



# Combining efforts to make maximum sustainable yields and good environmental status match in a food-web model of the southern North Sea



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## ABSTRACT

The southern North Sea is the stage of conflicting objectives of beam trawlers targeting flatfish; of shrimp trawlers fishing for brown shrimp with bycatch of juvenile flatfish; and of demersal trawlers, the main fishery on cod, a key predator of shrimp and other groups. To expose trade-offs between the fleets' objectives and to explore what a possible variant of a multispecies maximum sustainable yield (MSY) could look like, we parameterized an ecosystem model and subjected it to a range of different fishing effort levels of the three fleets. Long-term projections highlighted multiple fishing regimes that lead to catches of at least 30% of all focal stocks' single species MSYs at the same time. Trade-offs between the yields of shrimp fishers and demersal trawlers made higher simultaneous yields impossible. Besides optimizing multispecies catches, we identified effort regimes that satisfied a set of descriptors of good environmental status (GES). We found that GES can only be obtained through low efforts of beam and demersal trawlers, which cannot be aligned with our multispecies MSY variant without accepting trade-offs in fishing yields and/or conservation goals.

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## 1. Introduction

Within the North Sea, the shallow southern part (divisions IVb and IVc of the International Council for Exploration of the Sea, ICES) differs from the north (division IVa) through the importance of flatfish (particularly European plaice, *Pleuronectes platessa* and sole, *Solea solea*) and brown shrimp (*Crangon crangon*) in species and catch compositions. Policies designed to manage fisheries for the two groups face conflicting objectives, as (a) fishers barely fish one species alone, but generally extract several species and life stages together (*technical interactions*; Miller and Poos, 2010; Rijnsdorp et al., 2007), (b) fished species prey on other target and non-target species or are consumed themselves (*multispecies issues*; Temming and Hufnagl, 2014; Welleman and Daan, 2001) and (c) fishing has direct and indirect effects on the marine environment (Gislason,

1994; Jennings and Kaiser, 1998) – and vice versa (Hiddink et al., 2011; van Denderen et al., 2013). As such, young flatfish die as bycatch in shrimpers' nets (Berghahn and Purps, 1998); initiatives to recover European cod (*Gadus morhua*) may compromise yields of other species through predation and competition (Temming and Hufnagl, 2014); and other, more vulnerable species like turbot (*Scophthalmus maximus*) and spurdog (*Squalus acanthias*), are affected by extractions through fishing nets (Kerby et al., 2013). All above mentioned points underpin the necessity of ecosystem-based multiannual plans as expressed by the reformed European Union's common fisheries policy (CFP; Article 9, Regulation (EU) No. 1380/2013). Science should explore and inform on negotiation spaces in the form of a set of fishing policy options that lead to good results for all sectors (e.g. by providing yields close to the maximum sustainable yield, MSY) while minimizing the probability of bad outcomes for stakeholders and the marine environment. Thus, in this study, we want to:

- Parameterize an ecosystem model of the southern North Sea that is calibrated to historical records of biomasses and

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landings and plausibly reproduces population dynamics of the species included (Sections 2.1–2.3 and Appendix).

- Identify fishing policy options that lead to high yields for the three major fleets of the southern North Sea – beam trawler, brown shrimp trawler and demersal purser and seiner – simultaneously (Section 2.4).
- Examine how these three fleets would have to agitate to reach a good environmental status (GES) of the marine environment (Section 2.5).
- Test if both policy objectives, MSY and GES, are compatible or, if not so, which trade-offs in fishing yields and conservation goals would have to be accepted to bring both in acceptable accordance (Section 2.6).

Identifying and presenting a three-fleet negotiation space, in particular for fisheries on the southern North Sea's main commercial species cod, plaice, sole and brown shrimp, is a problem yet unsolved. ICES multispecies considerations for the North Sea stocks present trade-offs between fishing targets species-wise, as effect of each stock's target fishing mortality ( $F$ ) on spawning stock biomasses (SSB) and yields ( $Y$ ) of the very same and other stocks (ICES, 2013). This representation is well suited to comply with the current management maxims of target quotas and  $F$ s. However, it does not consider that  $F$ s may well stem from different fleets, and thus makes it difficult to account for inter-fleet interactions explicitly. Differently so in the work of Mackinson et al. (2009b) who, inspiring the idea presented in this paper, show yields of three demersal North Sea roundfish stocks as a function of the interaction of the two main fleets targeting them. Of any similarly computed or presented three-fleet negotiation space as the one presented here, however, we are unaware. Neither do we know of any multispecies or ecosystem model specifically designed or sufficiently parameterized to address conflicts between local fisheries for brown shrimp and mixed flatfish in an ecosystem context in the southern North Sea (see also Miller and Poos, 2010).

## 2. Methods

### 2.1. A southern North Sea food web model

The 'southern North Sea' as defined for this study, comprises ICES areas IVb and IVc. It is bordered by the coasts of France, Belgium, the Netherlands, Germany, Denmark and the United Kingdom. The study area spans between 51° and 56° North and 4° West and 9° East and covers 345,874 km<sup>2</sup>. The southern North Sea is a shallow sea on the European continental shelf of around 50 m depth, with maximum depths of 125 m, and is characterized by a strong terrigenous influence. It thereby differs from the northern part of the North Sea (IVa) with an average depth below 100 m and maximum depths down to 400 m, where Atlantic influence prevails.

We constructed a food web model of the southern North Sea using the Ecopath with Ecosim (EwE) software version 6.4.11414.0 (Christensen et al., 2008). The EwE software and model framework is designed to quantify the pools and flows of biomass and energy in an ecosystem and equipped to reveal the system's structure and dynamics (Christensen et al., 2008; Christensen and Walters, 2004). In essence, it resembles an accounting system for the food web. Following the assumption of mass-balance – that whatever is in the system must come from the system and stay in the system – it allows closing gaps in knowledge about the biomass, production, consumption and removal of some entities of the ecosystem by predators and fishers through knowledge of these parameters for other organisms. Also, single missing parameters for one group of organisms can be extrapolated if the other parameters for this group are known. All living components of the ecosystem are

represented in biomass 'pools', the functional groups (FGs). These groups are linked through feeding relationships and can be composed of a single species or groups thereof that form an ecological guild. The production of each functional group in EwE is expressed by Eq. (1), which terms can be split into predation mortality, fisheries removals, net migration, biomass accumulation and other mortality.

$$B_i \cdot \left(\frac{P}{B_i}\right) = \sum_{j=1}^n B_j \cdot \left(\frac{Q}{B}\right)_j \cdot DC_{ij} + Y_i + E_i + BA_i + \left(\frac{P}{B_i}\right) \cdot B_i(1 - EE_i) \quad (1)$$

Parameters are  $B_i$ =biomass of functional group  $i$ ;  $P/B$ =production per unit of biomass of the functional group  $i$ ;  $(Q/B)_j$ =consumption per unit of biomass of the predator  $j$  of biomass  $B_j$ ;  $DC_{ij}$ =proportion of prey  $i$  in the diet of predator  $j$ ;  $Y_i$ =exports from the system as fishery catches;  $E_i$ =net migration; and  $EE_i$ =ecotrophic efficiency of the functional group  $i$ . Energetic costs for the respective groups are described by Eq. (2):

$$\text{Consumption } (Q) = \text{production } (P) + \text{respiration } (R) + \text{unassimilated food } (U) \quad (2)$$

Equations, algorithms and assumptions beyond these two Ecopath master equations can be found in Christensen and Walters (2004) and Christensen et al. (2008).

Our food-web models 68 functional groups rang from planktonic and benthic invertebrates via commercial species targeted by the eleven fleets embraced to sharks, rays, marine mammals and seabirds. Commercially important species were implemented in *stanza groups*, i.e. divided into juveniles and adults with respective ontogenetic growth and diet parameters, to extend the detail of their population dynamics (Table A1). A list of all functional groups and a taxonomic scheme of assignment of non-vertebrate species to functional groups can be found in Appendix A. The initial static (Ecopath) version of our model represents the southern North Sea ecosystem at the annual average state in 1991, as this is the year for which most information on fish diets is available (ICES 'year of the stomach'). Fig. 1 shows a representation of that food-web, in which the main groups of this study and mass flows between them are highlighted.

Based on the Ecopath 'snapshot of the food-web' in 1991, we parameterized a time dynamic Ecosim version of the system. Ecosim simulates the effects of fishing and environmental forcing parameters over time, in our case the period 1991–2010. Changes in the biomass of each pool are expressed by

$$\frac{dB_i}{dt} = g_i \sum_j Q_{ij} - \sum_j Q_{ij} + I_i - (M_i + F_i + e_i)B_i \quad (3)$$

where  $dB_i$  is the growth of biomass of functional group  $i$ ;  $g_i$  is its growth's net efficiency, i.e. production/consumption;  $I_i$  is immigration rate; while  $e_i$  is emigration rate;  $M_i$  represents the non-predation natural mortality rate; and  $F_i$  is fishing mortality rate.

