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Ecosystem Based Fisheries Management for the Western Baltic Sea

Extended Report

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October 2019

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Abstract

Legal requirement in Europe asks for Ecosystem-Based Fisheries Management (EBFM) in European seas, including considerations of trophic interactions and minimization of negative impacts of fishing on food webs and ecosystem functioning.

Focusing on the interaction between fisheries and ecosystem components, the trophic model presented here shows for the first time the "big picture" of the western Baltic Sea (WBS) food web by quantifying structure and flows between all trophic elements and the impact of fisheries that were and are active in the area, based on best available recent data.

Model results show that fishing pressures exerted on the WBS since the early nineties of the past century forces not only top predators such as harbour porpoises and seals but also cod and other demersal fish to heavily compete for fish as food and to cover their dietary needs by shifting to organisms lower in the trophic web, mainly to benthic macrofauna and / or search for suitable prey in adjacent ecosystems such as Kattegat, Skagerrak, central Baltic Sea and North Sea.

While common sense implementations of EBFM have been proposed, such as fishing all stocks below F_{msy} and reducing fishing pressure even further for forage fish such as herring and sprat, few studies compared such fishing to alternative scenarios. Different options for EBFM, with regards to recovery of depleted stocks and sustainable future catches, are presented here based on the WBS ecosystem model, the legal framework given by the new Common Fisheries Policy (CFP) and the Marine Strategy Framework Directive (MSFD) of the European Union.

The model explores four legally valid future fishery scenarios: 1) business as usual, 2) maximum sustainable fishing ($F = F_{msy}$), 3) half of F_{msy}, and 4) EBFM with $F = 0.5\ F_{msy}$ for forage fish and $F = 0.8\ F_{msy}$ for other fish. In addition, a "No-fishing" scenario demonstrates, that neither individual stocks nor the whole system would collapse when all fishing activities from 2017 on would cease.

Simulations show that "Business as usual" would perpetuate low 2016 catches from depleted stocks in an unstable ecosystem where endangered species may be lost. In contrast, an "EBFM" scenario - with herring and sprat fished at 0.5 F_{msy} level and cod and other stocks fished at 0.8 F_{msy} level - allows the recovery of all stocks with strongly increased catches close to the maximum (at F_{msy}) for cod and flatfish and catches similar to the 2016 level for herring and sprat but with strongly reduced fishing effort.

Model and methodology presented here are considered suitable to assess MSFD Criterion D4C2 in the WBS.

Keywords

Ecosystem Based Fisheries Management (EBFM), food web, trophic model, western Baltic Sea, CFP, MSFD.

Introduction

Fishing belongs to the strongest negative anthropogenic interventions on marine ecosystems (Jones 1992, Hall et al. 2000, and Kaiser et al. 2006). In northern Europe, this is particularly true for the North and Baltic Seas and consequently also for the German Exclusive Economic Zone (EEZ) of both seas where all major species have been heavily overfished for decades. The new Common Fisheries Policy (CFP, 2013) of the European Union (EU) demands the end of overfishing latest in 2020. The Marine Strategy Framework Directive (MSFD 2008, 2017a,b) of the EU demands furthermore - as criteria of good environmental status - (1) biological diversity with species abundance or demographic characteristics not affected by anthropogenic pressures, (2) a healthy size and age structure of exploited stocks and (3) marine food webs with species composition, diversity, balance, and productivity of the trophic guilds not affected by anthropogenic pressures.

Ecosystem-Based Fisheries Management (EBFM) is a new direction for fishery management, which essentially reverses the order of management priorities so that management starts with the ecosystem considerations rather than the maximum exploitation of several target species (Pikitch et al. 2004). EBFM aims to sustain healthy marine ecosystems and the fisheries they support. Specifically, it aims to rebuild and sustain populations of non-target and protected species.

The purpose of this study was thus the creation of a first ecosystem model for the WBS ecosystem, using the best available recent data and focusing on the interaction between fisheries and ecosystem components. Of special interest were the impacts of long-term overfishing of important commercial stocks such as western Baltic cod (*Gadus morhua*) and western Baltic spring spawning herring (*Clupea harengus*), the role of herring and sprat (*Sprattus sprattus*) as low trophic level (LTL) key species in the food web, the level of cannibalism of adult cod on juvenile cod, the competition between marine mammals and fishers for fish, and the extraction of fish by seabirds.

Model results aim to offer suggestions for sustainable fisheries management measures according to Article 2.3 of the new CFP of the EU which calls for the implementation of “an ecosystem based approach for fisheries management by minimizing the negative impacts of fishing activities”.

The WBS fishery model is furthermore viewed as a supporting tool for comparing model results with stock assessments of the International Council for the Exploration of the Sea (ICES). The model serves also as a prerequisite for estimating the impact of the recently modified CFP on commercially exploited fish stocks and other elements of the WBS ecosystem.

Objectives

Based on the first ecosystem model for the WBS and the legal framework given by the CFP and MSFD, the goal of this study was to present and compare different options for EBFM with regard to recovery of depleted stocks and sustainable future catches.

A preliminary version of the WBS model was previously presented by Opitz & Garilao (2014). The model presented here is viewed as a prototype that may be updated when appropriate information / data becomes available and / or adapted to objectives of other studies.

For the Baltic Sea a series of earlier models exist although to date there is no published trophic network model of the WBS available. An overview of existing models may be found further below in chapter "Data Sources". All of them represent areas east of the Arkona Basin, and of the German NATURA 2000 areas. Furthermore, with one exception (Hansson et al. 2007), all models were prepared almost exclusively with data sets from the last third of the 20th century. Except for Harvey et al. (2003) and Hansson et al. (2007) the interaction between ecosystem components and fisheries was not the focus of those models. The preparation of updated models is thus not only of importance for the alignment of actions towards EBFM in the entire region and particularly in NATURA 2000 areas but also contribute to fill gaps of knowledge from a scientific point of view.

Project Description, Study Area (Map)

In the scope of the project "Ecosystem Based Fisheries Management in the German EEZ" implemented by the German Federal Agency for Environmental Protection (Bundesamt für Naturschutz BfN) impacts of commercial fisheries on the marine ecosystem in the German EEZ of the North and Baltic Seas, with special emphasis on NATURA 2000 areas are being studied by the use of trophic network models.

The model area covers ICES subdivisions (SDs) 22 and 24. The reason to fit the model to ICES management areas was that ICES has organized its fishery data by SDs which makes it convenient for model construction because quantification of biomass and catches of exploited fish stocks is (mostly) straightforward and more reliable. But our model area also represents an ecologically more uniform area than the surrounding regions. Salinity of SD 21 north of SD 22 is similar to conditions in the Kattegat and Skagerak and considerably higher than in the southern areas. SD 23, representing the sound that separates Sweden from Denmark has mostly rocky ground with ecological qualities different from the sandy-muddy areas in SDs 22 and 24. The model area is thus a compromise between data availability and ecological concerns.

Geographical regions represented by the WBS model are: Great Belt, Little Belt, Kiel Bay, Bay of Mecklenburg, Arkona Basin until West of Bornholm Basin (ICES subdivisions 22 and 24) and including all NATURA 2000 areas in the German EEZ (see Fig. 1).

NATURA 2000 areas in the German EEZ comprise Fehmarn Belt, Kadetrinne, Western Rönnebank, Adlergrund and Pomeranian Bay with Oderbank, while Pomeranian Bay is also a designated EU bird protection area (see Fig. 1).

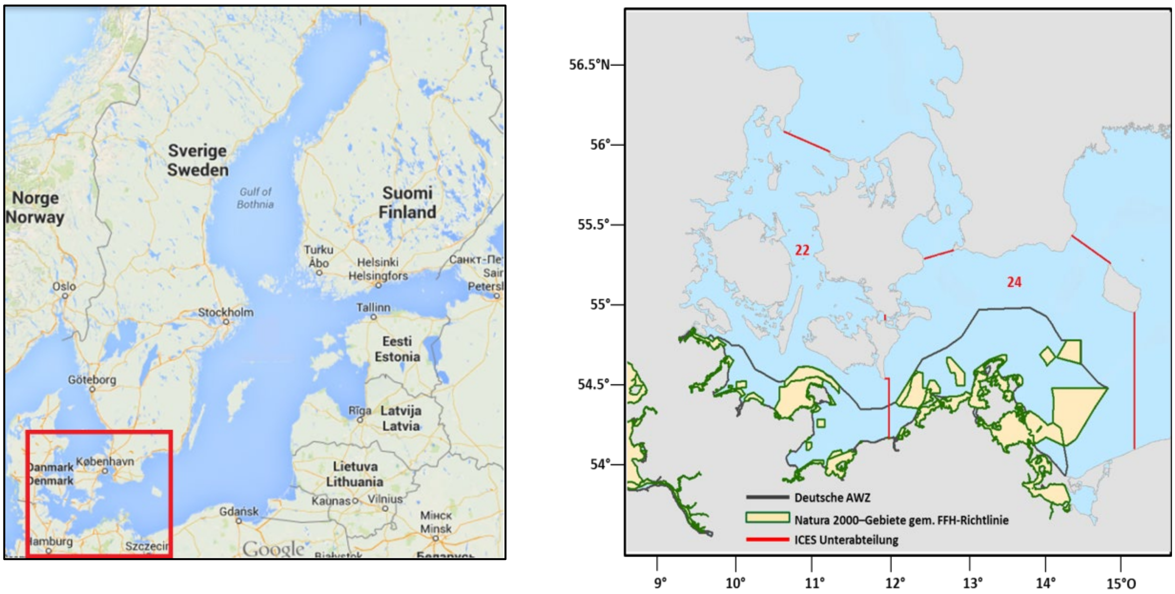

Figure 1: Area represented by the WBS ecosystem model: WBS with German EEZ (green line), NATURA 2000 areas (white) and ICES subdivisions 22 and 24 (red line).

Material & Methods

The basic trophic network model represents the WBS ecosystem in the year 1994 because this is the year when catch and stock size data were available online from ICES for the majority of fish stocks included in the model, but particularly for cod, herring, and sprat, the economically most important species in the WBS. Starting in 1994, it was possible to subsequently model dynamically a time span of >20 years (see below).

The Ecopath with Ecosim software package (EwE, www.ecopath.org) was used for model preparation. EwE is a software package suited for personal computers. The approach is thoroughly documented in the scientific literature (see. e.g. Polovina 1984, Christensen and Pauly 1992; Pauly et al. 2000). The EwE model software may be downloaded for free from www.ecopath.org/downloads.

The basic trophic network model representing the WBS ecosystem in the year 1994 was prepared using the Ecopath routine. Ecopath helps the user to create mass-balanced snapshots of the resources in an ecosystem and their interactions, represented by trophically linked biomass 'pools'. These may consist of a single species, or species groups representing ecological guilds. Pools may be further split into ontogenetically linked groups called 'multi-stanzas' such as done here for adult (>35 cm) and juvenile (<=35 cm) cod.

Ecopath bases the parameterization on an assumption of mass balance over an arbitrary period, usually a year. In accordance with this feature the WBS model used annual means as parameter inputs.

"The parameterization of an Ecopath model is based on satisfying two 'master' equations: The first equation describes how the production term for each group can be divided:

(1) Production = catch + predation + net migration + biomass accumulation + other mortality - import

The second 'master' equation is based on the principle of conservation of matter within a group:

(2) Consumption = production + respiration + unassimilated food

A detritus compartment (D) receives flows originating from "other mortality (M)" and "non-assimilated food (NA)", so that

(3) D = M + NA.

The model can accept accumulation and depletion of biomasses during the time period modelled despite of the steady state assumption. Thus, biomass accumulation or depletion rates can be quantified.

Input of three of the following four parameters is required for every functional group in a model: biomass (B), production/biomass ratio (P/B) (or total mortality Z), consumption/biomass ratio (Q/B), and ecotrophic efficiency (EE). Here, EE expresses the proportion of the production that is used in the system, (i.e. it incorporates all production terms apart from 'other mortality'). If all four basic parameters are available for a group the program can estimate either biomass accumulation or net migration. Ecopath sets up a series of linear equations to solve for unknown values establishing mass-balance in the same operation".

A wide range of information on structure and matter flows within an ecosystem can be obtained from Ecopath models. For more details see Christensen et al. (2000).

The Ecosim component of EwE provides a dynamic simulation capability at the ecosystem level, with key initial parameters inherited from the base Ecopath model.

The basics of Ecosim consist of biomass dynamics expressed through a series of coupled differential equations. The equations are derived from the Ecopath master equation and take the form

$$(4)\ dB_i / dt = g_i \sum j\ Q_{ji} - \sum j\ Q_{ij} + I_i - (MO_i + F_i + e_i)\ B_i$$

where dB_i / dt represents the growth rate during the time interval dt of group (i) in terms of its biomass B_i; g_i is the net growth efficiency (production/consumption ratio); $\sum j\ Q_{ji}$ total consumption by group i; $\sum j\ Q_{ij}$ total predation by all predators on group i; MO_i the non-predation ('other') natural mortality rate; F_i is fishing mortality rate, e_i is emigration rate, I_i is immigration rate (Walters et al. 1997, 2000).

By doing repeated simulations Ecosim allows for the fitting of predicted biomasses to time series data. "Sum of squares" (SS) in Ecosim is a measure for the goodness of fit between input values and model outputs.

Ecosim was used for the purpose of fitting model outputs and time series data of biomass, fishing mortality and catch.

Ecosim furthermore allows the dynamic forward projection of future biomass of trophic groups based on the reported or assumed F exerted on the commercial groups (from 1994 until 2016).

This feature was used to evaluate the impact of different fishery scenarios on stock size and catch into the future (from 2017 until 2050).

Trophic Groups in the Model of the WBS Ecosystem

The following 18 trophic groups - comprising the WBS ecosystem - are represented in our model:

Harbour porpoises: Due to their dietary preferences, harbour porpoises (*Phocoena phocoena*) act as top predators in the WBS ecosystem.

Seals: Due to their dietary preferences, seals also act as top predators in the WBS ecosystem. The group represents two species: Mainly grey seal (*Halichoerus grypus*) and harbour seal (*Phoca vitulina*) while the latter is much less common in the area than the former. Theoretically, also the river otter (*Lutra lutra*) should be included here, but no information on abundance was available to the authors.

(Sea-)birds: Theoretically, HELCOM (Helsinki Commission, see www.helcom.fi/) lists around 50 bird species as occurring in the WBS ecosystem. However, biomass values here are based only on the following 27 species occurring in different zones of the German Baltic(?) EEZ (Schleswig-Holstein and Mecklenburg - Western Pomerania): *Gavia stellata, Gavia arctica, Podiceps cristatus, Podiceps grisegena, Podiceps auritus, Fulmarus glacialis, Sula bassana, Phalacrocorax carbo, Aythya marila, Somateria mollissima, Clangula hyemalis, Melanitta nigra, Melanitta fusca, Mergus serrator, Hydrocoloeus minutus, Larus ridibundus, Larus canus, Larus fuscus, Larus argentatus, Larus marinus, Rissa tridactyla, Sterna sandvicensis, Sterna hirundo, Sterna paradisaea, Uria aalge, Alca torda, Cepphus grylle.*

Adult cod: "Cod >35 cm" represents adults of the WBS cod (*Gadus morhua*) stock. The cut-off length of 35 cm between adults and juveniles represents the official EU minimum landing length of cod in the Baltic Sea after 2014.

Juvenile cod: "Cod<=35 cm" represents juveniles of the WBS cod stock.

The "Flat fish" box incorporates 1) flounder (*Platichthys flesus*), 2) dab (*Limanda limanda*), 3) plaice (*Pleuronectes platessa*), 4) turbot (*Scophthalmus maximus*) and 5) brill (*Scophthalmus rhombus*). The Baltic stocks of flounder, plaice, and turbot are fully assessed by ICES, dab and brill stocks are not.

Other demersal fish represents > 130 species populating the lower parts of the water column of the WBS (for a list of fish species in WBS see www.fishbase.org); only 53 species from this list were caught in the DATRAS BITS surveys from which a first estimate of biomass for this group was calculated for 1994. It also includes 10 flatfish species not fully assessed by ICES.

Herring represents a single species: *Clupea harengus*. The WBS herring stock (western Baltic spring spawning herring (WBSS)) is fully assessed by ICES.

Sprat represents a single species: *Sprattus sprattus*. The Baltic Sea sprat stock is fully assessed by ICES.

Other pelagic fish represents about 35 species populating the upper and midwater parts of the water column of the WBS except for herring and sprat which are represented by single species compartments. Only 10 species (*Alosa fallax, Atherina presbyter, Belone belone, Engraulis encrasicolus, Osmerus eperlanus, Salmo trutta, Sander lucioperca, Sardina pilchardus, Scomber scombrus, Trachurus trachurus*) from this list are recorded in the DATRAS BITS surveys (designed for catching demersal fish) from which a preliminary estimate of biomass was calculated for 1994. The “true” biomass for "Other pelagic fish" though was assumed to be much higher.

Pelagic macrofauna comprises all animals >2 cm in size inhabiting the water column of the WBS. This is mainly jellyfish such as moon jellyfish (*Aurelia aurita*) and lion´s mane jellyfish (*Cyanea capillata*), other cnidarians such as hydrozoans, and several species of polychaetes.

Benthic macrofauna represents a vast number (>500) of invertebrate species (Annelida, Arthropoda, Bryozoa, Chordata, Cnidaria, Echinodermata, Mollusca, Nemertea, Phoronida, Platyhelminthes, Porifera, Priapulida, Sipunculida) >1 mm in size and associated with the benthic habitat of the WBS. A complete list of benthic macrofaunal species is available from the lead author and / or from www.sealifebase.org.

Benthic meiofauna represents all animals <1 mm in length associated with the bottom substrate in the WBS. These were not identified down to the species level.

Zooplankton merges micro-, meso-, and macrozooplankton into a single group. Microzooplankton comprises planktonic animals from 0.02 to 0.2 mm in size (e.g. phagotrophic protists such as flagellates, dinoflagellates, ciliates, acantharids, radiolarians, foraminiferans, etc., and metazoans such as copepod nauplii, rotiferan and meroplanktonic larvae); mesozooplankton comprises planktonic animals from 0.2 to 2 mm in size (in WBS mainly adult copepods and cladocerans); and macrozooplankton all planktonic animals >2 mm in size (in WBS mainly mysids and amphipods).

Bacteria / microorganisms represents bacteria and other microorganisms <0.02-0.03 mm in size and associated with the bottom substrate and/or with the water column in the WBS. Includes flagellates living in part autotrophically.

Phytoplankton comprises pelagic microalgae. Species composition in the WBS is unknown to the authors.

Benthic producers represents benthic (macro- and micro-) algae and seaweeds. Phyla occurring in WBS: Angiospermophyta, Charophyta, Chlorophyta, Ochrophyta, Phaeophyta, Rhodophyta, Xanthophyta. A tentative species list is available from the lead author and from www.sealifebase.org.

Detritus/DOM represents dead organic matter - particulate and dissolved.

Data Sources

Estimates of biomass (B), production (P/B year-1), consumption (Q/B year-1), unassimilated consumption (NA), diet composition (DC), catch (C), and fishing mortality

(F) in 1994 were obtained from various sources. And so were time series for (B), (C), and (F) for years 1994 to 2016.

Principal data sources were: FishBase (www.fishbase.org), SeaLifeBase (www.sealifebase.org), ICES database, ICES Advice, ICES Working Group Reports, ICES Stock Summaries, DATRAS, HELCOM, published ecosystem models of other areas in the Baltic Sea (see Table 1 below), other relevant literature, and - last but not least - personal communications by expert colleagues.

Table 1: Published models for other parts of the Baltic Sea with indication of publication year, model area, and modelling objectives.

