- In relation to stock reference points, the proxies used in this study require further validation. If they prove not to be adequate, other proxies need to be developed.

- For evaluation of gear changes, information from more species would be required to provide firm advice. The impact of gear changes should always be evaluated considering the impacts of effort reallocation as this study showed that the effects of gear changes may well be counterintuitive if effort is increasing in reaction to the changes.

- For evaluation of closed areas, a proper review process of the models should be constructed before they are used for operational advice. The impact of area closures or other spatial management measures should always be evaluated considering the impacts of effort reallocation as this study showed that the effects on value per unit effort may be susbtantial.

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