### 2.2. Input data

We collected estimates of biomass, production and consumption rates and information on diet composition from ICES single- and multispecies stock assessments (HAWG, 2013; WGNSSK, 2013; WGSAM, 2014), survey data (ICES International Bottom Trawl Survey, IBTS); ICES working groups (WGCRAN, 2012), the ICES 'year

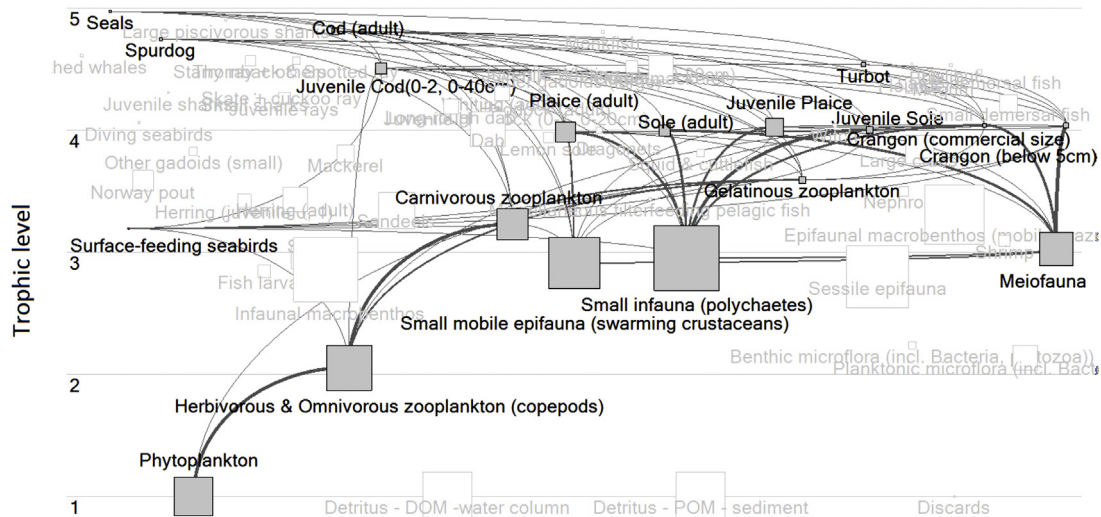


Fig. 1. Flow diagram of the southern North Sea food-web. Key species and flows relevant for this study are highlighted. Rectangle size indicates the biomass of the functional group and the thickness of the lines that represent predator-prey relationships is proportional to the importance of each respective flow.

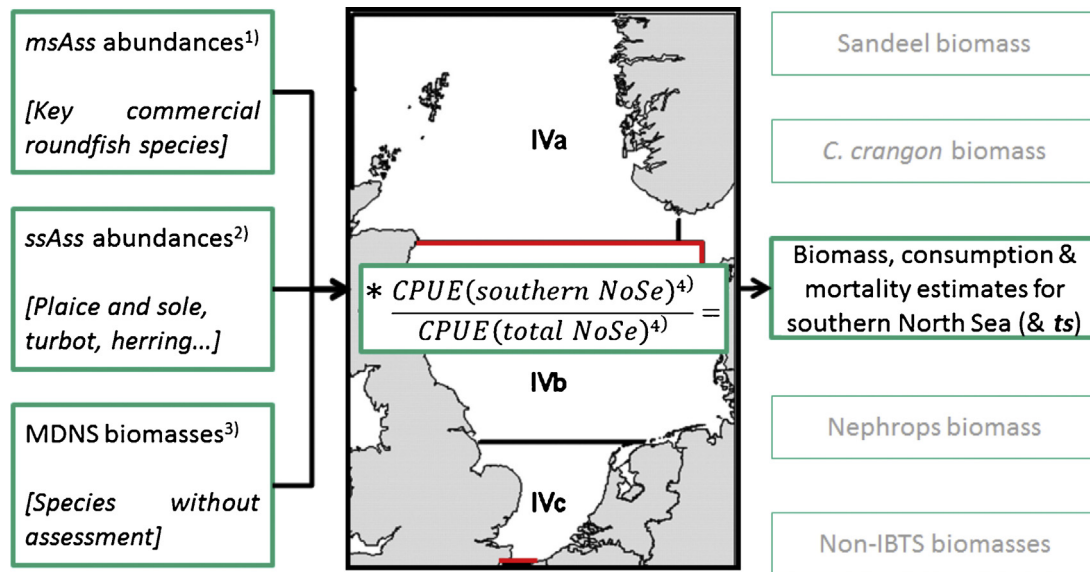


Fig. 2. Schematic representation of how biomasses for the southern North Sea EwE model were calculated. msAss: multispecies and ssAss: single species stock assessment. MDNS: Whole North Sea EwE. (1) Stochastic Multispecies Model (SMS). ICES WGSAM 2014 (2) XSA, Extended Survivors Analysis. ICES WGNSSK 2013 (3) North Sea EwE. Mackinson & Daskalov, 2007. CEPAS Sci. Ser. Tech. Rep. No. 142. (4) International Bottom Trawl Survey (IBTS). [http://datras.ices.dk/Data\\_products/Download/Download\\_Data\\_public.aspx](http://datras.ices.dk/Data_products/Download/Download_Data_public.aspx). Transparent boxes were calculated independent of IBTS data.

of the stomach' sampling project (Hislop et al., 1997) and peer-reviewed literature (Fig. 2). Where we could not obtain more local data, we referred to the Mackinson and Daskalov (2007) whole North Sea EwE model and updates thereof (Heymans et al., 2011; Mackinson et al., 2009a; WGSAM, 2011); with the underlying assumption that southern North Sea parameters do not differ to a critical extend. See Appendix A for a detailed overview of data sources and methods used to parameterize the various functional groups.

Eleven fishing fleets were implemented in our model. Depending on the gear used and the species targeted we separated, in alignment with the European Union data collection framework, between demersal trawl and seine; beam trawl (targeting flat-fish); sandeel trawl; pelagic trawl; drift and fixed nets; nephrops trawl; gears using hooks; brown shrimp trawlers; dredges; pots and others. For a gear and fleet classification see Appendix B, Table B1.

We consulted three different data sources to estimate fisheries' landings: The ICES EUROSTAT catch statistics (<http://info.ices.dk/fish/CATCHSTATISTICS.asp>, data downloaded 2 December 2012) ranging from 1950 to 2010 and landings data of the European Commissions' Scientific, Technical and Economic Committee for Fisheries (STECF, Rätz and Mitrakis, 2012; Appendix 08). The reason for using two different data sources was that EUROSTAT holds historic landings back to 1991, but does not inform about the particular gears the catch was taken with, while the STECF landings data is reliable 2009–2011 only, but offers the advantage of holding landings assigned to specific gears and mesh sizes. The catches of the brown shrimp fleet are from the ICES working group on crangon fisheries and life history (WGCAN, 2012). All landings and computation techniques are given in Appendix B.

Assuming the ratio of discards to landings to be comparable between the entire North Sea and the southern part, we calculated discards for our model based on Mackinson and Daskalov (2007)

and our localized landings. For plaice, sole, cod, whiting, turbot and brill, however, discard ratios were adopted from Appendix 2 in Rätz and Mitrakis (2012). We combined our landings calculated as above with discard ratios per species/fleet combination therein. According to WGCAN (2012), “the mean discard fraction of brown shrimp amounted to  $49.9\% \pm 10.6\%$  of the total brown shrimp catch in weight” (p. 51). Discards of non-crangonid shrimp are set to zero as we assume no catches of these species. All discards per functional group and fleet are summarized in Appendix B, Table B3.

With the goal of this study to assess the effect that the various fleets have on stocks and the ecosystem nowadays, we sought to parameterize the fleets with catch patterns that resemble the situation in 2010, rather than 1991. The implication of that is that in our 1991–2010 hindcast simulation the total amounts caught correspond to historic time series of that period, but that the distribution of species on the fleets' catches is incorrect prior 2010. A complete description of sources and calculation methods for landings and discards can be found in Appendix B.

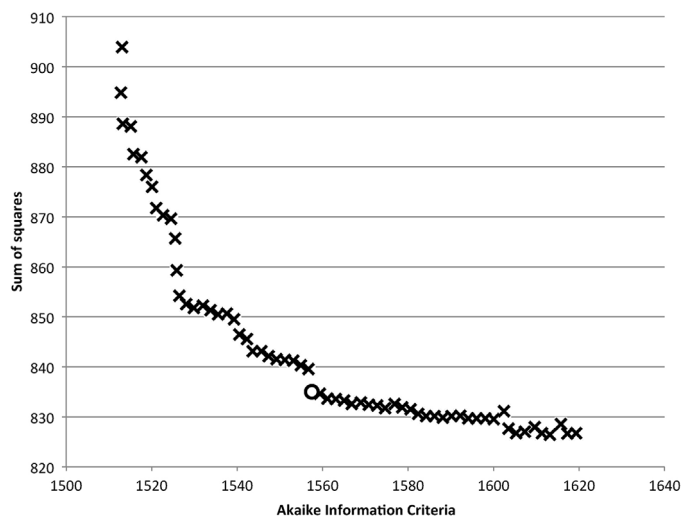
### 2.3. Fitting and calibrating the Ecosim model

Exploring fishing policy options in the southern North Sea requires the Ecosim model's population dynamics and responses to fishing to be as realistic as possible, where realism can be seen as the ability to reproduce patterns observed in the past. Primal instrument for this was to use Ecosim's non-linear fitting procedure. We fitted model predictions of biomass and landings to time series data across all trophic levels for the period 1991–2010, during which period the model was driven by our time series data of fishing effort and, in some stocks, fishing mortalities. These time series, again, represent our effort to collect and calculate as many, as precise and as locally rooted measures of pressure and state variables as possible.