Author	Publ. year	Baltic Sea Ecosystems modelled												Objectives
		Baltic Sea	Western Baltic Sea / German EEZ	Central Baltic Sea	Putziger Wiek	Curonian Spit	Litvanian Coast	Gulf of Riga	Bay of Parnu (Estonia)	Gulf of Finnland	Bothnian Sea	Öre estuary	Gulf of Bothnia	
Opitz et al.	present		■											**Analysis and improvement of Impact of commercial fisheries on the marine ecosystem and its components.**
Casini et al.	2012							■						Understanding the effects of flows across systems.
Tomczak et al.	2009				■	■	■	■ Coast	■					Comparative analysis of trophic networks and carbon flows in southeastern coastal ecosystems of the Baltic Sea.
Hansson et al.	2007			■										**Management of Baltic Sea fisheries under contrasting conditions of production and predation.**
Sandberg	2007			■				■		■	■		■	Analysis across ecosystems of pelagic web structure and processes of three main basins of the Baltic Sea.
Sandberg et al.	2004										■	■	■	Quantitative assessment of the relative significance of terrigenous dissolved organic substance (TDOC) as carbon source for secondary producers (e.g. bacteria) as structuring factor for the pelagic food web in the Gulf of Bothnia.
Harvey et al.	2003			■										**Evaluating interactions between fishery and food web.**
Sandberg et al.	2000			■							■		■	Re-evaluating carbon flows in food webs of the Baltic Sea using a mass balance approach.
Jarre-Teichmann	1995			■										Analysis of the seasonal energy budget and significance of interspecific control mechanisms of the Central Baltic Sea.
Rudstam et al.	1994			■				■		■	■		■	Overview on evidence for and possible consequences of top-down control in the pelagic ecosystem of the Baltic Sea.
Wulff & Ulanowicz	1989	■		■				■		■	■		■	Descriptions of structural and functional relationships on a system level in two strongly used marine systems, Baltic Sea and Chesapeake Bay.
Elmgren	1984	■		■				■		■	■		■	Overview on main biological energy flows in the light of most recent developments.

Preparation of Basic Model Inputs for EwE

Biomass (B)

Because biomass of a trophic group is far more ecosystem specific than physiological parameters like production and consumption, realistic biomass values are therefore of paramount importance for any model aimed to closely represent matter flow in a specific ecosystem. In the following it will be explained how biomass values for each trophic group was calculated. Wet or fresh weight was transformed into carbon by applying a factor of 10:1, if not otherwise stated. Values represent biomass in ICES subdivisions 22+24, if not otherwise stated.

Harbour porpoises: Value in wet weight (WW) was derived from biomass indications by A. Gilles (pers. comm.) and from Viquerat et al. (2014) for German coastal waters of the Baltic Sea.

Seals*:* Value in WW was derived from a trophic model by Harvey et al. (2003) representing ICES SDs 25-29 + 32 and covering years 1974 - 2000.

(Sea-)birds*:* Value in WW was derived from indications on number of individuals of 27 bird species in different zones (EEZ, coastal and offshore zones of Schleswig-Holstein and Mecklenburg - Western Pomerania) of the German part of the Baltic Sea (information kindly made available by colleagues from ECOLAB, FTZ Büsum; www.ftz.uni-kiel.de/de/forschungsabteilungen/ecolab-oekologie-mariner-tiere). Data are based on counts from the 1st decade of the 21st century. Number of individuals was multiplied with indications on mean WW of species - all values obtained through internet queries – the majority of values were derived from Wikipedia (www.wikipedia.org). Total weight for each species was then divided by the number of m^2 of total area (information on km^2 values per area kindly made available by colleagues from ECOLAB, FTZ Büsum).

Adult cod: B is based on data for western Baltic cod stock from Table 12 in ICES (2017a). SSB for age 3-5 for year 1994 was divided by area size for SD 22, 23 and 24 (44 746 km^2) to obtain $gWWm^{-2}$. The biomass value of cod should be treated with some caution as a recent comparison of cod otoliths readings from countries involved proved to be uncertain (R. Froese pers. comm.)

Juvenile cod: Value was calculated by multi-stanza routine in Ecopath based on B for adult cod. The stanza routine result was adapted to an external value of B for juvenile cod. The external value was calculated to be the difference between total stock B (TSB, obtained from Table 2.3.22 in ICES 2017b) and SSB (obtained from Table 12 in ICES 2017a), both for 1994. The difference was then divided by area size for SD 22, 23 and 24 (44,746 km^2) to obtain $gWWm^{-2}$.

Flatfish: dab, flounder, plaice, turbot, and brill: B for this group represents the summed total of the five species for year 1994. TSB for plaice in ICES SDs 21-23 is based on Table 5.2.7 in ICES (2016b). B for 1994 is back calculated based on mean exploitation rate (ExplR) for years 1999-2001. B in WW for 1994 was calculated from DATRAS BITS CPUE data separately for dab, flounder, turbot and brill as follows: number of individuals per length class from CPUE was multiplied by weight per individual per length class obtained from length - weight relationship (LWR) by species. Total B was then divided by area size for SD 22 and 24 to obtain gWWm^{-2}.

Other demersal fish: Original B for this group was calculated from DATRAS BITS CPUE data for demersal fish but excluding cod and the five species in the flatfish box (B proportion of flatfish on total group B was ca. 13.5 %). No. of individuals per length class from CPUE was multiplied by weight per individual per length class obtained from length - weight relationship by species. WW was converted into carbon weight. The B value of 0.0436 gCm^{-2} obtained from DATRAS BITS in this way was much too low to satisfy predator requirements (including fishery); the necessary minimum B was obtained during the balancing process by setting EE for this group to 0.99.

Herring: Original input B was obtained by dividing SSB for 1994 in ICES SDs 20 - 24 (WBSS herring) from Table 11 in ICES (2017i) by area size (102,288 km^2) to obtain gWWm^{-2}.

Sprat**:** Available SSB value for 1994 in ICES SDs 22-32 from Tables in ICES (2017j) was adjusted to SDs 22-24 by calculating ExplR (B / landings) for SDs 22-32 (median = 3.24 %) and calculating B for SDs 22-24 by applying this percent relationship to sprat landings for SDs 22-24 from tables in ICES (2017b).

Other pelagic fish: Original B was calculated from DATRAS BITS CPUE data for demersal fish. For species in the DATRAS database identified to be pelagic the number of individuals per length class from CPUE data was multiplied by weight per individual per length class obtained from LWR by species. Resulting B (0.00349 gCm^{-2}) was much too low to satisfy predator requirements (including fishery). This value might have strongly underestimated the real B of pelagic fish since DATRAS BITS surveys are made with bottom trawls targeting demersal species. An estimate of the necessary minimum B was obtained during the balancing process by setting EE to 0.99.

Pelagic macrofauna: Mainly medusae (several species); B is an average of B values in Harvey et al. (2003, 0.133 gCm^{-2}) and Jarre-Teichmann (1995, 0.27 gCm^{-2}) for Baltic Proper.

Benthic macrofauna: Fresh weight was read off an unpublished graph on benthic macrofauna for ICES SDs 22 and 24, kindly provided by M. Zettler, IOW Warnemünde.

Benthic meiofauna: An estimate of fresh weight was provided by M. Zettler, IOW Warnemünde (pers.comm.).

Zooplankton: B represents lumped B for macro (mainly mysids) -, meso-, and microzooplankton. B values for each group correspond to the mean of a range for each group from a series of published trophic models (see Table 1 for an overview). For conversion of WW into carbon a factor of 1 gWW = 12.07 gC and 1 gC = 0.0828 gWW was applied.

Bacteria/microorganisms: B represents the average of a range (0.21-0.42 gCm-2) from a series of published trophic models (see Table 1 for an overview).

Phytoplankton: B represents the average of a range (1.01-3.312 gCm^{-2}) from a series of published models (see Table 1 for an overview). For conversion of WW into carbon a factor of 1 gWW = 12.07 gC and 1 gC = 0.0828 gWW was applied.

Benthic producers: B represents a rough estimate between lower values (0.02 – 0.0214 gCm^{-2}) from several published models (see Table 1 for an overview), mainly Sandberg et al. (2000), Jarre-Teichmann (1995) for Baltic Proper, and Wulff & Ulanowicz (1989) (adopted from Elmgren, 1984) for the whole Baltic Sea, and a very high value of 65.74 gCm^{-2} (based on estimates of macroalgae production for the whole Baltic Sea in Bergström, 2012).

Detritus/DOM: Value represents the average of a range (680-885 gCm^{-2}) from Sandberg et al. (2000) for Baltic Proper and Wulff & Ulanowicz (1989) for the whole Baltic Sea.

Production / Biomass ratio (P/B)

Production refers to the building up of biomass by a group over the period considered, entered as P/B per year and transformed into absolute flows ($gCm^{-2}y^{-1}$) by the Ecopath software. Total mortality Z, under the condition assumed for the construction of mass-balance models, is equal to production over biomass (Allen, 1971) and was used for groups where no P/B value was available. Below, source of P/B model inputs are described individually for each trophic group.

Harbour porpoises: Adopted from Table 3 - Z for harbour porpoises – in Araújo and Bundy (2011).

Seals*:* P/B was adopted from Mackinson & Daskalov 2007 and Harvey et al. 2003

(Sea-)birds*:* Value represents mean of range (0.3 – 7.027 y^{-1}) of production values in Tomczak et al. (2009) for seabirds from five coastal ecosystems in the southern and south-eastern Baltic Sea.

Adult cod: Original Z for cod is the sum of M=0.288 from Froese & Sampang (2013) and F = 1.18 for ages 3-5 for year 1991 from ICES (2016a). Value was adjusted by multi-stanza routine in Ecopath to fit B of dependent stanza "juvenile cod" to external B for 1991 from ICES (2016a) and Q/B values from published models (see Figure 2 for a multi-stanza representation of cod).

Juvenile cod: Original input value = total of average natural mortality (0.37) and average fishing mortality (0.62) for year 1994 for age classes 0, 1, 2, and 3, based on Tables 2.3.21, and 2.3.25 in ICES (2016b). Just like for adult cod value was reduced in multi-stanza routine to match external B value (Figure 2).

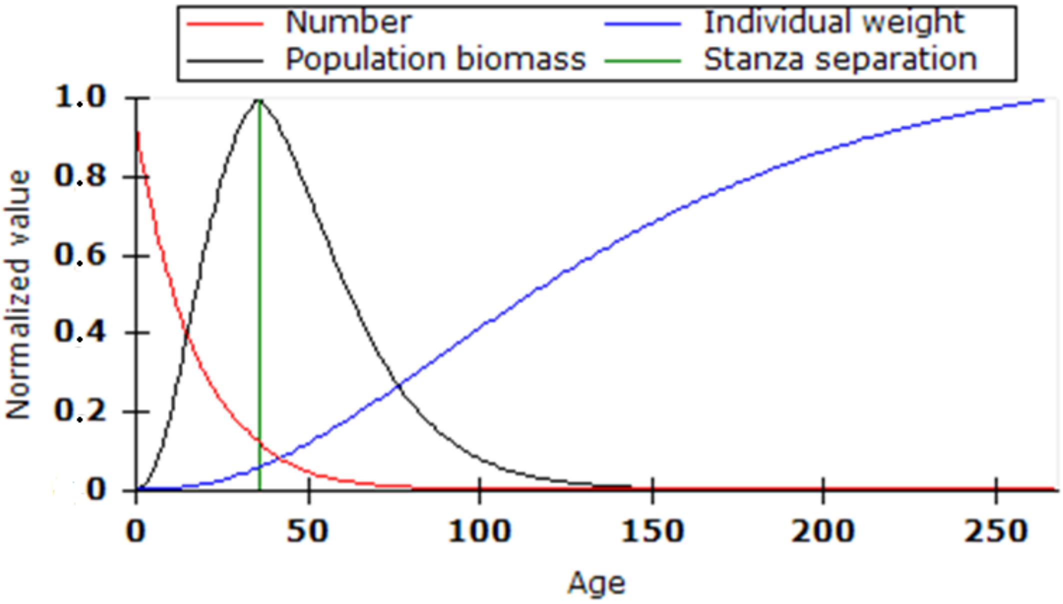

Figure 2: Multi-Stanza representation of cod. Age in months. Annual K (from VGBF) = 0.15, recruitment power = 1, Wmaturity/Winf = 0.9.

Flatfish (weighted mean of 0.85 for plaice and 0.86 for turbot / brill), Other demersal fish, and Herring (weighted mean of 0.8 for adult and 1.31 for juvenile herring): P/B values were read off Table 3.3 in Mackinson and Daskalov (2007).

Sprat: An average value was read off Table 3.3 in Mackinson and Daskalov (2007) and compared to values in published trophic models of the Baltic Sea (see Table 1 for an overview). The new value of 1.5 is higher but still compares to the P/B value of 1.1 calculated from data for P and B in Elmgren (1984) for the entire Baltic Sea.

Other pelagic fish: Adopted from Jarre-Teichmann (1995) for "other pelagic fish".

Pelagic macrofauna (3.3 -7.5), Benthic macrofauna (0.32 -1.41), Benthic meiofauna (4.1 – 6.17), Bacteria / microorganisms (143 – 149), and Phytoplankton (87.5 – 151.6):

Value for each of these trophic groups represents the average from two published models (Jarre-Teichmann 1995 and Harvey et al. 2003).

Zooplankton**:** Value represents average P/B value for macro-, meso-, and microzooplankton (weighted for differing production). P/B values for each group correspond to mean of range for each group from a series of published trophic models (see Table 1 for an overview).

Benthic producers: Value adopted from two predecessor models (Wulff & Ulanowicz 1989 and Jarre-Teichmann 1995).

Consumption / Biomass ratio (Q/B)

Consumption is the intake of food by a group over the time period considered. In Ecopath it is entered as the ratio of consumption over biomass (Q/B) per year. Absolute consumption computed by Ecopath in our model is then a flow expressed in $gCm^{-2}y^{-1}$. Below, source of Q/B model inputs are described individually for each trophic group.

Harbour porpoises: Value is based on information in Andreasen et al. (2017).

Seals: Value is the mean of Q/B y^{-1} for grey seal and harbour seal. Q/B y^{-1} for both species were calculated based on information of individual weight and daily food intake obtained from Stiftung deutsches Meeresmuseum (www.deutsches-meeresmuseum.de/wissenschaft/infothek/artensteckbriefe) and from Wikipedia (www.wikipedia.org). The Q/B y^{-1} value used here for seals is at the upper limit of food intake since maximum weight and maximum food intake were used for the calculation.

(Sea-)birds: Value is the mean of a range (5 -14.41 / year) of consumption values in Tomczak et al. (2009) for seabirds from five coastal ecosystems in the southern and south-eastern Baltic Sea.

Q/B values for all fish groups except for Other pelagic fish were read off Table 3.3 in Mackinson and Daskalov (2007). An updated Q/B value for Juvenile cod (<=35 cm) was calculated by the multi-stanza routine of the EwE software based on P/B and Q/B values for Adult cod and original Q/B for Juvenile cod. Q/B for Juvenile cod is thus a trade-off between values from the literature and stanza routine logic. Q/B value for Flatfish is the weighted (by consumption) mean of 3.68 for dab, 3.2 for flounder, 2.78 for plaice, and 2.2 for turbot. Q/B for Herring is the weighted (by consumption) mean of 4.34 for adult and 5.63 for juvenile herring.

Other pelagic fish: Value was adopted from Jarre-Teichmann (1995) for "other pelagic fish".

Values for Pelagic macrofauna (10.6 / 25), Benthic macrofauna (9.5 / 13), and Benthic meiofauna (31.17 / 33.9) represent each the average of two values (in parentheses) from two published models (Jarre-Teichmann 1995 and Harvey et al. 2003).

Zooplankton**:** Value represents the average Q/B value for macro-, meso-, and microzooplankton (weighted for differing consumption). Q/B values for each group correspond to the mean of a range for each group from a series of published trophic models for the Baltic Sea (see Table 1 for details).

Bacteria/microorganisms: Value represents the average of two published models (248 in Harvey et al. 2003 and 355 in Jarre-Teichmann 1995 for Baltic Proper).

Original input data for biomass, P/B ratio, Q/B ratio, for all groups (except fishery) are shown in the input – output tables in the results section.

Unassimilated Part of the Food

To correctly estimate flow of matter within the WBS ecosystem an estimate of the fraction of the food that is not assimilated by a group is needed as input. Non-assimilated food is directed towards the detritus pool. Table 2 below shows the fraction of food ingested by trophic group that is not assimilated.

Table 2: Fraction of food ingested per year by trophic group that is not assimilated.

Group name	Unassimil. / consumption (year^{-1})	Data sources
Harbour porpoises	0.15	Used same as for "seals”.
Seals	0.15	Harvey et al. (2003) for ICES SDs 25-29 + 32, 1974-2000.
(Sea-) birds	0.2	Default
Adult cod (>38 cm)	0.185	Mean of indications in Harvey et al. (2003) and Jarre-Teichmann (1995)
Juvenile cod (<=38 cm)	0.185	Mean of indications in Harvey et al. (2003) and Jarre-Teichmann (1995)
Flatfish	0.185	Adopted from cod
Other demersal fish	0.175	Mean of indications in Sandberg et al. (2000, adopted from Elmgren 1984 and Wulff & Ulanowicz 1994) and Jarre-Teichmann (1995).
Herring	0.23	Mean of indications in Harvey et al. (2003) and Jarre-Teichmann (1995)
Sprat	0.23	Mean of indications in Harvey et al. (2003) and Jarre-Teichmann (1995)

Other pelagic fish	0.175	Mean of indications in Sandberg et al. (2000, adopted from Elmgren 1984 and Wulff & Ulanowicz 1994) and Jarre-Teichmann (1995).
Pelagic macrofauna	0.195	Mean of indications in Harvey et al. (2003) and Jarre-Teichmann (1995)
Benthic macrofauna	0.465	Mean of indications in Harvey et al. (2003), Sandberg et al. (2000) and Jarre-Teichmann (1995).
Benthic meiofauna	0.35	Mean of indications in Harvey et al. (2003), Sandberg et al. (2000) and Jarre-Teichmann (1995).
Zooplankton	0.3	Mean of indications in Harvey et al. (2003), Sandberg et al. (2000) and Jarre-Teichmann (1995).
Bacteria / microorganisms	0.1	Mean of indications in Harvey et al. (2003) and Sandberg et al. (2000).

Diet Composition (DC)

In our trophic WBS models predation links together the different groups represented in the model and must be entered for all groups except for primary producers and detritus. DCs are expressed in percentages of volume or weight and should sum up to 1 for each trophic group.

Harbour porpoises: From Tables 6 and 8 in Andreasen et al. (2017) for the western Baltic Sea.

Seals**:** Adapted from data read off Table 13 and Figs. 20 and 21 in Gilles et al. (2008). Origin of data is mainly from North Sea individuals. Diet information of grey seals in the central Baltic Sea (Lundström et al. 2007) was also considered.

(Sea-)birds**:** Composed from quantitative, semi-quantitative, and qualitative information on food and feeding of seabirds in the Baltic Sea in Mendel et al. (2008) and weighted for abundance of species in the study area.

Adult cod: From Appendix Tables in Funk (2017) for the WBS. Prey groups were adapted to WBS model groups.

Juvenile cod: Based on data from Zalachowski (1985) for the southern Baltic Sea from 1977 to 1981 and published models from the 80s and 90s for Baltic Proper and eastern Baltic Sea. Data from Funk (2017) were not used, since "fish" food was not specified. Values from both sources are comparable for zooplankton and macrobenthos as food items.

Flatfish**:** DC for flounder, dab, plaice, turbot, and brill were adopted from Table 3.4 in Mackinson & Daskalov (2007) and weighted (by consumption) before calculating the mean.

