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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.

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 Fs. However, it does not consider that Fs 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^2. 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