The Ecosim fitting procedure searches for vulnerabilities ( $v$ 's) of selected predator groups that lead to the best representation of all groups. In Ecosim, which bases on the *foraging arena* hypothesis (Walters and Christensen, 2007; Walters et al., 1997), each prey pool is split into a fraction accessible to predation of a given predator, whilst the rest of the population remains non-vulnerable. Ecosim's vulnerability parameters determine the flow between these two pools and thus the flow between prey and predator. The default value for vulnerabilities of prey to a predator is two, typifying mixed control of the predator group. Larger values determine the predator to be top-down controlled, while values closer to one represent a bottom-up driven predator pool (Christensen et al., 2008).

Our goal when fitting the Ecosim model was not necessarily an utmost reduction of deviations from observed data. Instead, we followed a parsimonious approach, i.e. we aimed to outbalance better fit (as reduction in the sum of squared deviations (SS) of modelled log biomasses from log predicted biomasses) against the number of parameters estimated when fitting (number of predator groups to search vulnerabilities for; consumption forcing functions and primary production anomaly). Our 'best fit' was thus one with which the Ecosim model describes the data notably better than if any parameter was left out, while adding any further parameter would benefit SS reduction only marginally while leading to a higher risk of over parameterization (as represented by Akaike's information criterion (AIC) that is used in the Ecosim fitting interface to display and sanction against any further parameter added to explain time series data).

Using Ecosim's routine to check the *sensitivity of SS to vulnerabilities*, we identified which predator's vulnerabilities to be changed led to the highest contribution in the overall goodness of fit. This sensitivity check was performed one group after the other, and the resulting overall SS was recorded for each such fitting. Initially,



**Fig. 3.** Sensitivity of the sum of squared deviations (SS) and Akaike's information criterion (AIC) to fitting vulnerabilities. Marked with a circle is the selected fitting scenario of 32 groups, after which adding further groups to the fitting increases AIC more than it reduces overall SS.

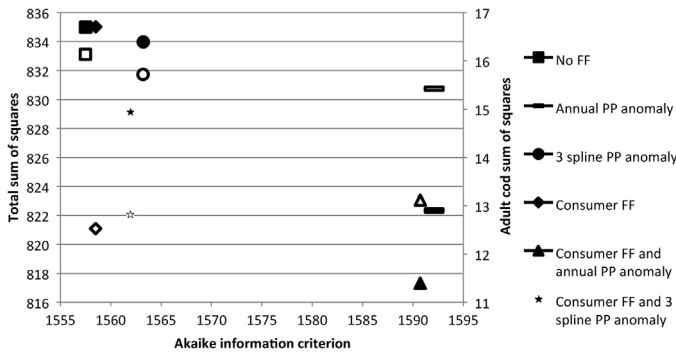
adding any other functional group to the fitting greatly benefited the reduction of total deviation from time series while adding relatively little to the fitting's AIC. With more and more FGs added, however, a point was reached at which adding more groups to the fitting only marginally improved the total deviation from observed data, while ever increasing AIC. For our model, this was the case for a pool of 32 functional groups (Fig. 3). These represent our selection of groups to fit vulnerabilities to for the most parsimonious approach. The selected groups ranged across all trophic levels, from marine mammals to copepods (Table D1 in Appendix D).

Up to this point, Ecosim was parameterized to explain historic patterns in biomasses and landings through fishing and trophic relationships alone. We did, however, test for potential environmental parameters to influence these trophic interactions as well. These can either apply to predator-prey interactions or affect primary production (PP).

Screening the literature for trophic interactions impacted by environmental factors in the study area pointed towards cod recruitment being negatively correlated with water temperature in the North Sea (O'Brien et al., 2000), supposedly due to a temperature induced change in plankton dynamics that affects food availability for larval cod (Beaugrand et al., 2003). To identify a suitable forcing function (FF), we sought correlation of cod recruitment with a set of environmental, particularly water temperature related indices: NAO, North Atlantic Oscillation; AMO, Atlantic Multidecadal Oscillation; average sea surface and bottom temperature in the southern North Sea from Núñez-Riboni and Akimova (2015); and HADSST, Hadley Sea Surface Temperature. We used the annual mean AMO index, which is basically mean sea surface temperature in the North Atlantic, as a proxy for North Sea sea surface temperature, as this index, of all tested, showed the strongest correlation with decreases in cod recruits 1991–2010. Note that we did not test for cod recruitment's correlation with plankton indices, as done by Beaugrand and Kirby (2010), because plankton is an intrinsic element of our model.

The Ecosim *fit to time series* routine allows estimating a PP anomaly that, additional to changing vulnerabilities and including consumer forcing functions, minimizes deviation of the model predictions from the observed data. It is based on the a priori assumption that changes in the food web, as represented by the time series' biomasses and landings, are importantly related to changes in primary production. There is reason to assume this to



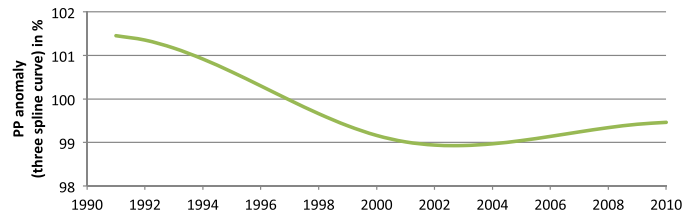


**Fig. 4.** Diagnostics of different strategies of including a primary production (PP) and/or a consumer forcing function (FF), solely or combined, in fitting Ecosim predictions to observations. Respective total system sums of squares are represented by filled, sum of squared deviations for adult cod by open markers.

hold relevance for many marine systems (Steinacher et al., 2009), including the North Sea (Mackinson, 2013). We tested different forms of this potential PP anomaly, either annually estimated ones or such generalized as a spline curve.

Both consumption and PP forcing functions' contribution to reducing total SS were tested, solely or in combination. For exploratory reasons, we also recorded SS of adult cod. Searching for a PP anomaly function, smoothed as a curve with three splines, resulted in slightly lower SS than the no FF fitting scenario, while annual PP anomaly estimates substantially increased AICs (filled marks in Fig. 4) and raised the number of parameters to be estimated from 32 to 51. Applying annual AMO values (as a North Sea surface temperature proxy) as consumer forcing function to juvenile cod led to no improvement in total SS, however, it did so for the fit of adult cod (open marks in Fig. 4). Only when consumer and PP forcing function in the form of a three spline PP anomaly were combined, we found an acceptable balance between decreasing total SS against increasing AIC and the number of parameters (short bar in Fig. 4). The resulting PP forcing function describes subtle deviations from the standard value 1 only and is depicted in Fig. 5.

Once the model was fitted by attempting the closest approximation of observed biomass and catch trajectories throughout the modelled time period, our model was calibrated. Other than fitting, calibration meant that we used information beyond that included in the model database to increase the plausibility of model simulations, even if that additional tuning should impair the fit to observed data points. Particularly, we referred to longer term data on recruitment behaviour from single species assessments (WGNSSK, 2013) and multi-species considerations (ICES, 2013) to ensure that Ecosim

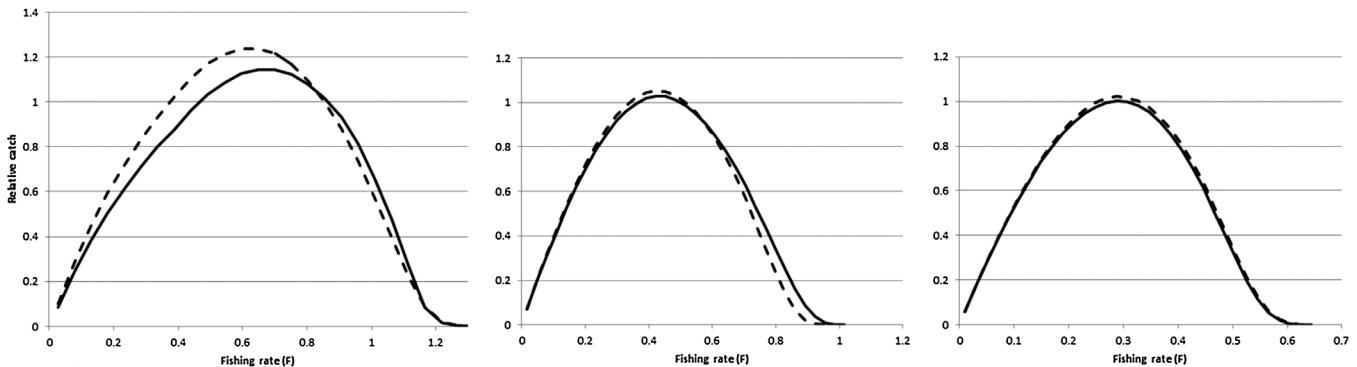


**Fig. 5.** Primary production anomaly estimated by Ecosim for the selected fitting scenario (with annual AMO values (as a North Sea surface temperature proxy) as consumer forcing function for juvenile cod).

reproduced the stock-recruitment behaviour of the key commercial stocks right. Cod, plaice, sole and brown shrimp make up the most important contributions to fisheries landings and profits in the southern North Sea, and are thus the scope species of this study. Calibrating the Ecosim model ensured that the equilibrium yield of stanza species peaks at a certain fishing mortality rate ( $F$ ). That peak marked the  $F$  associated with this single species' maximum sustainable yield ( $F_{msy}$ ) in our modelled system. We sought for the model to show highest single species yields at levels of  $F$  in the range of assessments' or multispecies advices'  $F_{msy}$  for the respective multi-stanza species (ICES, 2013; WGNSSK, 2013).