Other demersal fish: Composed of DC for (other) demersal fish from published models (Sandberg 2007, Sandberg et al. 2000, Jarre-Teichmann 1995).

Herring: Composed of DC for adult and juvenile herring from published models (Sandberg 2007, Harvey et al. 2003, Jarre-Teichmann 1995, Rudstam 1994, Elmgren 1984).

Sprat: Composed of DC for sprat from published models (Sandberg 2007, Harvey et al. 2003, Jarre-Teichmann 1995, Rudstam 1994, Elmgren 1984).

Other pelagic fish: Adapted from DC for other pelagic fish in Sandberg (2007) and Sandberg et al. (2000).

Pelagic macrofauna: Composed from DC for pelagic macrofauna in Harvey et al. (2003) and Jarre-Teichmann (1995). An assumed 5 % for cannibalism was included (based on pers. observation by S. Opitz: e.g. *Cyanea* feeding on *Aurelia aurita*).

DC for Benthic macrofauna**,** Benthic meiofauna and Bacteria / microorganisms were composed of DCs for these groups from published models (Sandberg 2007, Harvey et al. 2003, Sandberg et al. 2000, Jarre-Teichmann 1995).

Zooplankton**:** Composed of DC for macro-, meso-, and microzooplankton from published models (Sandberg 2007, Harvey et al. 2003, Sandberg et al. 2000, Jarre-Teichmann 1995). DC of Zooplankton was weighted for consumption of components.

Original DC composition input data are shown in the input - output tables in the Results section.

Fishery

The objectives of this study were to analyse the impact of commercial fisheries on the WBS ecosystem and to explore improved fisheries management options. To assemble reliable model inputs of fishery extractions was therefore of paramount importance.

The "fishery" in our WBS models is divided into pelagic and demersal fleets, a recreational fishery, and a bycatch / IUU (illegal, unreported, unregulated) fishery. Origin of inputs for landings, bycatch, and discards are described below (see also section *Data Sources* above). If not stated otherwise, fishery data represent values for ICES SDs 22 and 24 in 1994. Original catch / landing / discard values were transformed into $gWWm^{-2}year^{-1}$ by dividing weight (in tons) by area size (42.224 km^2). All landings, bycatch, and discard values in $gWWm^{-2}year^{-1}$ were then transformed into carbon by applying a conversion factor of 10:1.

Pelagic Fleet Landings

Herring: Original value for commercial landings (in tons) of WBSS herring in 1994 in subdivisions 20-24 is from Table 11 in ICES (2017i). This value was transformed into $gWWm^{-2}y^{-1}$ by dividing total weight of catch by area size (102, 288 km^2).

Sprat**:** Original value for commercial landings (in tons) in 1994 in WBS SDs 22 and 24 was extracted from Table 7.2 in ICES (2016b).

Other pelagic fish: Landings of "other fish" were read off appendix tables in Rossing et al. (2010) for Germany and Denmark. Mean from both countries for years 2003 to 2007 was used to calculate value. Total amount was divided into two equal parts for "Other pelagic fish" and "Other demersal fish".

Demersal Fleet Landings

Adult Cod (>35 cm): Original value for commercial landings in 1994 in WBS SDs 22-24 is from Table 6 in ICES (2017a). Original value was transformed into $gWWm^{-2}year^{-1}$ by dividing total weight by area size (44,746 km^2).

Flatfish**:**

- Dab landings extracted from Table 5.2 in ICES (2016b), (see also ICES 2017d).
- Flounder landings extracted from Table 4.2.2 in ICES (2016b), (see also ICES 2017 e,f).
- Plaice landings extracted from ICES (2017g,h) and Table 8.2.1 in ICES (2016b).
- Turbot landings extracted from Table 5.1 in ICES (2016b), (see also ICES 2017c).
- Brill landings extracted from Table 5.3 in ICES (2016b) for ICES SDs 22-24.

Landings were divided by area size (44,746 km^2) to obtain $gWWm^{-2}year^{-1}$.

Other demersal fish*:* Landings of "other fish" were read off appendix tables in Rossing et al. (2010) for Germany and Denmark. Mean from both countries for years 2003 to 2007 was used to calculate value. Total amount was divided into two equal parts for Other pelagic fish and Other demersal fish. Landings of salmon were added to Other demersal fish.

Recreational Fishery Landings

If not stated otherwise, catch values for recreational fishery used in the WBS models, originate from appendix tables for Germany and Denmark in Rossing et al. (2010). The mean from both countries for years 2003 to 2007 was used to obtain an estimate for the amount of fish extracted by that type of fishery.

Adult cod (>35 cm): Original value in ICES SDs 22-24 was adopted from Table 6 in ICES (2017a). This value was transformed into gWWm^{-2}y^{-1} by dividing total weight by area size (44,746 km^{2}).

Flatfish**:** 5% of catch of flounder, dab, plaice, turbot, and brill in ICES SDs 22-24.

Other demersal fish: 5% of catch of "other demersal fish" in SDs 22 and 24. Value for "salmon" (in Rossing et al. 2010) was added to "other demersal fish" in proportion to catch.

Herring: 2% of catch of herring in SDs 22 and 24.

Sprat: Values from Rossing et al. (2010) for Germany and Denmark resulted in a very low rate of 0.001 gCm^{-2}y^{-1} for both recreational and IUU fishery. Extraction by recreational fishery was therefore set to 0 in the model.

Other pelagic fish: 6% of catch of "other pelagic fish" in SDs 22 and 24.

Bycatch / IUU Fishery Landings

Since no official information on bycatch and IUU fishery landings was available to the authors, values of bycatch and IUU fishery used in the WBS models, originate from appendix tables for Germany and Denmark in Rossing et al. (2010). The mean from both countries for years 2003 to 2007 was used to obtain an estimate for the amount of fish extracted by that type of fishery.

Harbour porpoises, Seals, (Sea-)birds: Bycatch of fishery with fixed nets / traps:

To date, reliable quantitative information on bycatch numbers of marine mammals and birds ranges from scarce to non-existent for the model area. Therefore, also information from nearby regions was used to obtain preliminary bycatch estimates.

A recent estimate of 758 individuals of annual bycatch for the western Baltic harbour porpoise population for ICES SDs 21,22, and 23 was published by the North Atlantic Marine Mammal Commission and the Norwegian Institute for Marine Research (2019). When transforming this number into gCm^{-2}y^{-1} with an average weight of 50 kg per individual the resulting value amounts roughly to 10% of the annual population production.

The Finnish Game and Fisheries Research Institute (2013) estimated a by-catch rate of 7.7 – 8.4 % of grey seal population size for the eastern Baltic sea, while estimates of annual population growth rates for grey and harbour seal ranged from 3.5 % to 9.4 % for different periods and locations. A study by Vanhalato et al. (2014) suggests that >2000 seals - by-caught in the Eastern Baltic - represented at least 90% of the total by-catch in the whole Baltic Sea. Based on these informations we concluded that 10 % of annual population production being by-caught would be a conservative figure for the WBS model.

According to various authors (Zydelis et al. 2009, 2013, Bellebaum et al. 2012), a rough estimate of 100,000-200,000 waterbirds are drowning annually in the North and Baltic Seas, of which the great majority refers to the Baltic Sea. Derived from this information a preliminary estimate of 0,25 % of annual production was entered into the model to represent bycatch of seabirds.

Cod**:** 65 % of catch. This value was considered too high since both countries obtain the bulk of their landings form the eastern cod stock around Bornholm (ICES SD 25). Therefore, the same average estimate for all other fish groups (27% of landings) was used to calculate IUU of cod in WBS. Total amount was divided into two equal parts for adult and juvenile cod.

Flatfish, Other demersal fish, Herring, Sprat, and Other pelagic fish: 27% of catch in SDs 22 and 24 (corresponds to the average of all fish groups).

Benthic macrofauna: Bycatch of bottom trawling; an assumed 0.1% of annual production of benthic macrofauna was used as model input.

Fishery data used in the WBS model are listed in Tables 3 and 4 below.

Pelagic Fleet discards

All values for pelagic fleet discards were read off appendix tables for Germany and Denmark in Rossing et al. (2010). Mean % value from both countries for years 2003 to 2007 were used. Total amount for "other fish" in Rossing et al. (2010) was divided into two equal parts for Other pelagic fish and Other demersal fish.

Herring and Sprat**:** Discards of the herring and sprat fishery are considered negligible by ICES in contrast to estimates for Germany and Denmark in Rossing et al. (2010). Mean % value from both countries in 1994 was used here to calculate Herring (10%) and Sprat (11%) discard from catch data for both species in WBS.

Other pelagic fish**:** 12% of catch in WBS.

Demersal Fleet Discards

According to ICES (2017b) and Valentinsson et al. (2019) discards of the cod fishery in the Baltic sea consist primarily of juvenile cod and therefore discards of the cod fishery were set equal to catch of juvenile cod (discards for western Baltic cod in 1994 – assumed to be mostly juvenile cod - are based on values from Table 6 in ICES (2017a) in subdivisions 22-24) All other values for demersal fleet discards were read off appendix tables for Germany and Denmark in Rossing et al. (2010). Mean % value from both countries for years 2003 to 2007 were used to calculate discard rate for Flatfish (47 %) and Other demersal fish (12 %). Total amount for Other fish in Rossing et al. (2010) was divided here into two equal parts for Other pelagic fish and Other demersal fish.

Table 3: Commercial pelagic and demersal fleet landings, recreational catch and bycatch (seals, birds, and porpoises in gill and entangling nets) in ICES SDs 22 and 24 (WBS) in 1994 in $gCm^{-2}year^{-1}$. Values in *italics* were calculated based on figures in Rossing et al. (2010).

Group name	Pelagic fleet	Demersal fleet	Recreatio-nal fishery	Bycatch/ IUU fishery	Total extracted by fishery	Total extracted by fishery %
seals				0.000000475	4.75E-07	0.0001
(sea-) birds				0.00005	0.00005	0.01
harbour porpoises				0.000104	0.000104	0.02
Cod						
cod >35 cm		0.04785	0.0041	0.00644	0.05839	12.86
cod <=35 cm				0.00644	0.00644	1.42
flat fish		0.01725	*0.0015832*	0.0064022	0.0252354	5.56
other demersal fish		*0.0308821*	*0.00169851*	0.00830728	0.0408879	9.01
herring	0.169		*0.00338*	0.045461	0.217841	47.99
sprat	0.023			0.006725	0.029725	6.55
other pelagic fish	*0.03004*		*0.00165224*	0.00808094	0.0397732	8.76
pelagic macrofauna						
benthic macrofauna		0.0355			0.0355	7.82
benthic meiofauna						
zooplankton						
bacteria/microorganisms						
phytoplankton						
benthic producers						
detritus/DOM						
Sum	0.22204	0.1314821	0.01241395	0.088010895	0.4539469	100.00

Other Discards

Information on discards from recreational and IUU fishery was not available to the authors although attempts were made to obtain such data from vTI through the intervention of BfN.

Table 4: Fishery discards in ICES SDs 22 and 24 (western Baltic Sea) in 1994 in $gCm^{-2}year^{-1}$. Values in *italics* were calculated based on figures in Rossing et al. (2010).

Group name	Pelagic fleet	Demersal fleet	Recreational fishery	Bycatch /IUU fishery	Total
seals	no info	no info	no info	no info	
(sea-) birds	no info	no info	no info	no info	
harbour porpoise	no info	no info	no info	no info	
Cod					
cod >35 cm			no info	no info	
cod <=35 cm		0.005	no info	no info	0.005
flat fish		*0.0124986*	no info	no info	0.0124986
other demersal fish		*0.00376761*	no info	no info	0.00376761
herring	0.016562		no info	no info	0.016562
sprat	*0.002675*		no info	no info	0.002675
other pelagic fish	*0.00366496*		no info	no info	0.00366496
pelagic macrofauna			no info	no info	
benthic macrofauna			no info	no info	
benthic meiofauna			no info	no info	
zooplankton			no info	no info	
bacteria/microorganisms			no info	no info	
phytoplankton			no info	no info	
benthic producers			no info	no info	
detritus/DOM			no info	no info	
Sum	0.02290196	0.02126621			0.04416817

Data Pedigree

Quality of model inputs is an important issue when judging the results of a modelling exercise. In that context a qualitative ranking of model inputs – named here “data pedigree” - was prepared and is presented in Table 5 below. The first part provides ranking definitions applied in the second part to classify quality of model inputs.

Local input data for B of a group or species where ranked by precision (high, medium, low); in cases where no local data of B where available, as was the case for seals and the majority of lower trophic level groups, values were adopted from other Baltic sea models. For other pelagic and demersal fish the program estimated a more realistic value than the original ones calculated from DATRAS BITS data.

Catch data applied where “local high precision” data, except for marine mammals and birds, where published information on bycaught numbers of individuals were transformed into a rough estimate for “catch”. P/B and Q/B inputs ranged from “same species – similar system – high precision” to “from other model for similar system” according to availability. Input data for DC ranged from “sampling – same system – high precision” to “from other model for similar system” which applied to the majority of trophic groups / species.

Table 5: Quality pedigree of model inputs; LP = low precision, MP = medium precision, HP = high precision, sim = similar

Part 1: Ranking definitions

Rank	Biomass	Rank	Production / Biomass P/B	Rank	Consumption / Biomass Q/B	Rank	Diet	Rank	Catch
1	Sampling locally, HP	1	Same spec., sim. Sys., HP	1	Same spec., sim. Sys., HP	1	Sampling, same system, HP	1	Local data, HP
2	Sampling locally, MP	2	Sim species, sim system, HP	2	Sim species, sim system, HP	2	Sampling, similar system, HP	2	Local data, MP
3	Sampling locally, LP	3	Same species, sim system, LP	3	Same species, sim system, LP	3	Sampling, same system, LP	3	Local data, LP
4		4	Sim species, sim system, LP	4	Sim species, sim system, LP	4	Sampling, similar system, LP	4	
5	From other model	5	From other model for sim system	5	From other model for sim system	5	From other model for sim system	5	From other model for sim system
6	Estimated by Ecopath	6	Estimated by Ecopath	6	Estimated by Ecopath	6	Estimated by Ecopath	6	Estimated by Ecopath
7	Estimated by authors*	7	Estimated by authors*	7	Estimated by authors*	7	Estimated by authors*	7	Estimated by authors*

Part 2: Qualitative ranking of model parameter inputs

Group name		Biomass		P/B		Q/B		Diet		Catch
Seals	5	From other model	3	Same spec., sim system, LP	3	Same spec., sim system, LP	2	Sampling, similar system, HP	7	Estimate*
(Sea-)birds	3	Sampling locally, low precision	4	Sim species, sim system, LP	4	Sim species, sim system, LP	3	Sampling, same system, LP	7	Estimate*
Harbour porpoises	1	Sampling locally, high precision	3	Same spec., sim system, LP	3	Same spec., sim system, LP	1	Sampling, same system, HP	7	Estimate*
Adult cod > 35 cm	2	Sampling locally, MP	1	Same spec., sim. Sys., HP	1	Same spec., sim. Sys., HP	1	Sampling, same system, HP	1	Local data, HP
Juvenile cod <=35 cm	2	Sampling locally, MP	6	Estimated by Ecopath	1	Same spec., sim. Sys., HP	1	Sampling, same system, HP	3	Local data, LP
Flatfish	2	Sampling locally, MP	1	Same spec., sim. Sys., HP	1	Same spec., sim. Sys., HP	5	From other model for sim system	1	Local data, HP
Other demersal fish	6	Estimated by Ecopath	4	Sim species, sim system, LP	4	Sim species, sim system, LP	5	From other model for sim system	3	Local data, LP
Herring	2	Sampling locally, MP	1	Same spec., sim. Sys., HP	1	Same spec., sim. Sys., HP	5	From other model for sim system	1	Local data, HP
Sprat	2	Sampling locally, MP	1	Same spec., sim. Sys., HP	1	Same spec., sim. Sys., HP	5	From other model for sim system	1	Local data, HP
Other pelagic fish	6	Estimated by Ecopath	4	Sim species, sim system, LP	4	Sim species, sim system, LP	5	From other model for sim system	3	Local data, LP
Pelagic macrofauna	5	From other model	5	From other model for sim system	5	From other model for sim system	5	From other model for sim system		-1
Benthic macrofauna	1	Sampling locally, high precision	5	From other model for sim system	5	From other model for sim system	5	From other model for sim system	3	Local data, LP
Benthic meiofauna	1	Sampling locally, high precision	5	From other model for sim system	5	From other model for sim system	5	From other model for sim system		-1
Zooplankton	5	From other model	5	From other model for sim system	5	From other model for sim system	5	From other model for sim system		-1
Bacteria / microorganisms	5	From other model	5	From other model for sim system	5	From other model for sim system	5	From other model for sim system		-1
Phytoplankton	5	From other model	5	From other model for sim system		-1		-1		-1
Benthic producers	5	From other model	5	From other model for sim system		-1		-1		-1
Detritus / DOM	5	From other model	5	From other model for sim system		-1		-1		-1

*see text on bycatch / IUU fisheries above.

Balancing Process

Flows based on original model inputs did not balance in every case, i.e. consumption by certain system elements exceeded production of their prey - in some cases considerably.

Imbalances of model inputs, originating from prey groups with EEs >1 were then balanced by applying the following strategies:

Raise the biomass (B) of a trophic group by a) immigration or b) letting the model software estimate the minimum B needed to satisfy predator requirements (including fisheries) by entering a limiting EE value of 0.99. In cases where a) and b) were not applicable, "import" of the respective food item by the predator was assumed. Furthermore, c) small shifts of diet between food items served to eliminate "questionable" food requirements (derived from published models) or to smooth out initial inputs. Hereafter, the balancing process is described in detail by trophic group.

Juvenile cod*:* Excess predation pressure by its main predator, the Harbour porpoises (30 % of its diet), was shifted to "import" hypothesizing that if not enough juvenile cod is available within the system highly mobile harbour porpoises must obtain this food item elsewhere in a neighbouring system (Kattegat, North Sea, etc.). Consumption by Herring was viewed as "questionable", therefore reduced from 1.7% to 0% and shifted to "import". For the same reason the very small share (0.025%) of Juvenile cod in the diet of Benthic macrofauna was set to 0 and shifted to Benthic macrofauna (cannibalism).

Other demersal fish**:** Strategy b) was applied since initial input value from DATRAS data of 0.043 gCm^{-2} was way to low to satisfy food requirements of predators (including fishery).

Other pelagic fish: For the same reason as Other demersal fish, strategy b) was also applied to this group; start value from DATRAS was 0.003 gCm-2.

Sprat: Predation by Herring was considered questionable (eventually only larvae as part of macrozooplankton), therefore reduced to 0 and shifted to Zooplankton. Predation by Benthic macrofauna was reduced from 0.3 % to 0.02 % and shifted to Benthic macrofauna (cannibalism).

Pelagic macrofauna**:** Predation by Herring was set to 0 since *Mysis* in our model forms part of macrozooplankton instead of Pelagic macrofauna as in the published models – source of information on herring diet.

Benthic meiofauna**:** A 90% reduction of this group in the diet of Benthic macrofauna reduced EE of Benthic meiofauna to 0.824. The missing amount in the diet composition of Benthic macrofauna was shifted to Detritus DOM.

Bacteria/Microorganisms: Consumption by Zooplankton was reduced from 0.228 to 0.15 and shifted to Zooplankton (cannibalism) and Detritus/DOM. Cannibalism within this group was reduced from 18.8% to 15% and shifted to Detritus/DOM. Final EE of 0.926 is <1 but still very high.

Phytoplankton: A slight reduction of grazing pressure by Benthic macrofauna, Zooplankton, and Bacteria/microorganisms resulted in a modest reduction of EE from 0.974 to 0.964. This value is still very high and should be more in the range of 0.4 to 0.6. Standing stock B of 2.16 gCm^{-2} for phytoplankton was adopted from published models for other parts of the Baltic Sea. More recent values for years 1990 to 1997, e.g. in Thamm et al. (2005) for the WBS were even lower and in the range of 1.5 gCm^{-2} .

Benthic producers: Consumption by Benthic macrofauna was reduced from 1.25% to 0.1% and shifted to Detritus/DOM. The resulting EE of 0.952 is < 1 but still very high.

Start and end EEs for all trophic groups and shifts within the diet matrix are listed in the input-output tables in the Results section below.

Dynamic Modelling of Different Fishery Management Scenarios

This part of the study was performed in two steps.

Step 1: Using the mass-balanced *Ecopath* model for 1994 as a starting point, model runs were executed with *Ecosim* after loading time series of B, catch and F / ExplR of important commercial fish stocks such as cod, herring, sprat and several flatfish species lumped into a "flatfish" box (see "Trophic Groups in the Model of the WBS Ecosystem") for years 1994 to 2016 into the model software. Purpose was to check whether the model reflected realistic fishing scenarios of the past prior to applying it to fishing scenarios reaching far into the future. F or ExplR was the driving parameter that would eventually be modified for a better fit between modelled and external B and catch data (thus the depending parameters).

Since harbour porpoise data were not readily available to the authors, a time series for this group was derived (see Figure 3) from rough quantitative information over the past 25 years (Hammond et al. 1995, Hammond et al. 2002, and SCANS II 2008). It was then included into the modelling process with the objective to test the longstanding fisherman's view that this top predators is a serious competitor for fish.

Cod F and herring ExplR were fitted in such a way as to reduce sum of squares (SS) for these stock parameters. For cod there was a considerable deviation of model outputs from input data for the time period 1994 to 2003, i.e. for less than the first half of the time series. Model algorithm and - consequently model output - is sensitive to the start value of a time series. Thus, F inputs were reduced to better fit model data (mirrored in the reduction of SS). Fishing pressure during that time period was obviously less than indicated by data in DATRAS.

For herring, the fitting exercise was more challenging to deal with since a large proportion of the WBSS herring stock spends part of its annual cycle outside of the model area for feeding. Except for catch data, no data for B and F were available for the model area. It was thus estimated as a first approach, that spawning stock biomass inside the model area is about half the size of the area covered by the WBSS herring stock. ExplR was then calculated from catch/B. ExplR was then adapted slowly for a better fit of model calculations to inputs. Table 10 in the Results section shows the complete set of time series 1994 – 2016 with adult cod F and herring ExplR fitted as described.

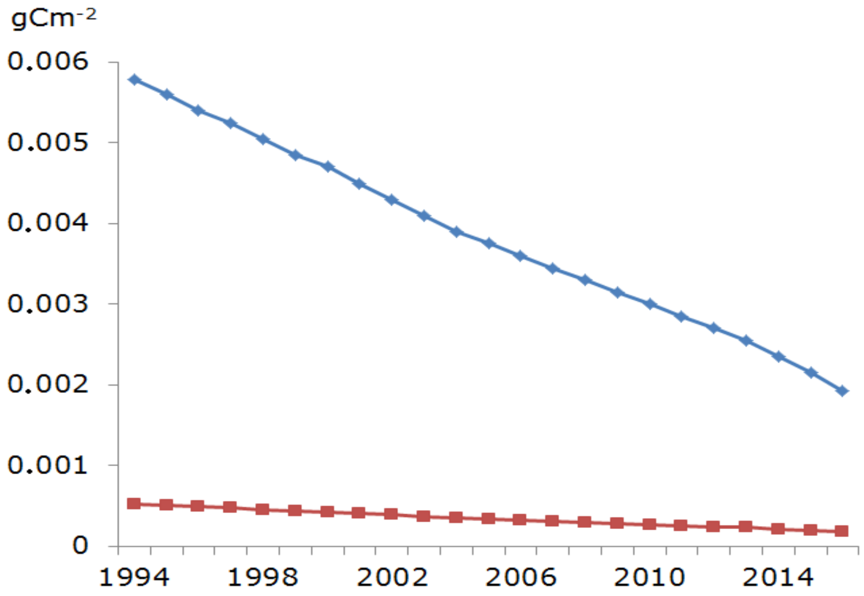

Figure 3: Tentative time series of harbour porpoise biomass (top line in blue) and catch (bottom line in red) in the WBS ecosystem for years 1994 to 2016.

Step 2: In light of the question "Which EBFM provides for (1) the most economically important species in the German EEZ and the German NATURA 2000 areas of the Baltic Sea, (2) the highest catch with the least negative impacts on the ecosystem as specified by the CFP ($F< F_{msy}$) and the MSFD ($B > B_{msy}$) , (3) healthy size and age structure of the stocks, and (4) food web elements that ensure long-term abundance and reproduction)?", step 2 involved model supported calculation of possible impacts changes in fishing pressure may exert on all trophic groups in the WBS ecosystem.

Starting from a

1. Scenario *No fishing*: Stock development resulting from the closure of all fishing activities from 2017 until 2050,

four distinct future fishing mortality scenarios have been tested covering a 34 years time span (2017 - 2050) including:

2. Scenario *Business as usual* (BAU): Stock development from 2017 until 2050 under the same fishing pressure as in 2016.
3. Scenario F_{msy}: Stock development when fishing pressure F from 2017 until 2050 is reduced (if previously higher) or raised (if previously lower) to a value F, where fishery yield / catch is sustainably at or slightly below a maximum level (if available).
4. Scenario *Half* F_{msy}: Stock development when fishing pressure F from 2017 until 2050 is reduced to (if previously higher) ½ F_{msy}.
5. Scenario *Ecosystem Based Fisheries Management* (EBFM): Herring and sprat fished at ½ F_{msy} and other stocks at 80% F_{msy}.

Table 6 shows the species / trophic groups and respective fishing mortalities used for the simulation of fishing management scenarios into the future. F_{msy} values indicated in Table 6 below are official reference values for the respective stocks from ICES.

Table 6: Fishing mortalities (F) used for the simulation of fishing management scenarios into the future.

Species / Trophic group	F 2016 and earlier	F_{msy}	F = 0.8 F_{msy}	F = 0.5 F_{msy}
Harbour porpoises	0.144	0.144		0.072
Adult cod	0.99	0.26	0.208	0.13
Juvenile cod*	0.461	0.121	0.097	0.061
Herring*	1.5	0.32		0.16
Sprat	0.223	0.26		0.13
Flatfish*	0.178	0.154		0.077
- *Plaice, Turbot, Brill*	*0.322*	*0.37*	*0.296*	*0.185*
- *Flounder**	*0.179*	*0.179*	*0.179*	*0.179*
- *Dab**	*0.053*	*0.053*	*0.053*	*0.053*

*Exploitation rate (catch / biomass) used since no F was available for these groups. ICES uses biomass at the beginning of the year to calculate F.

Results

Starting Situation in 1994 Represented by the Static Model

Input – Output Tables for the static model and results of the balancing process (see above) are presented in the following "before-after balancing" tables.

Table 7 below provides an overview of basic model parameters before and after balancing.

Table 8 shows DC values for WBS ecosystem model components before and after balancing.

Table 9 shows consumption by ecosystem components after balancing and extraction by fisheries.

Except for benthic producers and pelagic (mostly jellyfish) and benthic macrofauna all system resources (trophic groups) were scarce; benthic macrofauna therefore exerted a strong predation pressure on its prey organisms - usually low in the food web. On the other hand, benthic macrofauna offered a rich source of food for organisms higher in the food web, particularly for demersal fish species and seabirds.

Consumption of fish by fisheries and other predators exeeded the annual production of fish. Competition for fish as food (mainly juvenile cod, herring and sprat) occurred between the fisheries and other top predators such as harbour porpoises and seals, with the fishery taking about 4-5 times more than harbour porpoises and seals combined (see Figs. 38a – 41a). Strong competition for herring and sprat as food occurred between fisheries, harbour porpoises, and (adult and juvenile) cod (see Table 9 for comparison of predator impact including fisheries).

Biomass production of small pelagics (particularly herring and sprat) in the system was hardly sufficient to satisfy food requirements by natural predators and at the same time withdrawal by fisheries (to be demonstrated by the high EEs for these groups, see Table 7). Fisheries withdrew too many small pelagics which are an important food source particularly for adult and juvenile cod. They were forced to shift their dietary needs to other food sources such as benthic macrofauna. Particularly for herring the demand could only be balanced assuming immigration of herring and to a small extent – sprat.

Such migrations are well known for the WBSS herring, which feed in summer off western Sweden and bring biomass increased by somatic growth back into the WBS when they return (e.g. van Deurs et al. 2016, Clausen et al. 2015, van Deurs & Ramkaer 2007, Nielsen 2001).

Also, other species can enter the WBS e.g. as summer guests (known for mackerel (*Scomber scombrus*) or mullets (*Mugil cephalus*)) and are preyed upon in the system. These species form part of "other" pelagic and "other" demersal fish, respectively.

Predators like harbour porpoises had to look for other food sources as well, since there was not enough fish – and particularly juvenile cod - in the system to satisfy their dietary needs. As harbour porpoises do not feed on macrobenthos, they are forced or to go hungry or to search for food elsewhere (Kattegat, Skagerrak, North Sea).

Table 7: Basic Model Parameters before and after balancing. Numbers in bold = estimated by the model software; numbers in **bold** = reduction, numbers in ***bold italics*** = increase; numbers in grey fields = estimated by model software.

Group No.	Group name	Trophic level	Biomass End (gC/m²)	Biomass Start (gC/m²)	Z (/year)	Production / Biomass (/year)	Consumption / Biomass (/year)	Net migration (gC/m²/year)	Ecotrophic efficiency Start	Ecotrophic efficiency End
0	Recreational fishery	4.44								
0	pelagic fleet	4.40								
0	bycatch / IUU fishery	4.41								
0	demersal fleet	4.10								
1	seals	4.39	5.00E-05			0.095	20.000		0.058	***0.100***
2	(sea-) birds	3.73	0.00572			3.565	12.282		0.050	***0.100***
3	harbour porpoises	4.40	0.00579			0.180	28.000		0.052	***0.500***
	Cod									
4	cod >35 cm	3.52	0.071		0.9		1.92		0.751	***0.937***
5	cod <=35 cm	3.19	***0.0377***		0.683		**3.815**		5.543	**0.984**
6	flat fish	3.22	0.020			0.928	3.257	-0.0218	2.129	**0.977**
7	other demersal fish	3.42	***0.287***	0.043		0.640	3.950		4.186	0.990
8	herring	3.40	0.266			0.860	4.500	-0.065	1.283	**0.998**
9	sprat	3.40	0.114			1.500	7.660	-0.020	4.066	**0.975**
10	other pelagic fish	3.48	***0.578***	0.003		0.280	2.850		66.025	0.990
11	pelagic macrofauna	3.18	0.202			5.400	17.800		0.182	***0.285***
12	benthic macrofauna	2.01	41.000			0.865	11.250		0.085	***0.109***
13	benthic meiofauna	2.00	0.360			5.135	32.500		8.809	**0.824**
14	zooplankton	2.43	0.697			76.690	271.360		0.640	**0.849**
15	bacteria/microorganisms	1.98	0.315			146.000	301.000		1.346	**0.926**
16	phytoplankton	1	2.161			120.000			0.974	**0.964**
17	benthic producers	1	1.000			234.000			1.190	**0.020**
18	detritus/DOM	1	782.500					-212.400	0.738	**0.643**
	Total		829,622							

Tab. 8: Diet composition matrix for the WBS ecosystem before (b) and after (a) balancing; numbers in **bold** = reduction, numbers in ***bold italics*** = increase.

Group no.	Prey \ Predator	1	2	3b	3a	4	5	6	7	8b	8a	9	10	11	12b	12a	13	14b	14a	15b	15a
1	seals																				
2	(sea-) birds																				
3	harbour porpoises																				
4	cod >35 cm			0.0093	0.0093																
5	cod <=35 cm	0.104	0.03	0.3007	**0.033**	0.043	0.003	0.00031		0.017	**0**				$2.5*10^{-5}$	**0**					
6	flat fish	0.077	0.01			0.013															
7	other demersal fish	0.145	0.23	0.39	0.39	0.193	0.036	0.10714	0.011				0.0035								
8	herring	0.434	0.07	0.26	0.26	0.071	0.012	0.00016													
9	sprat		0.05	0.04	0.04	0.048	0.016	0.0011	0.12	0.0345	**0**				0.00267	**0.0002**					
10	other pelagic fish	0.24	0.06				0.04		0.093				0.0005								
11	pelagic macrofauna		0.03					0.03672		0.0035	**0**		0.077	0.05							
12	benthic macrofauna		0.31			0.613	0.812	0.82289	0.576	0.063	0.063	0.0002	0.032		0.0045	***0.006***					
13	benthic meiofauna		0					0.0008							0.0352	**0.0032**	0.004				
14	zooplankton		0.03			0.019	0.073	0.03087	0.2	0.877	***0.91***	0.9798	0.887	0.75	0.0025	0.0026		0.152	***0.2***		
15	bacteria / microorganisms																	0.228	**0.15**	0.198	**0.15**
16	phytoplankton													0.2	0.2222	0.222		0.554	**0.55**	0.469	**0.45**
17	benthic producers														0.0125	**0.01**					
18	detritus/DOM		0.05				0.008			0.005	0.005	0.02			0.7204	***0.756***	0.996	0.066	***0.1***	0.333	***0.4***
	import		0.13	0	***0.2677***					0	***0.0197***										
	total	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Import seabirds: part of diet covered by freshwater and terrestrial organisms.

Import harbour porpoises and herring: juvenile cod that should be available in neighbouring marine areas.

Table 9: Consumption matrix (values in $gCm^{-2}y^{-1}$) for the WBS ecosystem after balancing; numbers in **bold** = reduced during balancing, numbers in ***bold italics*** = increased during balancing; fishery catches in *italics* were calculated based on figures in Rossing et al. (2010) and official landings. Numbers >0 =<0.00009

	Predator / Prey	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Phyto-plankton	Benthic producers	Detritus	Import	Sum
	pelagic fleet								0.169	0.023	*0.030*										0.222
	demersal fleet				0.048		0.017	*0.031*					0.036								0.131
	recreational fishery				0.004		*0.002*	*0.002*	*0.003*		*0.002*										0.012
	bycatch/IUU fishery	>0	0.002	0.0005	0.006	0.006	0.006	0.008	0.045	0.007	0.008										0.090
	discards				0.005		*0.012*	*0.004*	0.017	*0.003*	*0.004*										0.044
1	seals					>0	>0	>0	>0		>0										0.001
2	(sea-) birds					0.002	0.001	0.016	0.005	0.004	0.004	0.002	0.022		0.002				0.004	0.009	0.070
3	harbour porpoises				0.002	**0.005**		0.063	0.042	0.006										***0.043***	0.162
4	cod >35 cm					0.006	0.002	0.026	0.010	0.007			0.084		0.003						0.136
5	cod <=35 cm					>0		0.005	0.002	0.002	0.006		0.117		0.010				0.001		0.144
6	flatfish					>0		0.007	>0	>0		0.002	0.055	>0	0.002						0.066
7	other demersal fish							0.012		0.135	0.105		0.649		0.226						1.128
8	herring					**0**				**0**		***0***	0.075		***1.092***				0.006	**0.024**	1.197
9	sprat												>0		0.856				0.017		0.873
10	other pelagic fish							0.006			0.001	0.126	0.052		1.452						1.637
11	pelagic macrofauna											0.179			2.690		0.717				3.587
12	benthic macrofauna												***2.768***	**1.476**	1.199		102.490	**4.613**	***348.705***		461.250
13	benthic meiofauna																		11.653		11.700
14	zooplankton														***37.825***	**28.369**	**104.018**		***18.912***		189.124
15	bacteria / microorganisms															**14.222**	**42.667**		***37.926***		94.815
	Sum	>0	0.002	0.0005	0.060	0.025	0.040	0.181	0.293	0.187	0.159	0.310	3.857	1.476	45.357	42.591	249.892	4.613	417.225	0.076	766.345

Even when excluding fishery from the model there is not sufficient juvenile cod in the system to satisfy feeding requirements of its natural predators such as harbour porpoises, birds, and adult cod. Lack of juvenile cod must be balanced through "imports", i.e. predators find this type of food partly in adjacent ecosystems (Kattegat, Skagerrak, Central Baltic Sea), or by immigration of juveniles.

According to model results cannibalism occurs within the cod population, with 4.3 % of the diet of adult cod consisting of juvenile cod, and 0.3 % of the diet of juvenile cod consisting of other juvenile cod. These percentages are low and have only a marginal effect on the population.

Trophic Flows within the Western Baltic Sea Food Web

Figure 4 provides a schematic representation of trophic groups and flows within the WBS food web.

In this and the subsequent graphs, trophic groups are represented by squares. The area of the squares is proportional (on a square-root scale) to the biomass of the group. The colour of the squares is related to the type of group, with dark grey = detritus, green = primary producers, yellow = secondary non-fish producers, blue = fish, red = fishing fleets). Trophic flows are indicated by grey lines. In Figures 4 to 15 with individual groups highlighted, inflows to a compartment from other groups are green, outflows to other system elements (predators) are bright red. Flow size is relative and scaled individually by group and cannot be compared directly to flows of another group. Also, size of in- and outflows to and from a group cannot be compared directly. The true magnitude of the flows between groups (including fisheries) is presented in Table 9 above. A dark blue arrow indicates import of food from adjacent ecosystems by a certain group. A red arrow indicates that biomass of a certain group was raised by immigration from adjacent ecosystems. A curved green arrow indicates cannibalism within a group. Note: Size of arrows is not in proportion to the size of import / immigration / cannibalism.

Harbour porpoises and seals are the top predators (trophic level > 4) in the system (see Figs. 4, 5, and 6), but have only a small biomass and hence a small consumption compared to the fisheries operating at the same trophic level, i.e. pelagic fleet, recreational fleet and bycatch/IUU fishery (Figs. 4, 8, 9, 15, see also Table 9 for a comparison of consumption / extraction). The demersal fleet operates at a slightly lower trophic level (Fig. 12). Adult and juvenile cod (Figs. 10 and 11), flatfish and other demersal and pelagic fish are the main predators on herring, sprat and benthic macrofauna.

Harbour porpoises (Fig. 5) and seabirds (Fig. 7) also feed in part outside of the WBS, as indicated by dark blue arrows.

Figure 13 illustrates the key role of herring in the WBS by magnifying the flows to (green) and from (red) that group. Herring feeds mainly on zooplankton and makes the energy that is contained in the tiny animals of that level available to a wide array of predatory fish, birds, seals and harbour porpoises that cannot consume plankton, fisheries included. The fishery “consumed‟ about 95% of the annual production of the herring stock – to compensate lack of herring as prey for “other predators” immigration of herring from adjacent ecosystems was assumed (symbolized by a red arrow).

Figure 14 shows the role of sprat in the WBS. While it also transports energy from the zooplankton level to the upper trophic levels, its role is less prominent compared to herring, because its biomass has been drastically reduced by past overfishing.