Beyond determining single species equilibrium yields, we calibrated the model such that compensatory responses in recruitment would resemble stock-recruitment behaviour in assessments, analogue to the approach outlined in Mackinson et al. (2009b): Based on biomass estimates from WGNSSK (2013), we calculated the ratio of recruits' ( $R$ ) to spawning stock biomass (SSB) for each year and used these ratios' median across all years to compare the degrees of compensation in recruitment between species. The aim of calibrating our Ecosim models' stock-recruitment was that simulated  $R/SSB$  medians for plaice and for sole would relate to simulated  $R/SSB$  of cod in a manner similar to how they relate to each other according to stock assessments (Fig. 7). While for sole this could be well achieved, plaice in our model remain more productive than according to stock assessments. Any further cuts in plaices' productivity, however, lead to erratic behaviour of Ecosim runs.

Calibrating Ecosim to produce both credible  $F_{msy}$  and stock-recruitment behaviour required changes to be made to the model's vulnerabilities fitted as described above. These changes are summarized in Table 1. Note that they may lead to historic time series being less well represented by the model than it was the case in the initial fitted version, but that population and exploitation dynamics are better represented in the calibrated model. Our focus on policy explorations let us decide for the latter variant.



**Fig. 6.** Ecosim equilibrium relationships between fishing mortality and relative catches of cod, plaice and sole. Solid lines represent results when all other groups of the food-web were allowed to vary in biomass as response to the assessed species being fished (full compensatory assessment sensu Walters et al., 2005). Broken lines represent results when all but the investigated species biomasses' were held constant (stationary system).

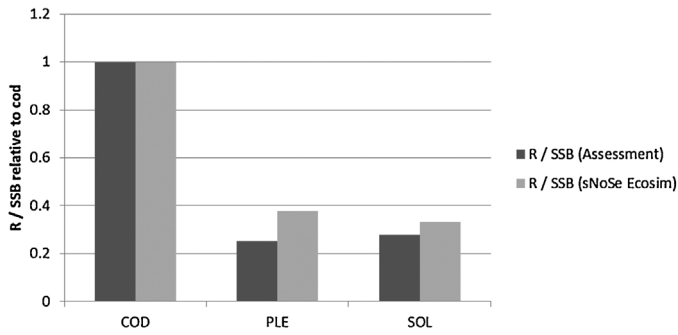


Fig. 7. Ratio of median recruits biomass against spawners biomass (R/SSB), relative to that of cod.

2.4. Evaluating fishing yield optimization scenarios

With the aim of testing the state of the southern North Sea food-web and its exploited stocks as a function of all possible combinations of fishing efforts (and associated fishing mortalities) by demersal, beam and shrimp trawlers, we created time series of varying efforts of the three respective fleets – ranges from zero to three fold 2010er efforts for beam and demersal trawlers, with a step size of 30%; and from zero to six fold for shrimpers, with a 60% step size. All eight other fleets were kept at the 2010 level.

Table 1  
Changes to fitted vulnerabilities of stanza groups for model calibration. All other vulnerabilities remained as fitted (see Appendix D).

Predator functional group	$\nu$ fitted	$\nu$ calibrated
Juvenile cod	1.00	10.00
Adult cod	1.00	3.50
Juvenile whiting	10382.13	10.00
Juvenile haddock	1.00	1.10
Adult haddock	1.00	1.10

As we had used the  $F$  of main commercial groups as forcing variables when fitting and calibrating Ecosim, we also did so for the policy evaluation time series. For each effort combination, we computed corresponding  $F$ s based on partial fishing mortalities per fleet exerted on the respective stocks in our calibrated 2010 Ecosim run. In the such composed effort and  $F$  time series, each fishing regime sustained 30 years, a period during which we had found the stock dynamics to reach an equilibrium state in prior testings. We ran each time series in Ecosim, with no further forcing functions loaded. As Ecosim simulations can last 500 years at most, we had to split the effort scenarios onto multiple time series to load and run in Ecosim. After each run, we extracted the annual average state variables biomass, catch and fishing mortality of each FG, along with the corresponding forcing variables as beam trawl, shrimp and demersal fleets' efforts, using the CEFAS results extractor plugin.

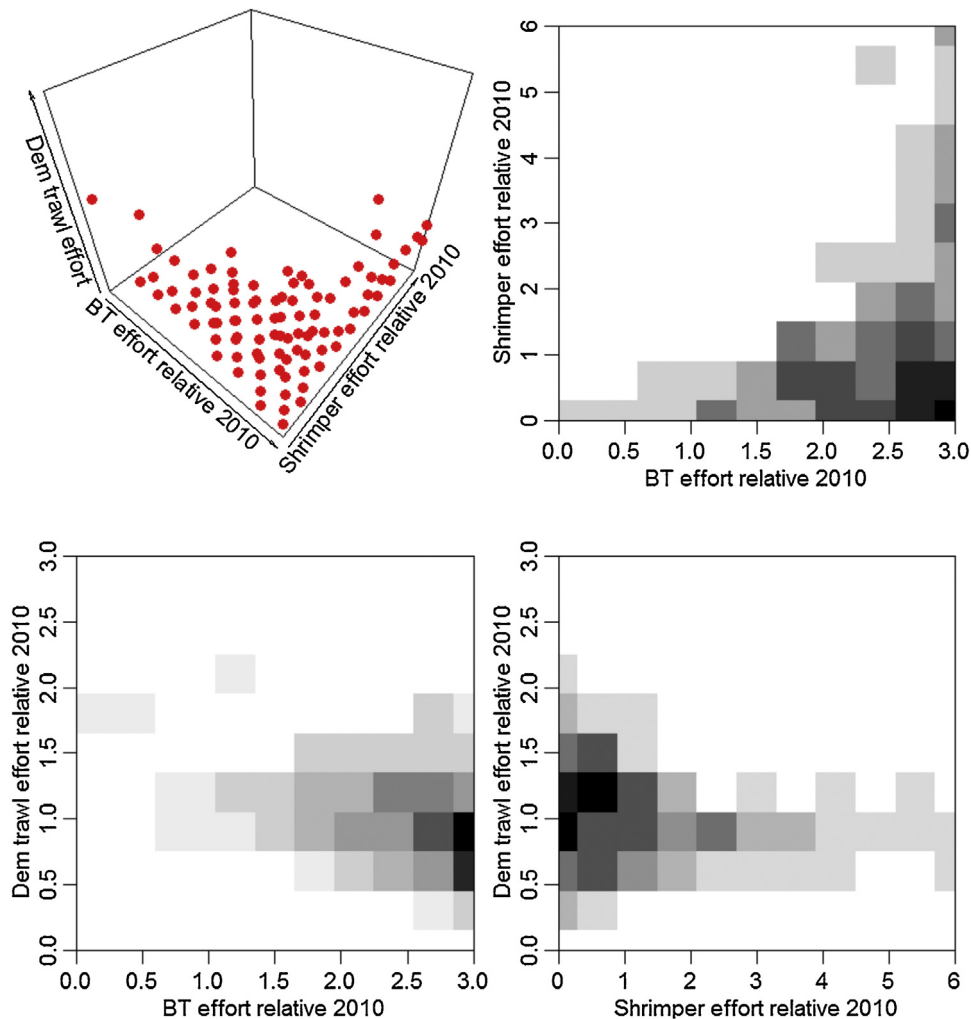


Fig. 8. Spheres indicate effort combinations of demersal, shrimp and beam trawlers (BT) that lead to long-term prediction of catches of cod being 80% or more of the maximum possible catch of that species. Shades are projected on the respective planes to assist visual perception. The shades of grey correspond to the amount of overlaying spheres.