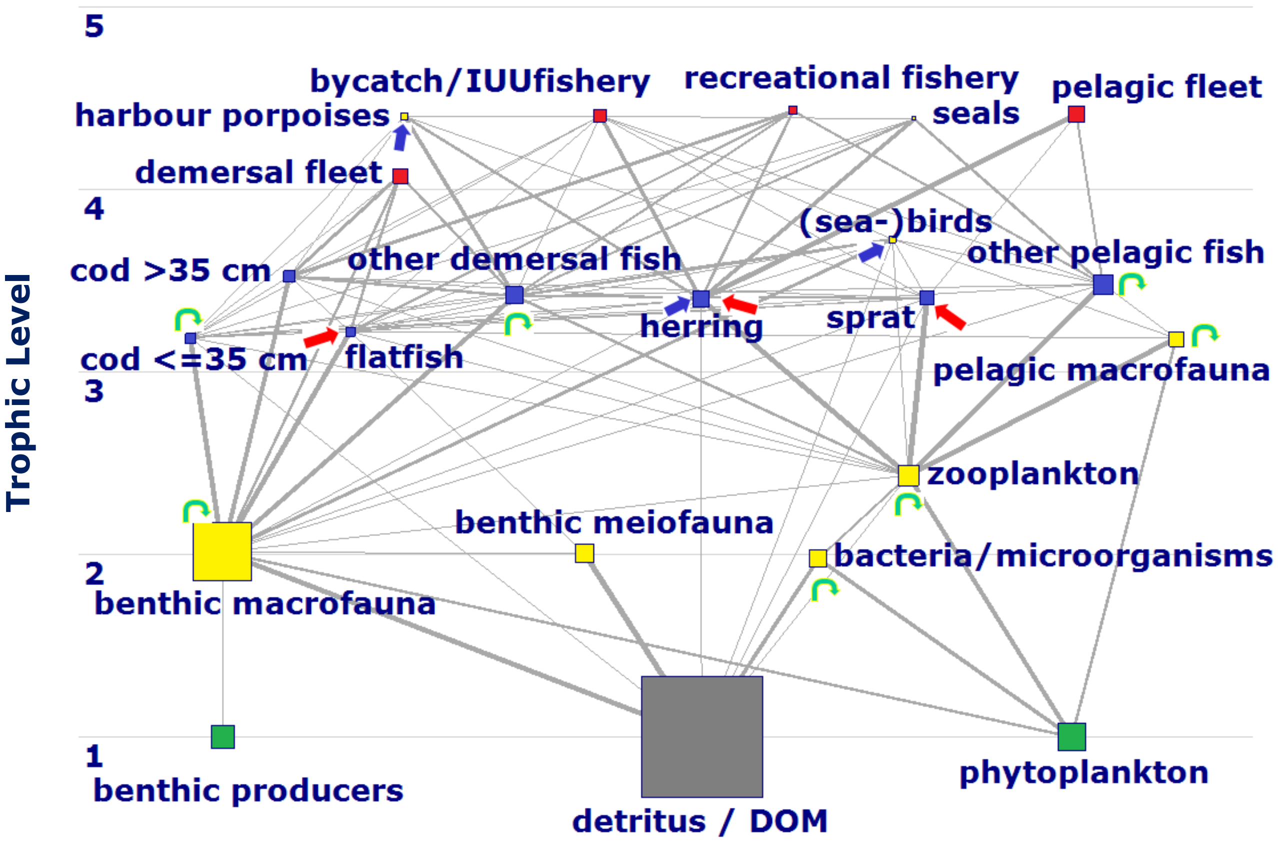

Figure 4: Representation of the trophic flows (grey) between 18 major species or functional groups (squares) in the WBS. Since the flow diagram routine of the EwE software does not allow color coding of flows by size see Table 9 above for size of flows in absolute numbers.

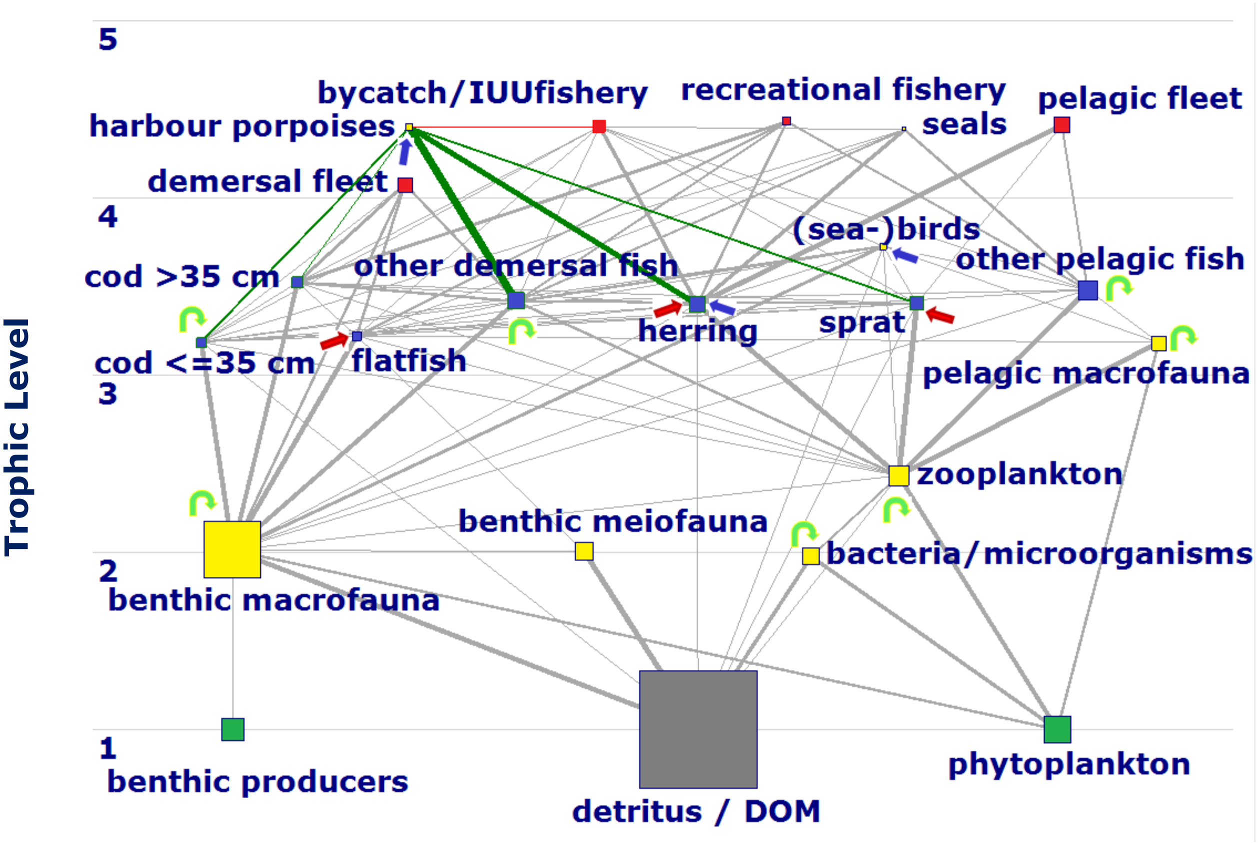

Figure 5: **Harbour porpoises** (with fishery acting as predator through bycatch).

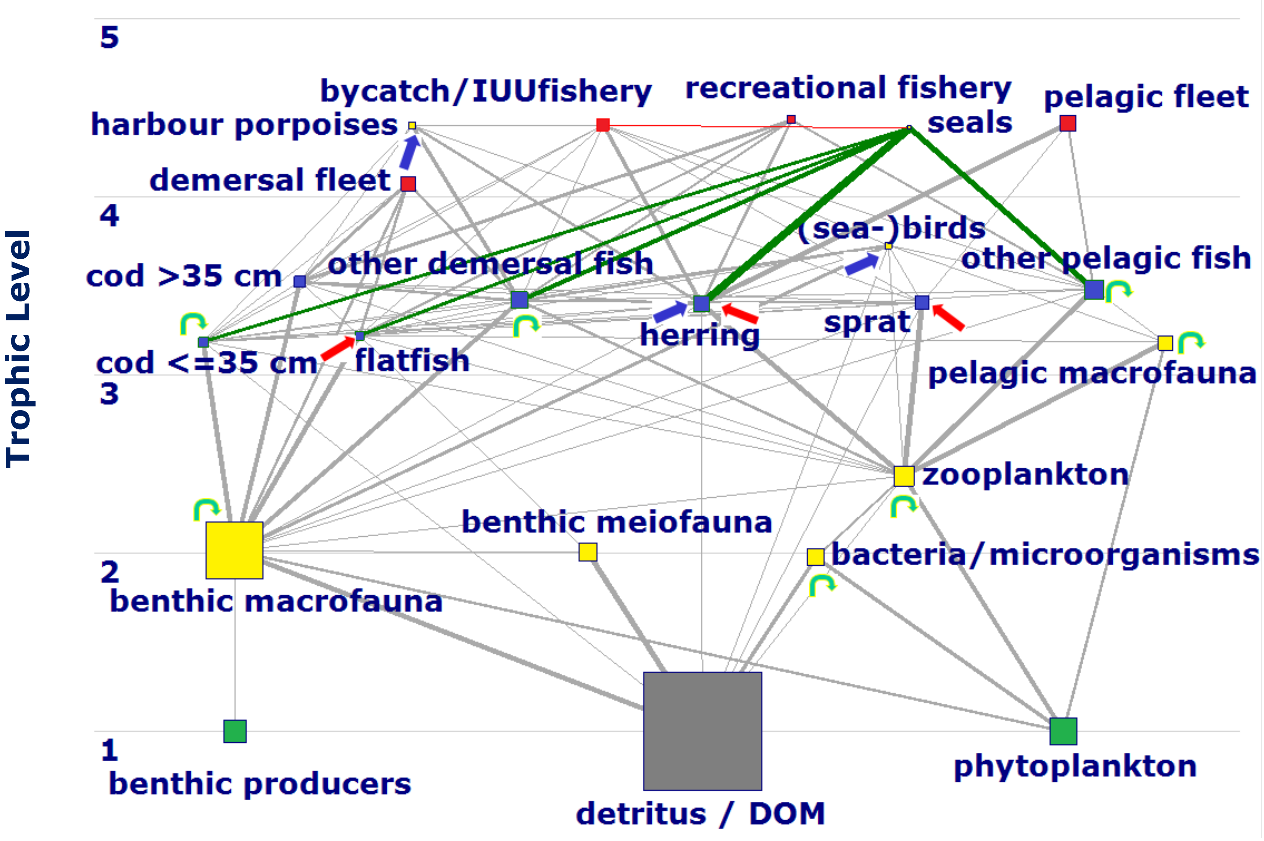

Figure 6: **Seals** (with fishery acting as predator through bycatch)**.**

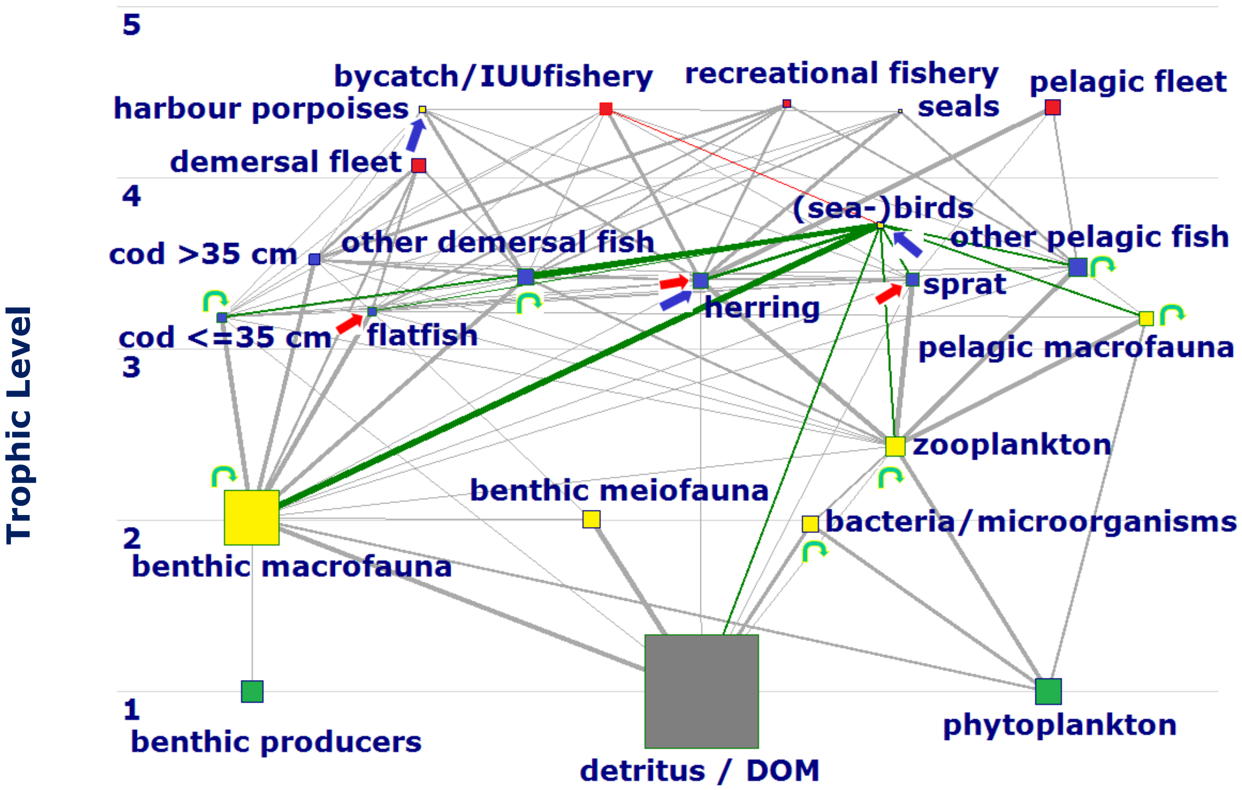

Figure 7: **(Sea-)birds** (with fishery acting as predator through bycatch).

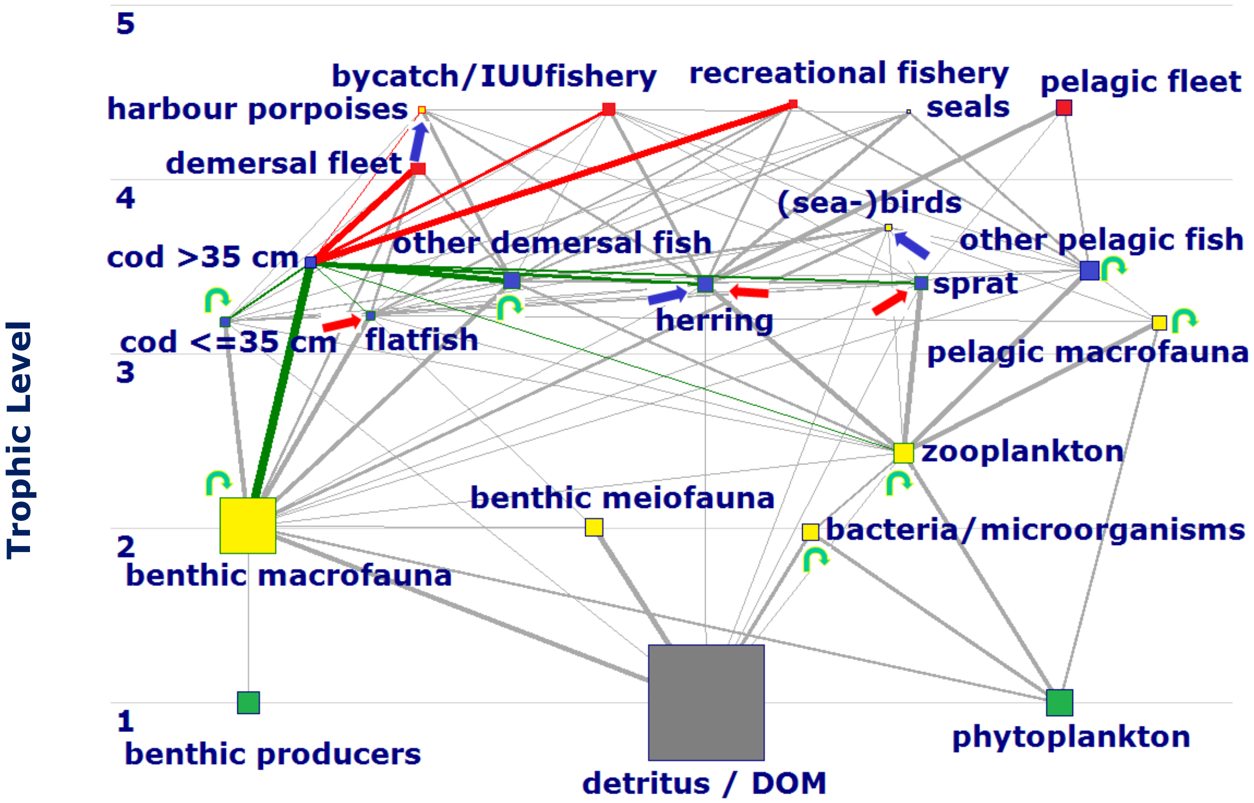

Figure 8: **Adult cod** (with fishery acting as predator through catches, discards and bycatch).

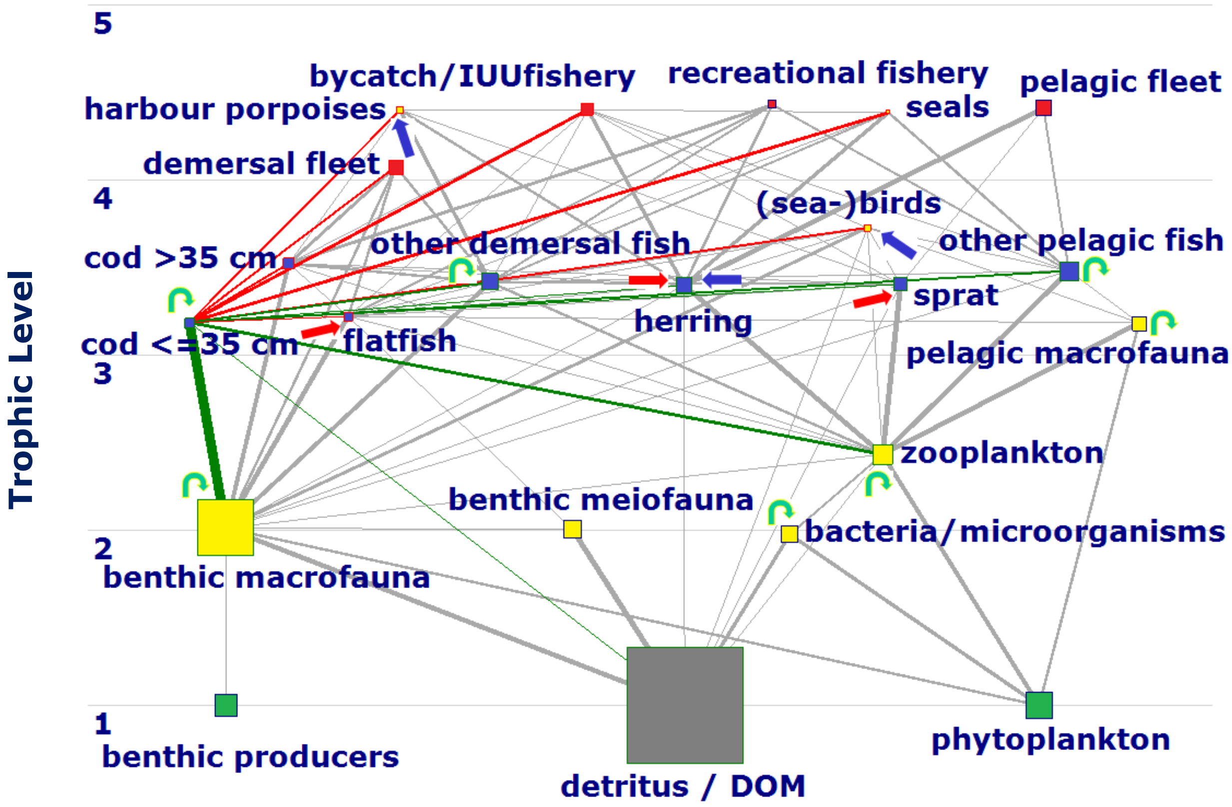

Figure 9: **Juvenile cod** (with fishery acting as predator through discards).

According to model results, cannibalism occurs within the cod population, with 4.3 % of the diet of adult cod consisting of juvenile cod, and 0.3 % of the diet of juvenile cod consisting of other juvenile cod. These percentages seem low and having only a marginal effect on the population. Harbour porpoises consumed about eight times more juvenile cod than did adult cod; due to higher mobility of harbour porpoises lack of juvenile cod as food source in the system was shifted largely to food imported, i.e. a food resource obtained by harbour porpoise in neighbouring ecosystems outside the model area- . Thus, adult cod became the main predator on juvenile cod in the baseline model by consuming up to almost 23 % of juvenile production which corresponds to slightly more than 23 % of juvenile total mortality (including predator and fishing mortality). Such impact may not seem marginal but figures here should be viewed as an artefact resulting from the balancing strategy.

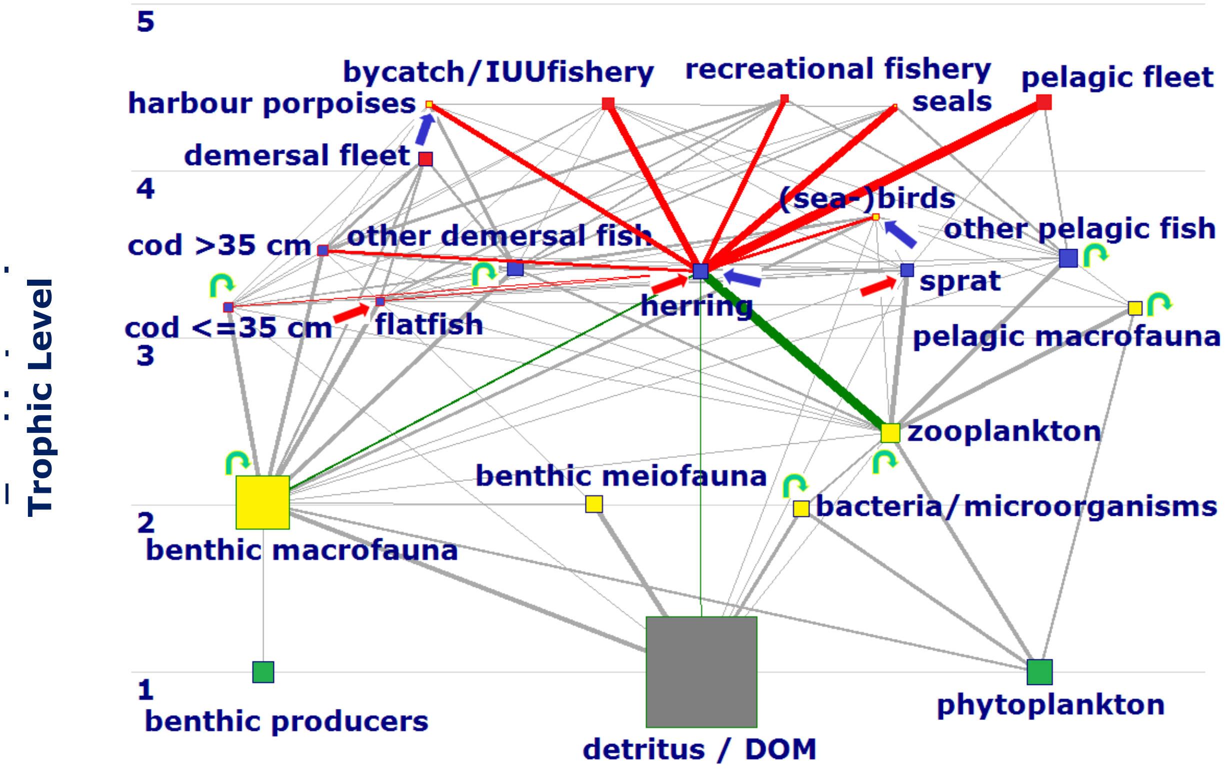

Figure 10: WBS food web in 1994 with trophic group **Herring** highlighted. In red: flows from the herring stock to its predators; in green: flows to the herring stock from its prey.

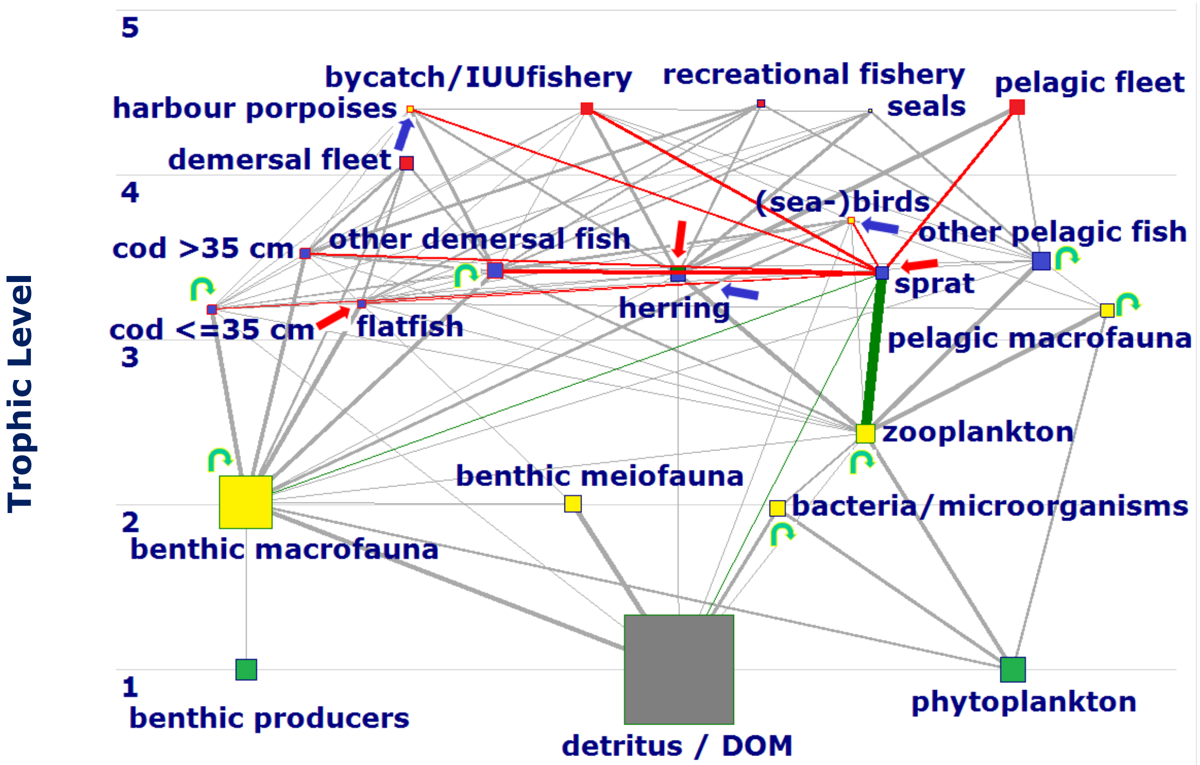

Figure 11: WBS food web with trophic group **Sprat** highlighted. Trophic group "*other demersal fish*" acted as main predator. To compensate for lack of sprat as prey for other predators and the fishery, a slight immigration of sprat from adjacent ecosystems was assumed (symbolized by a red arrow).

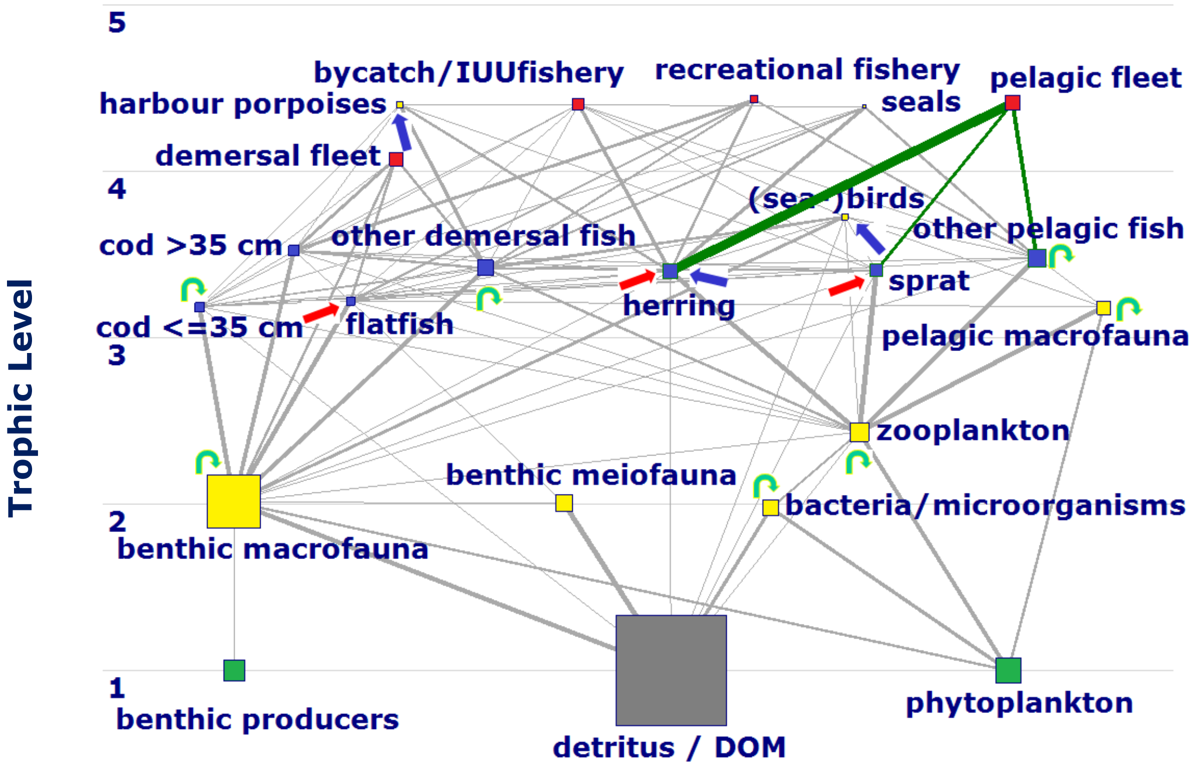

Figure 12: Fishing pressure (catch and discards combined) exerted on ecosystem components by the **Pelagic fleet**.

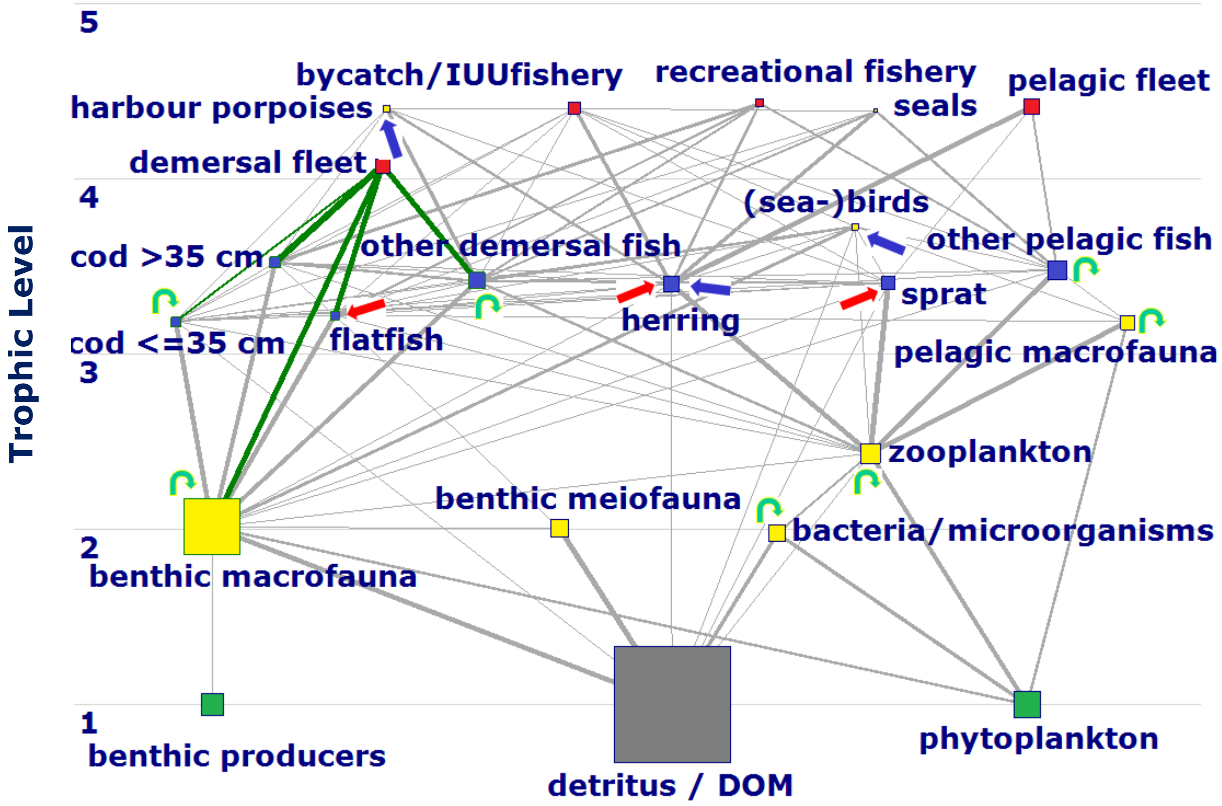

Figure 13: Fishing pressure (catch and discards combined) exerted on ecosystem components by the **Demersal fleet**.

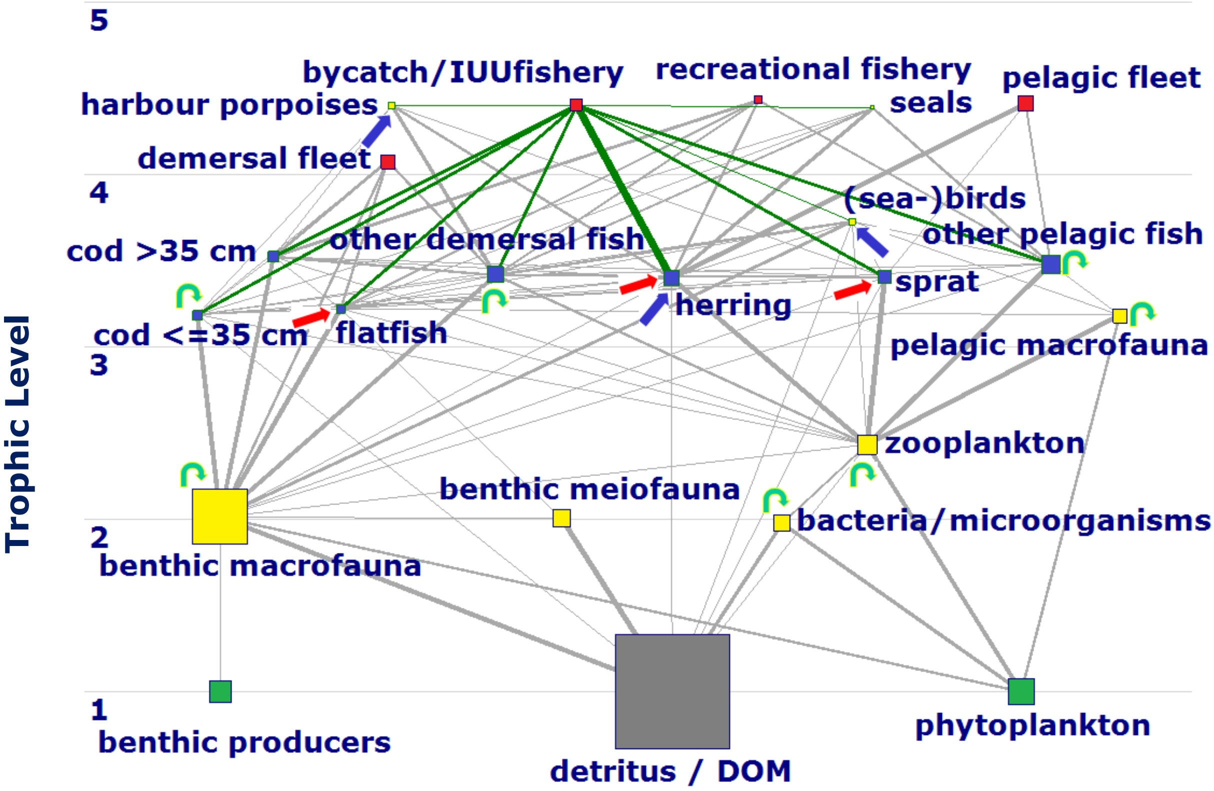

Figure 14: Fishing pressure exerted on ecosystem components through **Bycatch and IUU** (Illegal, Unreported, Unregulated) **fisheries**. Flows from non-fish groups into fisheries result from bycatch, mainly in gill nets and other entangling nets.

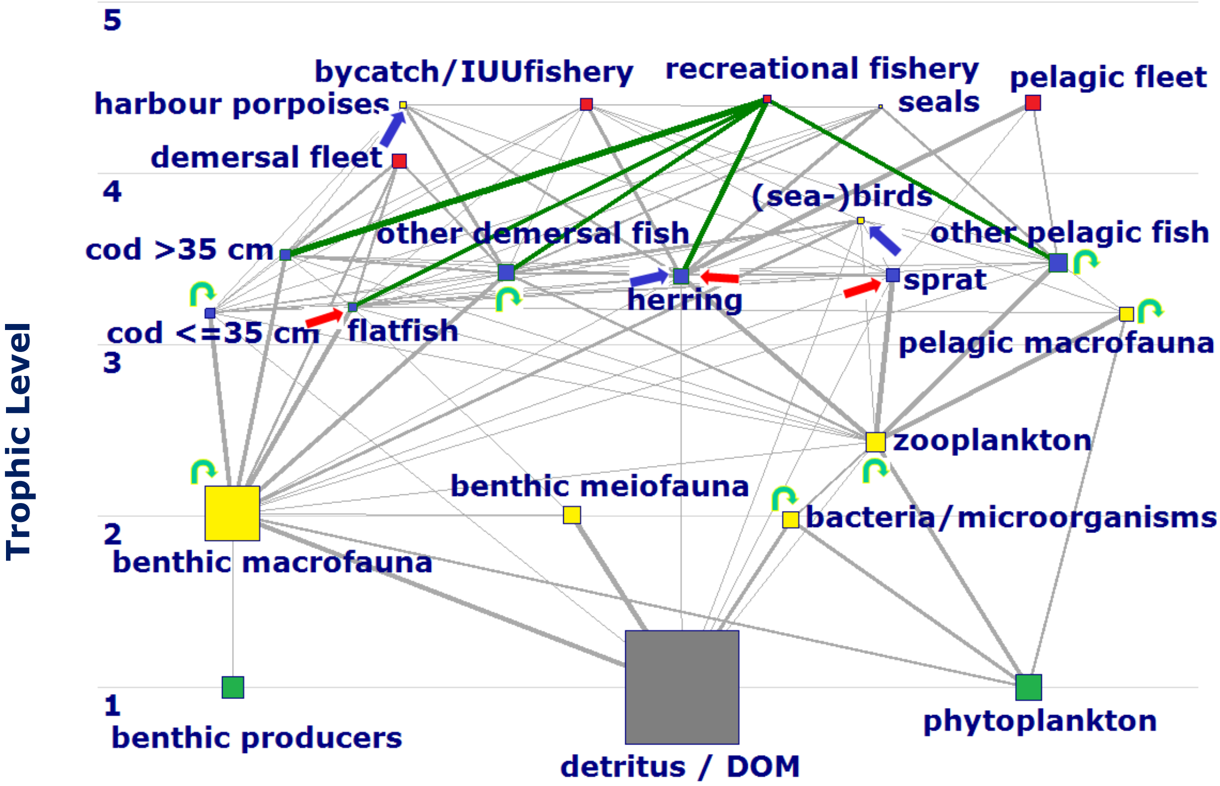

Figure 15: Fishing pressure exerted on ecosystem components by **Recreational fishing**.