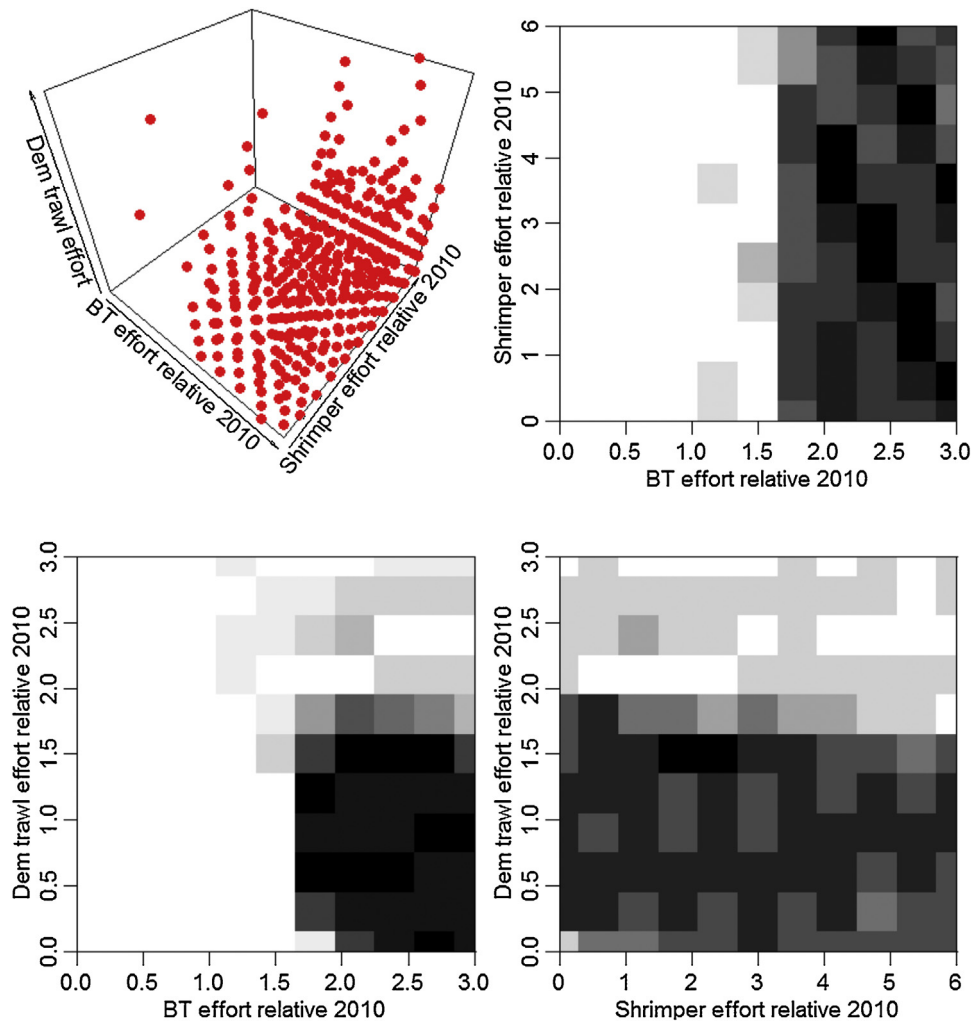


Fig. 9. Effort combinations that lead to long-term prediction of plaice catches being 80% or more of the maximum possible catch of that species.

We then picked the values of the state variables biomass,  $F$ , and catch for all FGs at the equilibrium of each fishing regime.

We defined an ‘acceptable outcome for all fleets’ and thus a negotiation space for the southern North Sea fisheries as the result of effort regimes that lead to all scope species being extracted at a certain percentage of their respective single species MSYs at the same time. In our particular case, this single species MSY variant was the amount caught of a certain species if all fleets’ efforts were optimized for that one goal only. That could include cases in which fleets not targeting the particular species either reduced efforts to allow higher forage species biomasses, or cases where non-targeting fleets increased efforts to cut down predators or competitors of the focal species. This single species MSY variant translates to the maximum of a respective species caught in any of the tested effort combinations.

### 2.5. Identifying good environmental state scenarios

Beyond identifying outcomes of high fishing yields, we sought effort regimes that result in a good environmental status of the ecosystem in long term predictions. For our study, rather than testing a complete set of descriptors of GES as demanded by the European Union’s Marine Strategy Framework Directive (MSFD), we focused on a smaller selection of descriptors. We deemed our GES proxy as satisfied under the following conditions:

- Biomass of adult plaice and sole should be above the target biomass set as a precautionary approach ( $B_{pa}$ ) (WGNSSK, 2013). We referred to the entire North Sea  $B_{pa}$ , as the vast majority of the two stocks reside in our model area.
- Cod  $B_{pa}$  for the entire North Sea is given as 150,000 t (WGNSSK, 2013). Between 1991 and 2010, an average annual 25.9% of the whole SMS biomass of adult cod was in our model area. We thus adopted a localized cod  $B_{pa}$  threshold of 38,865 t.
- Turbot  $F$  is above precautionary proxy based on  $F_{0.1}$ , relative to the average of the time series in the 2014 assessment for 2010:  $F=0.22$  (WGNSSK, 2014).
- $F$  of spurdog below the  $F_{MSY}$  proxy of 0.029 suggested by the ICES working group on elasmobranch fishes (WGEF, 2014).
- The large fish indicator (LFI), i.e. the biomass contribution of demersal fish with a common length >40 cm to the total biomass of demersal fish, is larger 30% (Greenstreet et al., 2011).

Note that we used  $B_{pa}$  instead of  $F$ -related indicators for sole, plaice and cod, as the latter, such as our original threshold candidate  $F_{msyUPPER}$  from WKMSYREF3 (2014), stem from single species models. Single species reference  $F$  values are hard to align with ecosystem models’  $F_{msy}$  estimates (Walters et al., 2005), while this is less of an issue for those biological reference points that are biomass related.

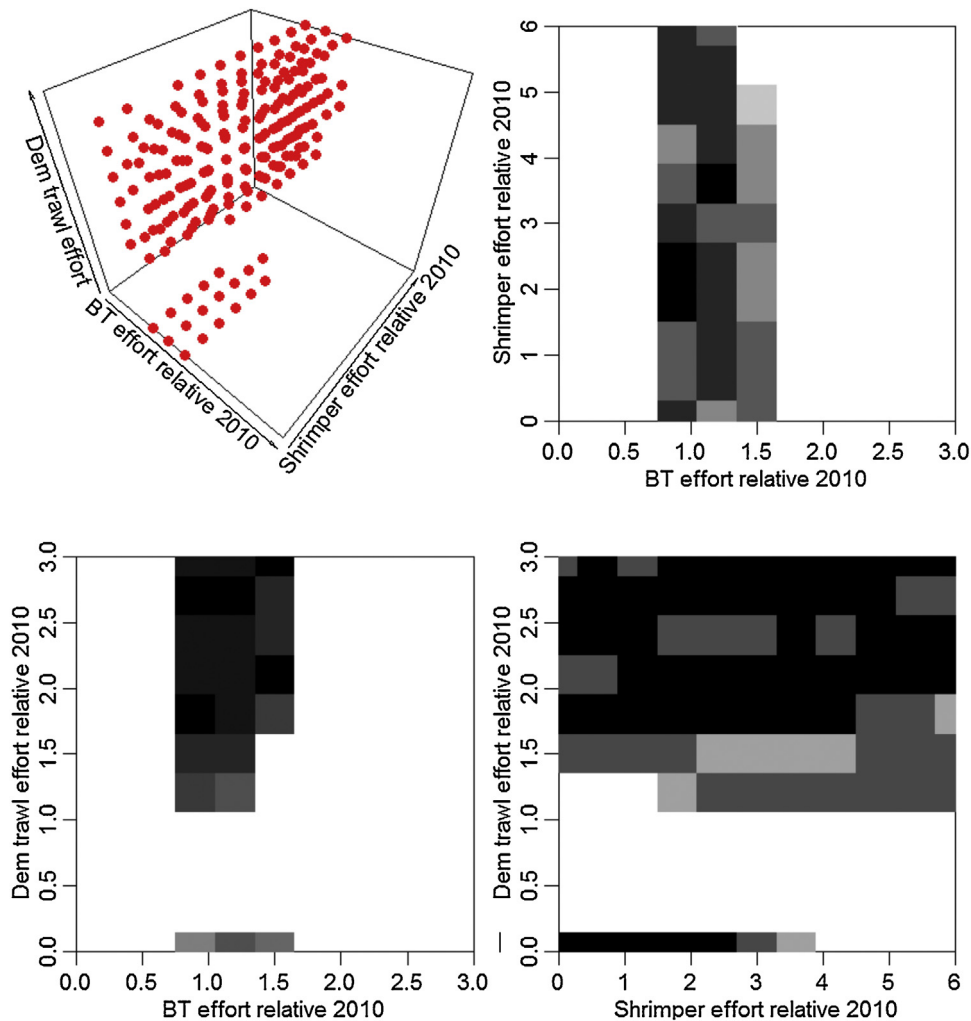


Fig. 10. Effort combinations that lead to long-term prediction of sole catches being 80% or more of the maximum possible catch of that species.

## 2.6. Matching GES and optimized yields

With a set of effort regimes that should lead to optimized yields for all fleets simultaneously on the one hand and those that produce GES on the other hand, we sought options that would lead to both objectives' criteria to be satisfied. Those effort regimes would fulfil variants of both the Common Fisheries Reforms' demand for MSY and the MSFD's GES. If no overlap between initial conditions of GES and MSY existed, we would present trade-offs in conservation and fishing targets that have to be accepted to obtain such a match.

## 3. Results

### 3.1. Single species maximum yields

The combination of efforts of beam trawlers (BT), demersal trawlers (DEM) and shrimpers (SHR) that led to the highest equilibrium catches of cod was, relative to 2010: 300% BT; 90% DEM; 0% SHR. For a maximum equilibrium catch of plaice, this was 210% BT; 240% DEM; and 0% SHR; for sole the combination was 120% BT; 300% DEM; and 540% SHR. Uttermost equilibrium catches of brown shrimp were obtained at 300% BT; 270% DEM; and 480% SHR. These solutions represent our purposive variant of single species MSYs, and whilst they may occur at the extremes of the effort levels tested (in particular for non-targeting fleets), neighbouring and lower

effort levels did well produce yields close to these MSYs. Figs. 8–11 show combinations of efforts that led, for the four scope species cod, plaice, sole and brown shrimp, respectively, to equilibrium catches of at least 80% of these maximally possible catches.

### 3.2. Multispecies yields

With the goal of presenting a negotiation space that leads to acceptable outcomes for all three fleets, we sought for effort combinations that would result in all four scope species being caught at a certain, ideally high, percentage of the maximum possible catch for the particular species. We did, however, not find any such solution until we lowered this percentage down to 30%. Responsible for that low outcome are trade-offs between the yields of demersal and shrimp trawlers, as further described in Section 4.3. The resulting negotiation space is shown in Fig. 12, which indicates effort regimes that led to catches of every focal species, cod, plaice, sole and brown shrimp, of at least 30% of what would be possible if all three fleets were managed just to obtain maximum yields of that particular species.

### 3.3. Good environmental status

No effort regime succeeded to satisfy all indicators that we chose for our proxy of a good environmental status, as the demand for a spurdog  $F$  below the  $F_{MSY}$  proxy of 0.029 suggested by WGEF



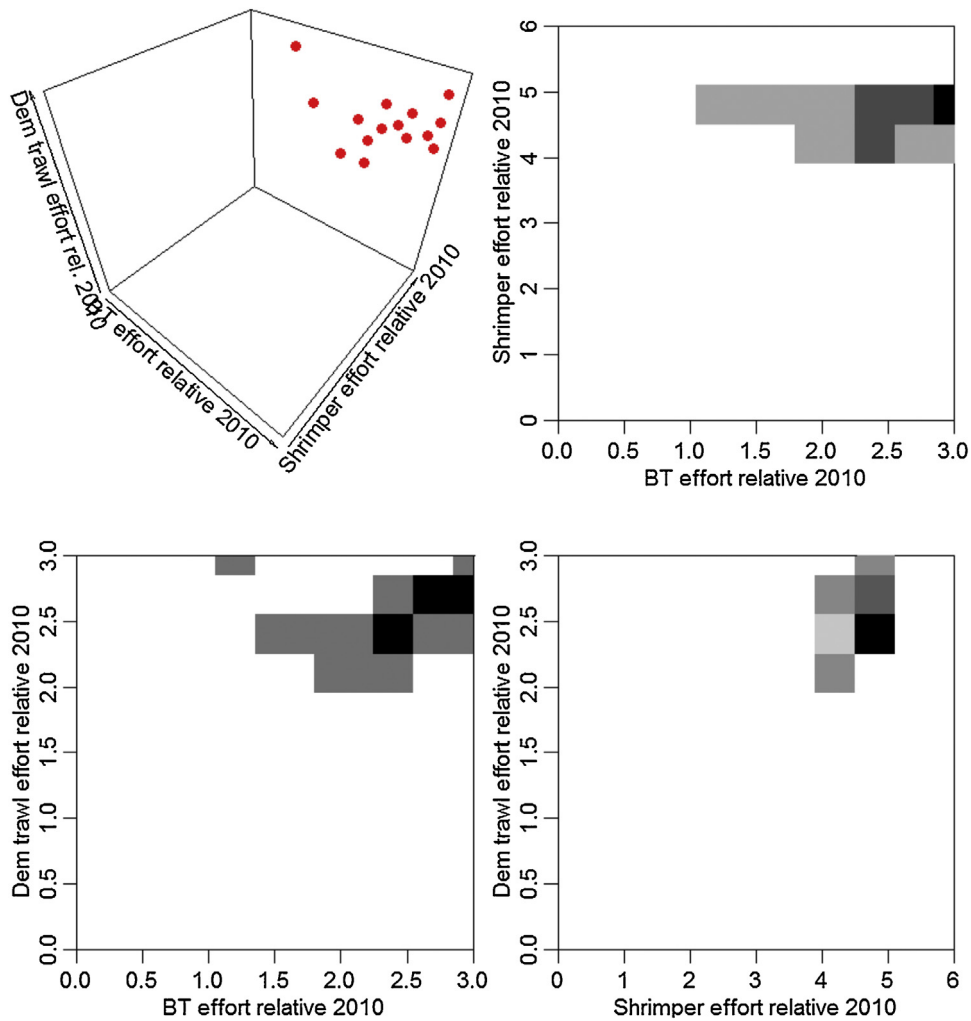


Fig. 11. Effort combinations that lead to long-term predictions of brown shrimp catches being 80% or more of the maximum possible catch of that species.

(2014) proved impossible to meet through management of beam, demersal, and shrimp trawlers alone in the southern North Sea. We thus replaced this threshold value and allowed fishing mortality for spurdog to reach up to 0.1, as, according to our model, spurdog can recover to a biomass of around twice the one in 1991 at this  $F$ . The resulting effort combinations leading to satisfaction of the updated set of GES indicators are shown in Fig. 13. They show strong dependency of GES on beam trawling effort, whilst, based on the set of indicators selected, no effect of shrimpers could be demonstrated. The results suggest that, when aiming to achieve GES, demersal trawling effort should not significantly be increased beyond 2010er levels.

### 3.4. Matching GES and optimized yields

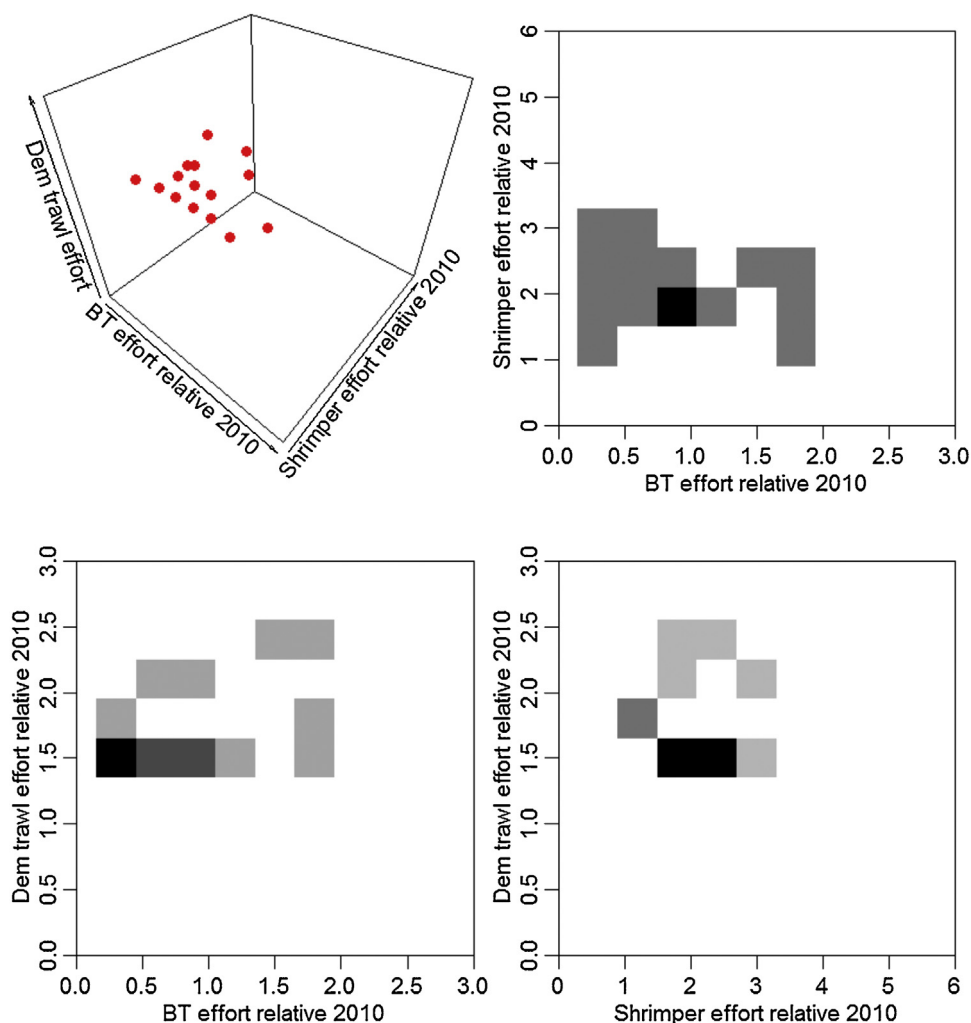
We found no overlap between those fishing regimes that lead to long-term predictions of at least 30% catch of each scope species (Fig. 12) and other regimes that produced a long-term GES (Fig. 13) without accepting trade-offs in the definition of thresholds. One such alternative threshold for turbot comes from ICES single species assessment for 2013, which suggested  $F_{max}$  as a proxy for  $F_{MSY}$ , with a range of 0.31–0.37. Even the higher of the two, however, does not allow GES and optimized fishing yields to coexist. We thus abandoned an  $F$  limit for turbot, and rose the acceptable  $F$  limit of spurdog by another 20% to  $F=0.12$ , a value still allowing recovery of the stock according to our model. Fig. 14 presents the set of effort

regimes that allow all species being fished at at least 30% of their maximum possible rate, whilst safeguarding  $B_{pa}$  of cod, sole and plaice and with a large fish indicator above the 0.3 threshold. In the three cases indicated, fishing mortality of turbot ranges from 0.42 to 0.65.