Relative Total Impact

Figure 16 below illustrates the relative impact of herring on the food web based on a comparison of keystone indices for all trophic system groups. For theoretical background of the keystoneness concept see e.g. Libralato et al. (2006). Herring shows the highest value as a single fish species with a relatively large stock biomass feeding low in the food web and thus transporting matter from low trophic levels to predators high in the food web (LTL species with high impact on the food web). Although its feeding habits are similar - compared to herring the impact of sprat on the food web is much lower - due to its low stock biomass.

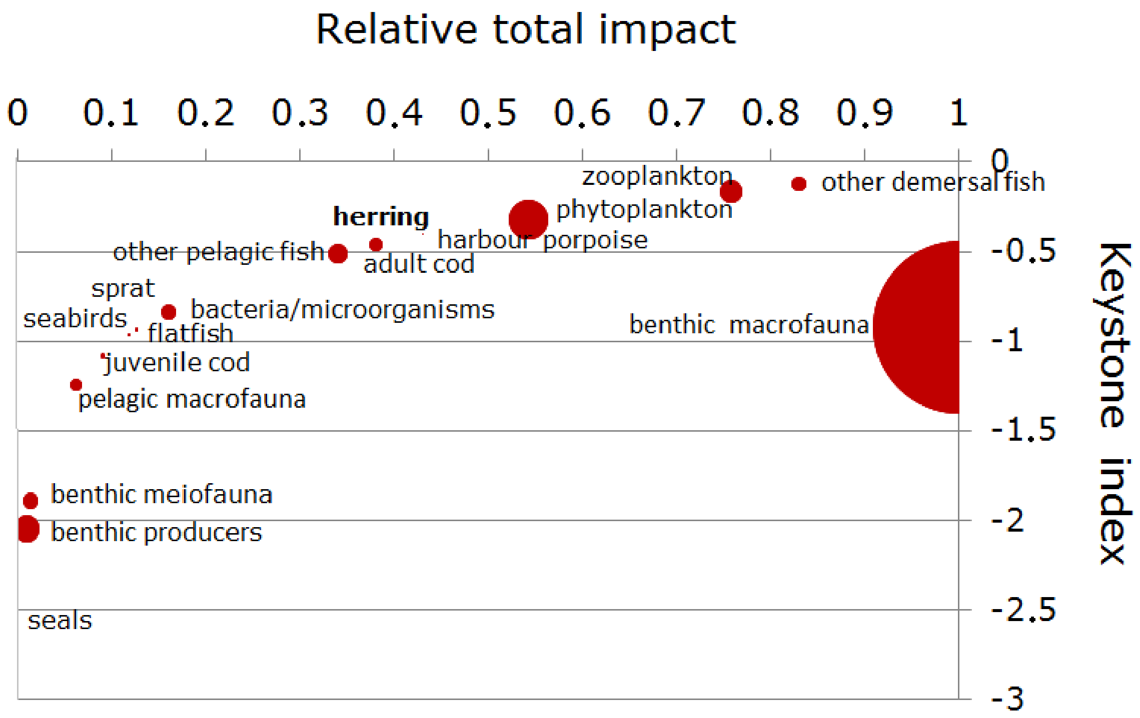

Figure 16: Shows strength of impact of trophic groups on food web. Herring shows highest value as a single fish species transporting matter from low trophic levels to predators high in the food web (LTL species with high impact on the food web). Dot size is proportional to biomass of trophic group.

Mixed Trophic Impacts

Based on the static model for year 1994 Figure 17 shows positive and negative direct and indirect impacts, a biomass increase of an impacting group would have on other groups within the WBS food web. Most striking is the strong negative effect of an increase in bycatch on the biomass of marine mammals and seabirds. Strength of impact is relative but comparable between trophic groups.

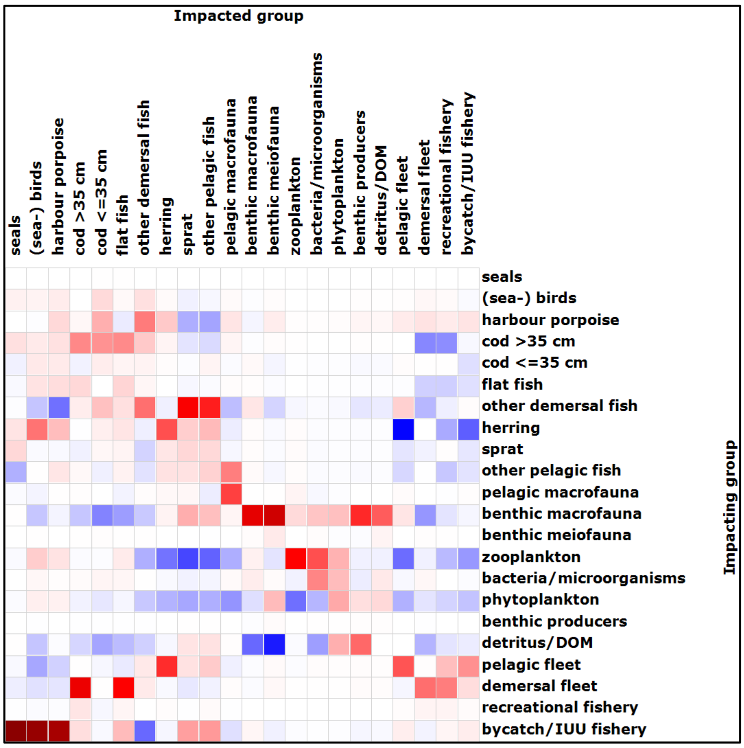

Figure 17. Impact on biomass of impacted groups by an increase of biomass of impacting groups. Blue = positive impact, red = negative impact.

Dynamic Modelling of Different Fishery Management Scenarios

As stated in the M&M section - Ecosim allows the dynamic forward projection of future biomass of trophic groups based on the reported or assumed F exerted on the commercial groups.

For groups where independent estimates of biomass and catch are available, F can be adjusted (= corrected in hindsight) such that catch and biomass are compatible with the productivity of the species given the available food sources and natural predation. Such corrections were necessary for adult cod, where the reported F had to be decreased before 2000, and for herring where the reported F had to be increased after 2000 to obtain satisfactory fits between reported and modelled biomass and catches (see Figs. 18 and 19 below).

In the first run - with F for cod and ExplR for herring not yet fitted - sum of squares (SS) was >100. At the end of the fitting process SS was down to 25.19. Figure 18 shows the difference between original and fitted F for cod. The relatively low F in 1994, the start year of the time series, may be explained as a consequence of the high cod recruitment in 1992 (ICES 2003), a value mirrored by model calculations for biomass and catch. These values give a much better overall fit (low SS) for cod than using back calculated input values of F from later years (ICES 2017a). Additionally, in 1994, ICES data for SD 24 at that time did not yet discriminate between western and eastern Baltic cod stock and therefore not properly reflect true biomass and catches for the western Baltic cod stock during that time period.

Figure 19 shows the difference between original and fitted ExplR for herring over the years 1994 – 2016 (length of the time series). Provided that the assumption of 50% SSB inside the model area holds true, results of this adaptation / fitting process suggest that fishing pressure inside the model area has not been reduced along the years but has increased compared to data of F published by ICES for the entire WBSS herring stock.

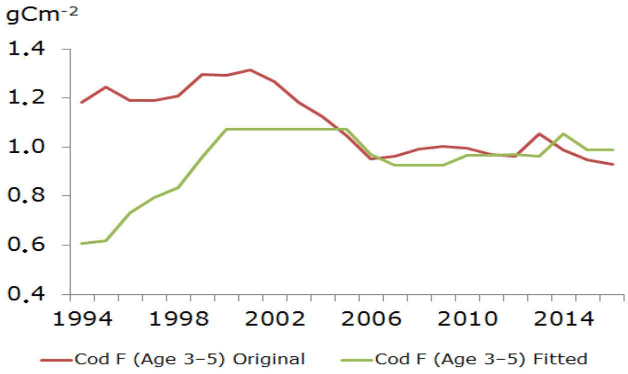

Figure 18: Difference between original and fitted model inputs of annual F for adult western Baltic cod.

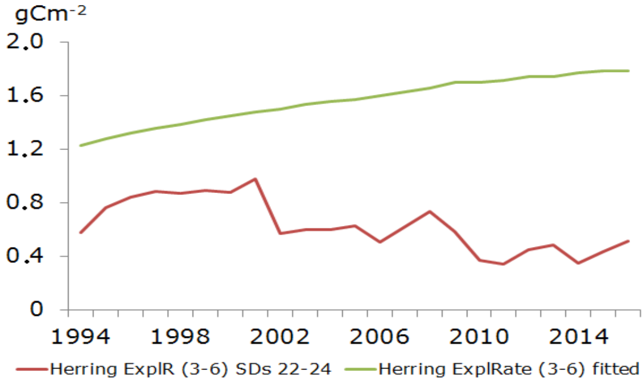

Figure 19: Difference between original and fitted model inputs of annual ExplR for adult WBSS herring.

Figure 20 shows the biomass of the cod, herring and sprat stock in the WBS ecosystem (ICES subdivisions 22+24) for years 1991 (herring and sprat) and 1994 (cod), respectively, until 2016.

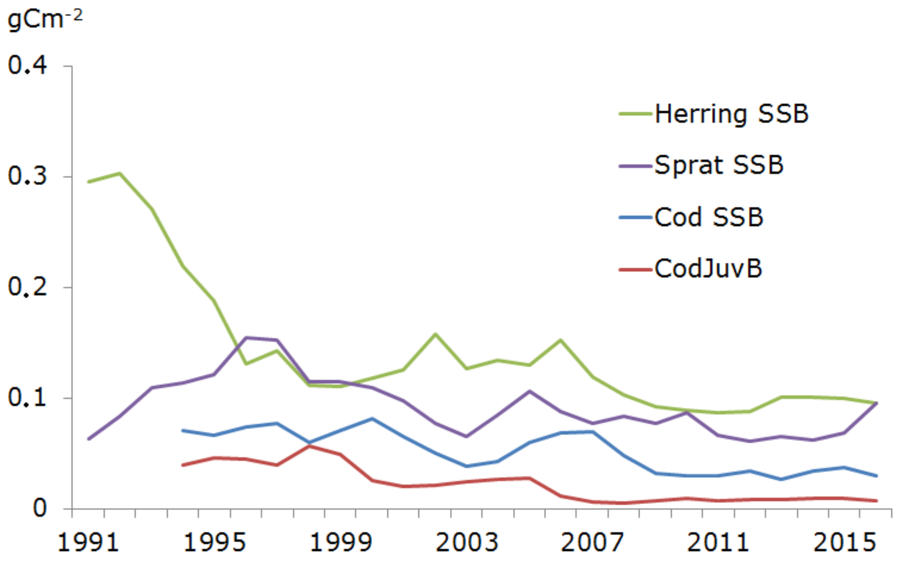

Figure 20: Biomass of the cod, herring and sprat stock in gCm^{-2} in the WBS ecosystem (ICES subdivisions 22+24) for years 1991 (herring and sprat) and 1994 (cod) until 2016. SSB = Spawning stock biomass, B = Biomass. Note different scale in following figures.

Five flatfish stocks were merged into a single flatfish compartment in the static model (see M&M for details) and subsequently, for the dynamic modelling, biomasses and catches respectively of those flatfish stocks were merged into a combined time series. Flounder and dab provided the bulk of biomass in the group. Figure 21 shows the biomass from 1991 to 2016 for the five flat fish stocks.

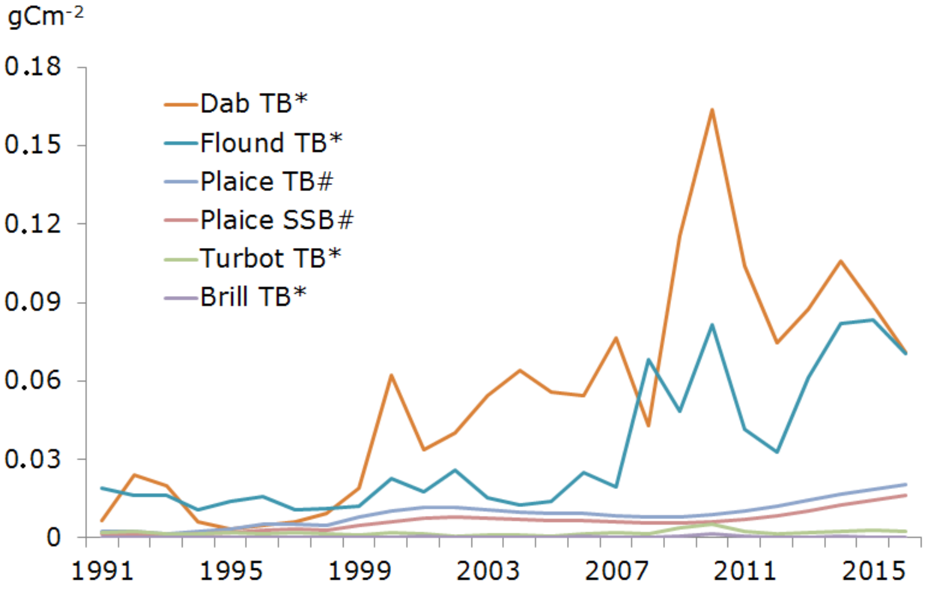

Figure 21: Biomass of different flatfish stocks from 1991 to 2016 in gCm^{-2}. SSB = spawning stock biomass, TB = total stock biomass. #Derived from ICES Advice 2017 for plaice in SDs 21-23; * derived from DATRAS BITS data in SDs 22+24.

Figure 22 shows annual fish landings and catches in the western Baltic Sea from 1991 (1994 for cod) to 2016.

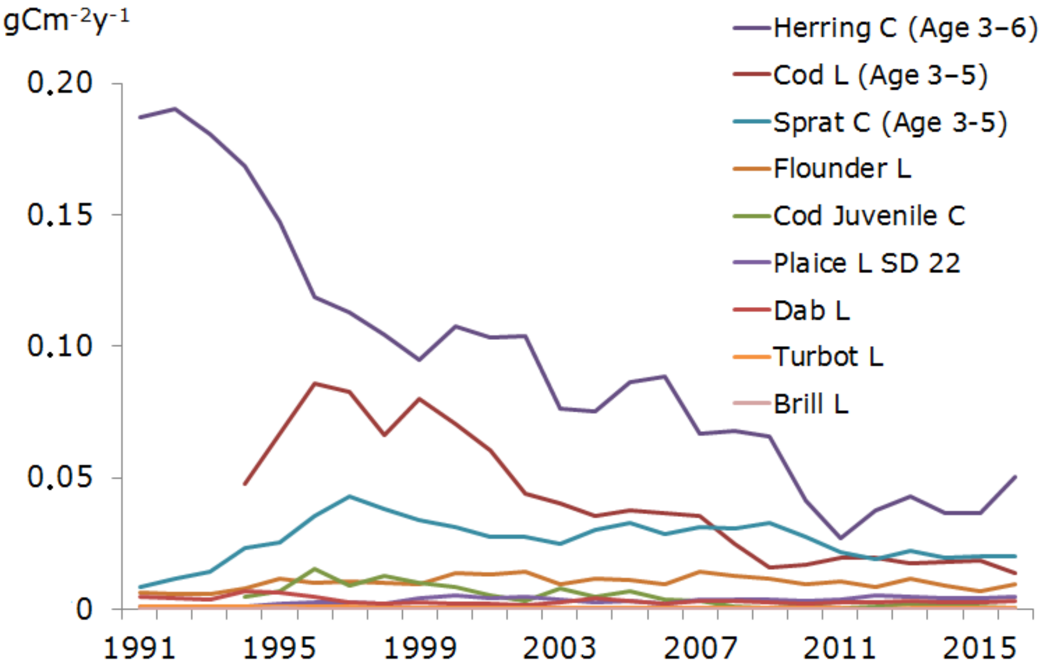

Figure 22: Annual fish landings and catches in the western Baltic Sea in $gCm^{-2}y^{-1}$; L = landings, C = catch (includes discard), SD = ICES Subdivision.

Figure 23 shows annual discards of demersal fish stocks from 1991 to 2016. Discard of the cod fishery has been distinctly reduced within this time span but so has the catch itself. Flatfish discards in the demersal fishery are still high.

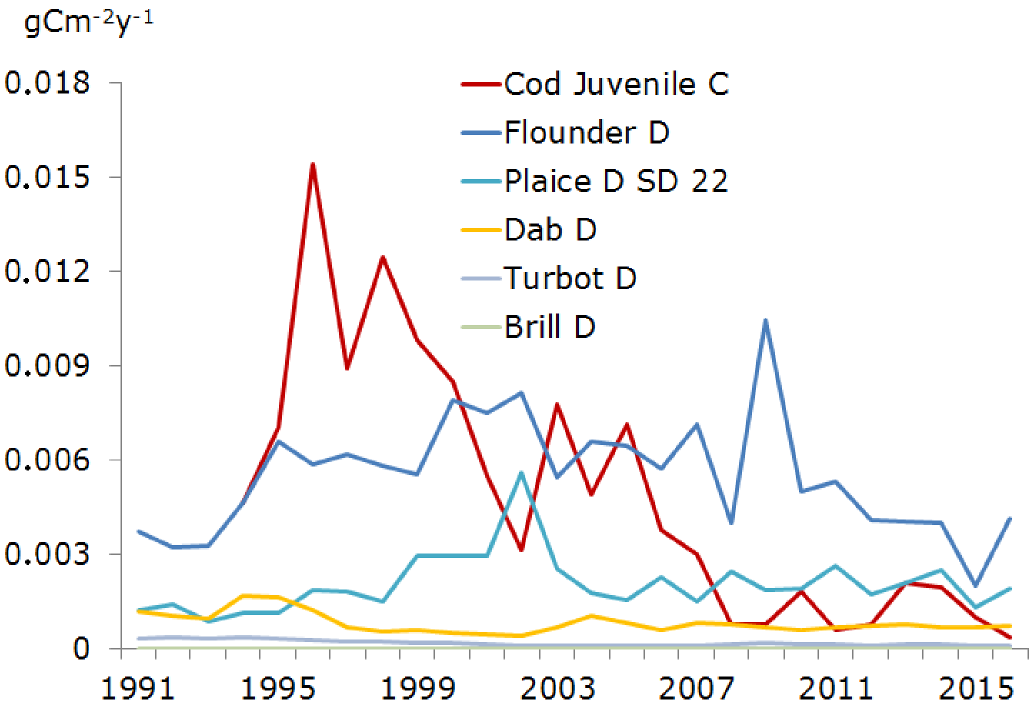

Figure 23: Annual discards (D) of demersal fish stocks in the WBS ecosystem in $gCm^{-2}y^{-1}$. Juvenile cod C corresponds to discards of the cod fishery.

Table 10: Time series 1994 – 2016 for economically most important fish stocks in the WBS ecosystem after fitting cod F and herring ExplR: B = biomass, SSB = spawning stock biomass, eff SSB = effective spawning stock biomass (see text for explanation), TB = total biomass (all in gCm^{-2}) ExplR = exploitation rate (y^{-1}), F = fishing mortality (y^{-1}), A = age class.