## 4. Discussion

### 4.1. A southern North Sea food web model

Parameterizing our southern North Sea model for 1991 and driving it to 2010 as a ‘hindcast’ allowed us to ascertain that the Ecosim model proved capable of accounting for the interactions between and across fleets and species, as demonstrated through the plausible representations of  $F_{msy}$  values and stock recruitment relationships (Section 2.3). This approach runs the risk of overlooking changes in fish’ and invertebrates’ diets that may have occurred since 1991. However, the ICES year of the stomach data still provides the most comprehensive assessment of fish diets in the North Sea, while newer studies are locally restricted. Together with those associated to stomach sampling, our model inherits the uncertainties of the surveys, stock assessments and multispecies model (SMS) data it was parameterized with and fitted to. As technological development increases the efficiency of fishing vessels (Eigaard et al., 2014), it is questionable in how far STECF effort statistics (Rätz and Mitrakakis, 2012) alone deliver a complete picture



**Fig. 12.** Spheres indicate effort regimes that lead to all four scope species – cod, plaice, sole and brown shrimp – to be simultaneously caught at 30% of their respective maximal possible catches. Shades projected on planes.

of the fishing pressure the species were subjected to or whether the so called technological creep may play a role here. Including estimates of technological development in fitting and parameterizing ecosystem models is certainly a promising future exercise.

The fitted and calibrated Ecosim model was able to reproduce trends in most biomass pools estimated for the southern North Sea 1991–2010 (Fig. D1 in Appendix D). As outlined in Section 2.3, it would have theoretically been possible to acquire an even better fit to the data points by including more groups into the fitting routine or by searching for a primary production function with more than three splines. However, this would have increased the risk of an over parameterization of the model and contradicted the parsimonious approach we followed. Of the scope species of our policy exploration exercise, we achieved a good approximation to the observed biomass time series of plaice and sole, while the model underestimates biomasses of cod in earlier years of the simulation. The upward trend of southern North Sea cod in the later 2000s is, however, well represented. We found the high turnover dynamics of brown shrimp challenging to implement in Ecosim, particularly in an MSY context, as information on their recruits' trophic role and population dynamics are scarce. Generally, our model's most critical uncertainties relate to the quality and implementation of diet data and the fitting and calibration of the vulnerability parameters that designate population and trophic behaviour of the groups. In the latter lay the fundamental challenges posed to ecosystem models for fisheries management: the effect of fishing on

marine systems and their fish stocks is often such convoluted with environmental and trophic effects that it is ambitious to impossible to disentangle (Mackinson, 2013; and references therein). Where this endeavour succeeds, the use of ecosystem models for fisheries management traditionally faces debates on the need to incorporate a large set of parameters with associated uncertainties (Essington, 2004; Pikitch et al., 2004). We thus state our findings as being of qualitative rather than quantitative nature. Nevertheless, our approach demonstrates how trade-offs between MSY and GES related policies can lead to serious conflicts. We propose a way to identify likely trade-offs and to find compromises between different objectives and policies.

#### 4.2. Single species maximum yields

Our equilibrium simulations of the effect of different fishing effort regimes of demersal, beam, and shrimp trawlers on long term catches of cod indicate that the southern North Sea stock is likely to produce best results at a demersal trawler effort level around the one in 2010 (Fig. 8). This is in alignment with what we would expect from the relationships between fishing mortalities and catches we established in the calibration of our Ecosim model (Fig. 6):  $F$  at highest Ecosim yields is fairly close to adult cods'  $F$  in 2010 according to the ICES stock assessment (WGNSSK, 2013). Interestingly, good cod catches are predominantly obtained at high BT efforts. We suspected this effect to relate to competition

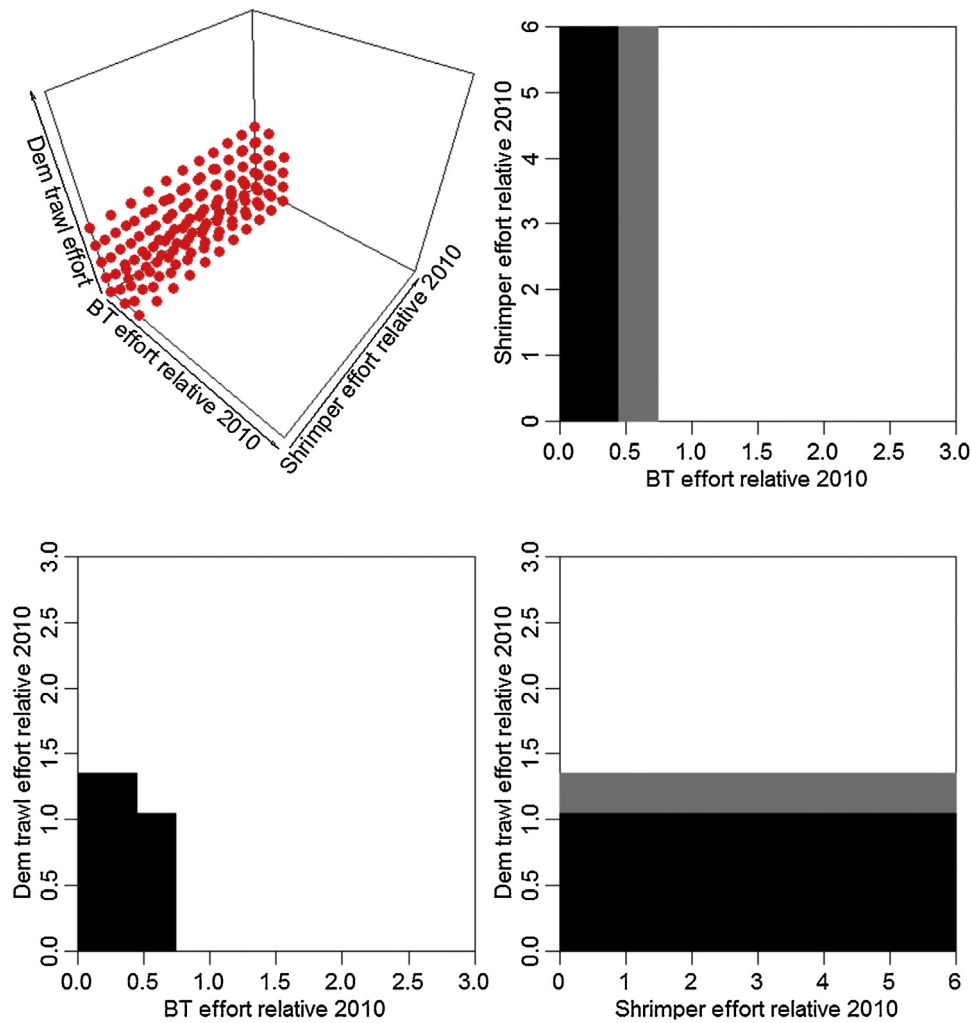


Fig. 13. Effort combinations that lead to equilibrium states of the ecosystem deemed to represent a good environmental status.

for food between cod and plaice. We found considerable predator niche overlaps (Christensen et al., 2008) between adult plaice and juvenile (0.5, with 0 meaning no and 1 meaning largest overlap) and adult (0.7) cod for our Ecosim food-web. Similarly, cod on the eastern Scotian Shelf show considerable niche overlap with flatfish, in this case with Long-rough dab, *Hippoglossoides platessoides* (Bundy and Fanning, 2005). In our system, a reduced plaice stock through high beam trawl efforts thus allows eminent cod catches, suggesting that indirect food-web effects counterbalance direct bycatch effects for BT on cod. Cod in the southern North Sea generally benefit from low shrimper effort, as brown shrimp is one of the main preys consumed by cod juveniles (Table A3 in Appendix A).

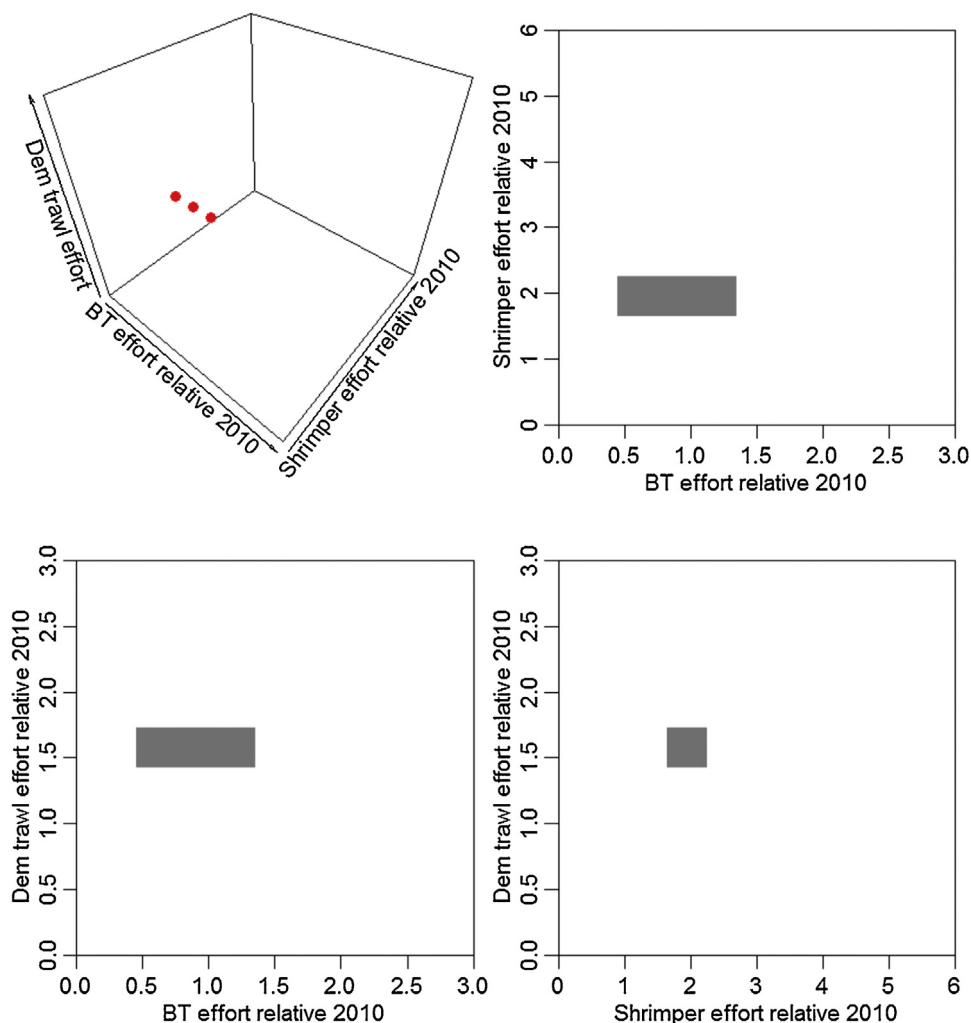
High long term catches of plaice (Fig. 9) and sole (Fig. 10) appear rather subtly dependent on the extend of demersal and shrimp trawling, but scale around beam trawl effort levels that produce  $F$  values close to our Ecosim calibrations'  $F_{msy}$  for the two species (Fig. 6). This is particularly the case for sole, while plaice shows more interactions with demersal trawls, which contributed around 20% to its fishing mortality. This bycatch surmounts the positive effect of otter trawling on plaice abundance and catch through the above mentioned food-web interaction with cod. A minor impact of shrimp fishing on flatfish catches can be perceived from the precise effort combinations leading to absolute maximum catches of plaice and sole (Section 3.1): While plaice are vulnerable to fishing for shrimp through bycatch of their recruits (around 12% of juvenile plaices' total  $F$  was caused by shrimpers in our Ecosim hindcast in

2010), sole appear to indirectly benefit from shrimp trawling: their bycatch in this fishery is negligible, whilst they are in competition for food with plaice when adult, as indicated by a 0.95 predator niche overlap.

Catches of brown shrimp (Fig. 11) show a clear benefit from 'culling' of cod through demersal trawling. Cod is crangon's main predator in our model, and its diminution appears to allow the shrimp stock to very well sustain fishing efforts five times higher than the one executed in 2010. Being a low trophic level species with high turnover rates, brown shrimps run a low risk of recruitment overfishing. The suggestion of these high fishing pressure being beneficial must however be interpreted with care; it is sensitive to the parameterization of cods' diet and to the population dynamics of the recruits' stanza of brown shrimp, for which information is scarce. Temming and Hufnagl (2014) found reduced predator stocks to benefit commercial landings of brown shrimp alike. They do, however, warn that, at the current state, the fishery already contributes the major part of brown shrimps' mortality and that a potential growth overfishing of the stock is indicated.

#### 4.3. Multispecies yields

A first striking insight from the attempt to show effort regimes leading to 'pretty good yields' – not quite *sensu* Hilborn (2010) – from all species simultaneously is that these yields are pretty low. There are regimes that lead to all species being extracted at 30%



**Fig. 14.** Spheres show fishing effort combinations that safeguard  $B_{pa}$  of cod, plaice, and sole, assure LFI larger 0.3 and simultaneously provide at least 30% of the uttermost possible catches of cod, plaice, sole and brown shrimp in long-term predictions.

of their maximum possible rate (Fig. 12); however, the fact that no such results exist when 35% are demanded suggests that in the 30% solutions, at least one species produces poor catches. Responsible for that is the interplay between two fleets, but not, as one might expect, a negative one. Much more so, the fishery for brown shrimp benefits so significantly from reduction of its predators cod (and NB also whiting, *Merlangius merlangus*) through the demersal trawlers that yields of at least 30% of the highest possible brown shrimp catch require demersal trawl efforts far beyond those that lead to maximum catches of cod. The resulting negotiation volume is a trade-off between high brown shrimp catches and not entirely ruined cod stocks, which would be substantially overfished at this state. Similarly, Mackinson et al. (2009b) found it impossible to achieve single species MSY of cod, haddock and whiting at the same time in the North Sea. Prior to our study, we thus had not expected yields close to single species MSYs for the much interlinked southern North Sea food-web either. The actual impossibility of achieving even acceptable yields simultaneously, however, is new. The question is in how far that insight represents a failure of our concept of the negotiation space or if rather the approach inherits the problems demonstrated for a variety of systems in which lower trophic species are fished: That considerable increases of fishing pressure are required to produce catches close to maximum sustained yields (Walters et al., 2005), which goes along with significant impacts on predatory species and the ecosystem (Smith et al., 2011).

#### 4.4. Good environmental status

Effort regimes leading to long-term predictions that satisfied our GES descriptors are depicted in Fig. 13. The results are quite direct consequences of the respective effort levels and not marked by unexpected indirect effects. As such, beam trawlers can only fish at the lowest effort rate investigated (30% of 2010), and only so at minimal fishing activities of the demersal fleet, as else turbot fishing mortality overshoots the precautionary proxy  $F$ . Demersal trawling effort is limited first by adult cods' biomass falling below  $B_{pa}$ , and thus unable to exceed 120% of the effort in 2010. None of the indicators included so far is sensitive to the effort of shrimp trawlers, which is a factor worthwhile considering in future studies. Candidate indicators for this should certainly include measures of the impact of trawling on seabed integrity. Note that, with such descriptors missing from the current analysis, our conservation scenarios can only be considered as proxies for the GES actually demanded by the MSFD.

#### 4.5. Matching GES and optimized yields

The initial impossibility of aligning optimized yields and GES in our modelled ecosystem illuminates challenges that may await Europe's fishing grounds. There is a need to localize indices and thresholds, as demonstrated for the limiting spurdog  $F$  suggested



by the ICES working group on elasmobranch fishes. This threshold proved unfeasible for our model area, potentially because it is derived from assessments of a whole Northeast Atlantic stock. Local populations and catch patterns, though, may significantly differ, and for some fisheries, e.g. the southern North Sea's beam trawl fleet, these could well be relevant management entities. Even more importantly, our results caution that the selection of descriptors and thresholds, but also of postulated yields, is critical to allow realistic coexistence of the Common Fisheries Policies' MSY and the MSFD's demand for a GES.

## 5. Conclusions

With this study, we have suggested one possible interpretation of a multispecies or ecosystem scale variant of MSY for the southern North Sea. We tested the application of the concept and demonstrated that it is impossible to achieve good yields of all species simultaneously. While doing so, we quantified technological and trophic interactions between species and fisheries that lead to trade-offs between policy goals for the respective fleets and marine conservation. The studies' intuitively inconvenient result can be seen as a humble contribution to the question of what we want in fisheries management. In our concrete case, this could mean a discussion about which percentages of the maximum possible single species yields we are willing to accept as 'good outcomes' and in how far these shares can differ between species. Including GES descriptors helps to frame this discourse and shows which conservation thresholds are particularly costly in terms of yields and vice versa.

Our study aligns with others questioning the classic MSY approach in multispecies and mixed fisheries concepts (Hilborn, 2010; ICES, 2013; Mackinson et al., 2009b; Walters et al., 2005). In a certain acceptance of that fact, it is now understood in the ICES and also European Commission context that MSY targets should be perceived as ranges, rather than precise values, a notion that lead the development of long term management plans and guided the ICES-MYFISH Workshop to consider the basis for  $F_{msy}$  ranges for all stocks (WKMSYREF3, 2014). However, as our study indicates, there is a risk that even this range-based approach may not lead to results that are perceived as satisfactory.

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## Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ecolmodel.2016.01.020>.

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