Trophic group / Year	Harbour porpoise B	Harbour porpoise Bycatch	Harbour porpoise ExplR	Cod SSB	Cod catch (A 3-5)	Cod F (A 3–5)	Juvenile cod B	Juvenile cod Catch	Juvenile cod ExplR	Herring eff SSB	Herring Catch	Herring ExplR	Sprat SSB	Sprat Catch	Sprat F (A 3-5)	Flat fish TB	Flat fish Catch	Flat fish ExplR
1994	0.00579	0.00083376	0.144	0.071	0.058	0.606	0.04	0.011	0.277	0.266	0.218	1	0.114	0.032	0.259	0.021	0.038	1.825
1995	0.0056	0.0008064	0.144	0.067	0.08	0.618	0.046	0.016	0.338	0.228	0.229	1.053	0.121	0.035	0.336	0.022	0.045	2.027
1996	0.0054	0.0007776	0.144	0.074	0.094	0.732	0.045	0.018	0.412	0.159	0.177	1.105	0.154	0.049	0.284	0.028	0.041	1.46
1997	0.00525	0.000756	0.144	0.077	0.091	0.795	0.04	0.012	0.314	0.173	0.192	1.14	0.152	0.058	0.396	0.024	0.036	1.49
1998	0.00505	0.0007272	0.144	0.06	0.075	0.833	0.057	0.016	0.274	0.136	0.152	1.197	0.114	0.051	0.388	0.026	0.032	1.25
1999	0.00485	0.0006984	0.144	0.07	0.09	0.959	0.049	0.015	0.302	0.133	0.148	1.239	0.115	0.045	0.376	0.04	0.034	0.848
2000	0.0047	0.0006768	0.144	0.081	0.081	1.073	0.026	0.013	0.518	0.143	0.158	1.285	0.109	0.04	0.314	0.097	0.038	0.388
2001	0.0045	0.000648	0.144	0.065	0.07	1.073	0.021	0.01	0.482	0.153	0.178	1.316	0.098	0.029	0.288	0.066	0.035	0.534
2002	0.0043	0.0006192	0.144	0.05	0.052	1.073	0.021	0.006	0.302	0.191	0.136	1.366	0.077	0.034	0.381	0.079	0.039	0.498
2003	0.0041	0.0005904	0.144	0.039	0.049	1.073	0.024	0.012	0.472	0.154	0.11	1.399	0.065	0.031	0.41	0.082	0.028	0.344
2004	0.0039	0.0005616	0.144	0.043	0.044	1.073	0.026	0.008	0.317	0.163	0.115	1.45	0.084	0.043	0.498	0.088	0.032	0.364
2005	0.00375	0.00054	0.144	0.06	0.047	1.073	0.027	0.01	0.37	0.157	0.117	1.476	0.106	0.044	0.46	0.081	0.03	0.372
2006	0.0036	0.0005184	0.144	0.069	0.044	0.972	0.011	0.007	0.629	0.184	0.112	1.489	0.088	0.039	0.376	0.091	0.027	0.292
2007	0.00345	0.0004968	0.144	0.069	0.042	0.926	0.006	0.006	0.98	0.144	0.103	1.505	0.078	0.037	0.348	0.106	0.037	0.345
2008	0.0033	0.0004752	0.144	0.048	0.031	0.926	0.005	0.004	0.845	0.124	0.105	1.545	0.083	0.037	0.367	0.121	0.032	0.261
2009	0.00315	0.0004536	0.144	0.032	0.023	0.926	0.007	0.004	0.528	0.111	0.079	1.553	0.077	0.039	0.444	0.176	0.036	0.207
2010	0.003	0.000432	0.144	0.029	0.025	0.966	0.01	0.005	0.521	0.107	0.054	1.562	0.087	0.034	0.359	0.262	0.028	0.107
2011	0.00285	0.0004104	0.144	0.03	0.027	0.966	0.007	0.004	0.52	0.105	0.05	1.579	0.067	0.028	0.338	0.159	0.031	0.192
2012	0.0027	0.0003888	0.144	0.034	0.028	0.971	0.008	0.004	0.493	0.107	0.062	1.579	0.061	0.025	0.325	0.122	0.028	0.228
2013	0.00255	0.0003672	0.144	0.027	0.025	0.964	0.008	0.005	0.681	0.122	0.073	1.579	0.065	0.028	0.386	0.166	0.031	0.187
2014	0.00235	0.0003384	0.144	0.034	0.027	1.056	0.01	0.005	0.528	0.123	0.057	1.579	0.062	0.026	0.34	0.207	0.028	0.135
2015	0.00215	0.0003096	0.144	0.038	0.029	0.99	0.009	0.004	0.458	0.12	0.066	1.579	0.069	0.026	0.268	0.195	0.023	0.119
2016	0.00193	0.00027792	0.144	0.03	0.022	0.99	0.008	0.004	0.461	0.115	0.073	1.579	0.095	0.026	0.223	0.165	0.029	0.178

Modelled curves and original input data for biomass and catch for harbour porpoise, juvenile cod, sprat and flatfish matched very well. Modifications on input values were not necessary. Figure 24 below shows the resulting fits for the main exploited groups and bycatch for harbour porpoises.

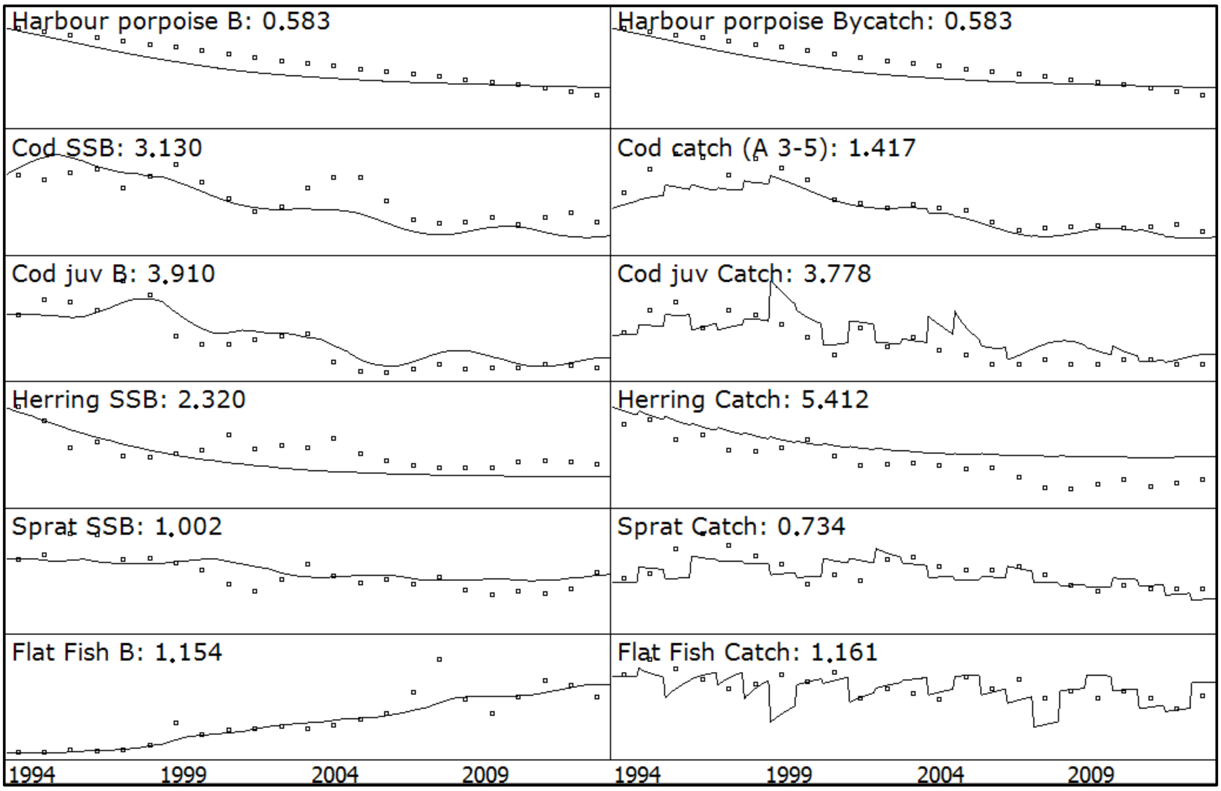

Figure 24: WBS – Basic dynamic model: Development of stock size (B) and fishing yield (catch) for selected fish stocks from 1994 to 2016. Compatibility between model calculations (lined) and time series from external sources (dotted) like ICES advice, BITS, literature-based estimates for harbour porpoise. B = biomass, SSB = spawning stock biomass, eff SSB = SSB effective in ICES SDs 22+24 (see M&M for explanation). Numbers represent sum of squares as a measure for goodness of fit.

Exploring Ecosystem Development Until 2050 Under Different Scenarios

The modelled curves of catch and biomass where extended up to the year 2050 for the four fishery scenarios described previously and the scenario without fishing (Figs. 25, 26, 27, 28, and 29).

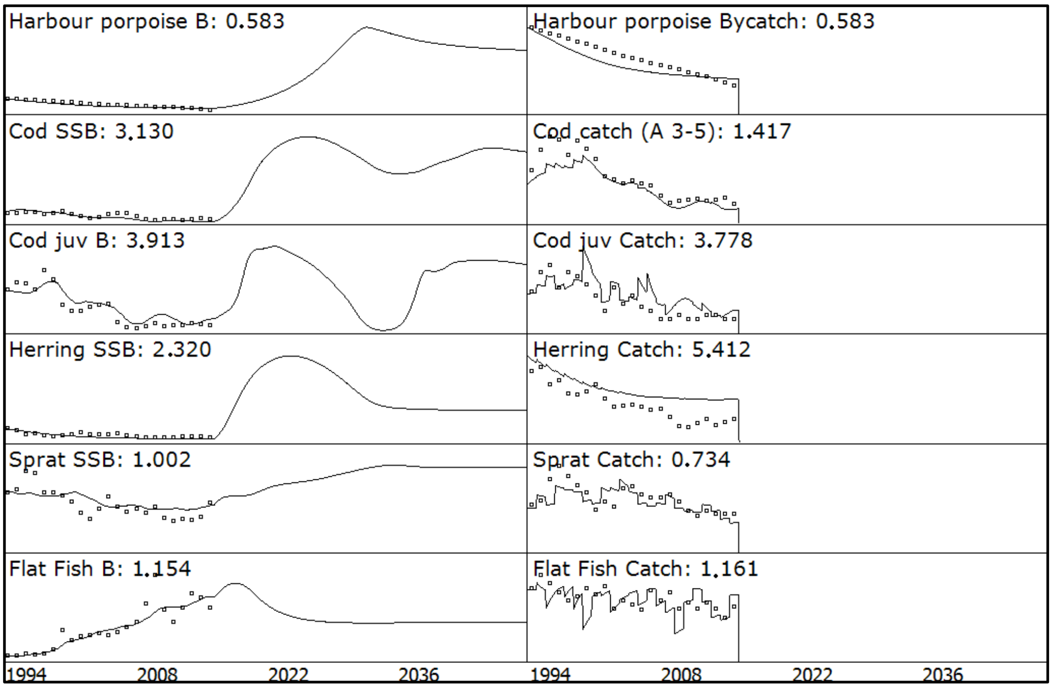

Figure 25: Scenario *No fishing*: Stock development resulting from the closure of all fishing activities from 2017 until 2050.

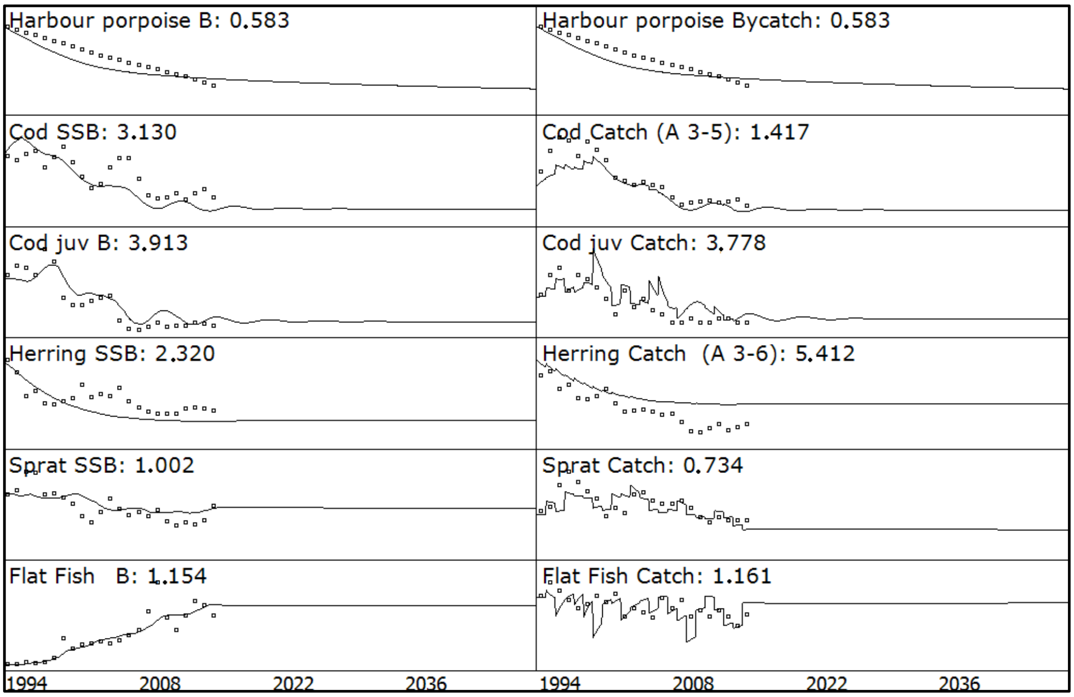

Figure 26: Scenario *Business as usual*: Stock development from 2017 to 2050 under the same fishing pressure as before 2017.

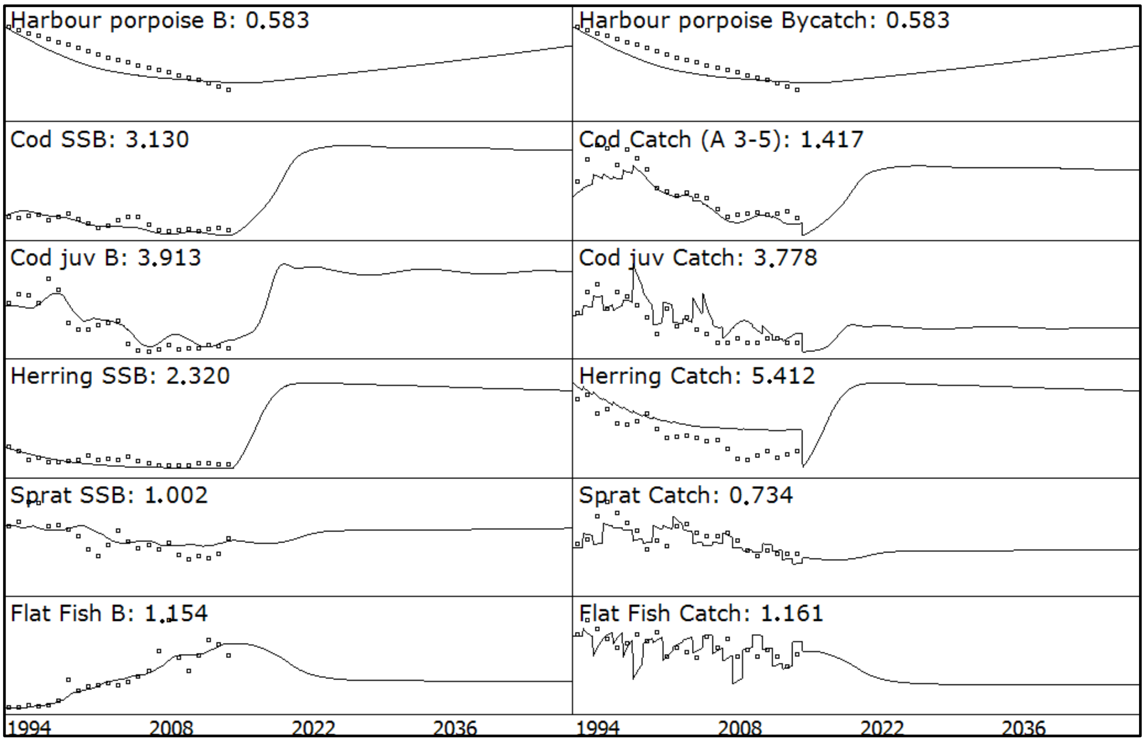

Figure 27: Scenario F_{msy}: Stock development when fishing pressure F from 2017 -until 2050 is reduced (if previously higher) to or raised (if previously lower) to a value F, where fishery yield / catch is sustainably at or slightly below a maximum level (if available).

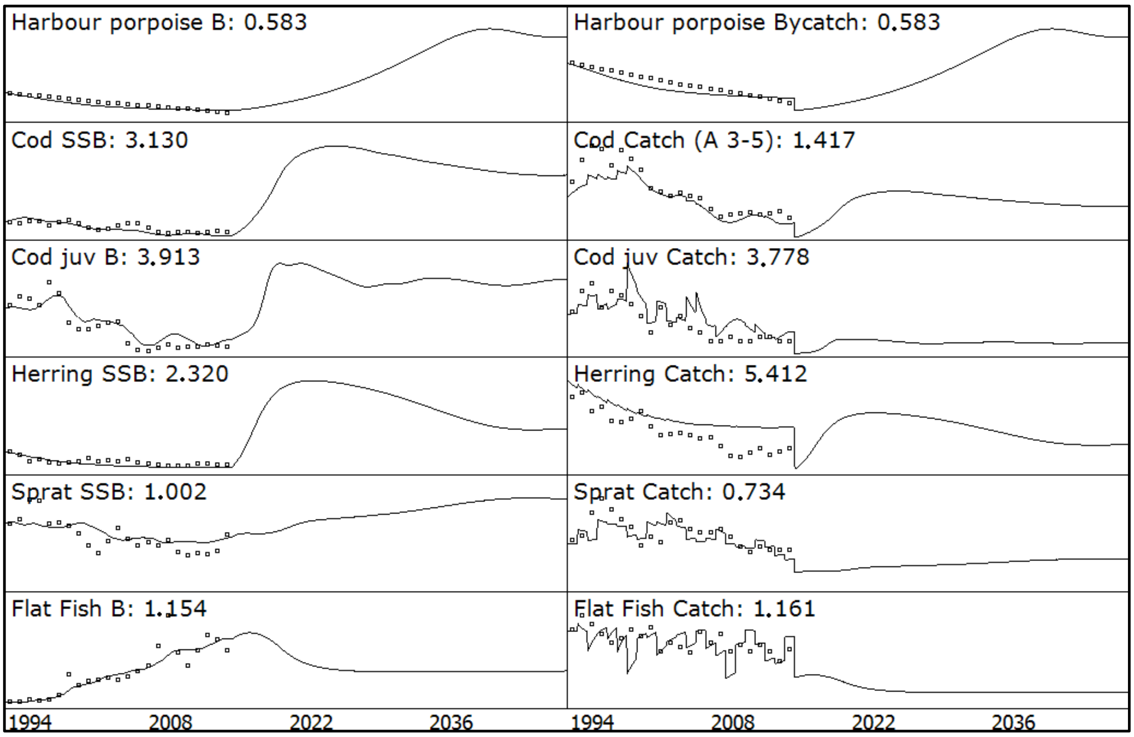

Figure 28: Scenario *Half* F_{msy}: Stock development when fishing pressure F from 2017 until 2050 is reduced to (if previously higher) ½ F_{msy}.

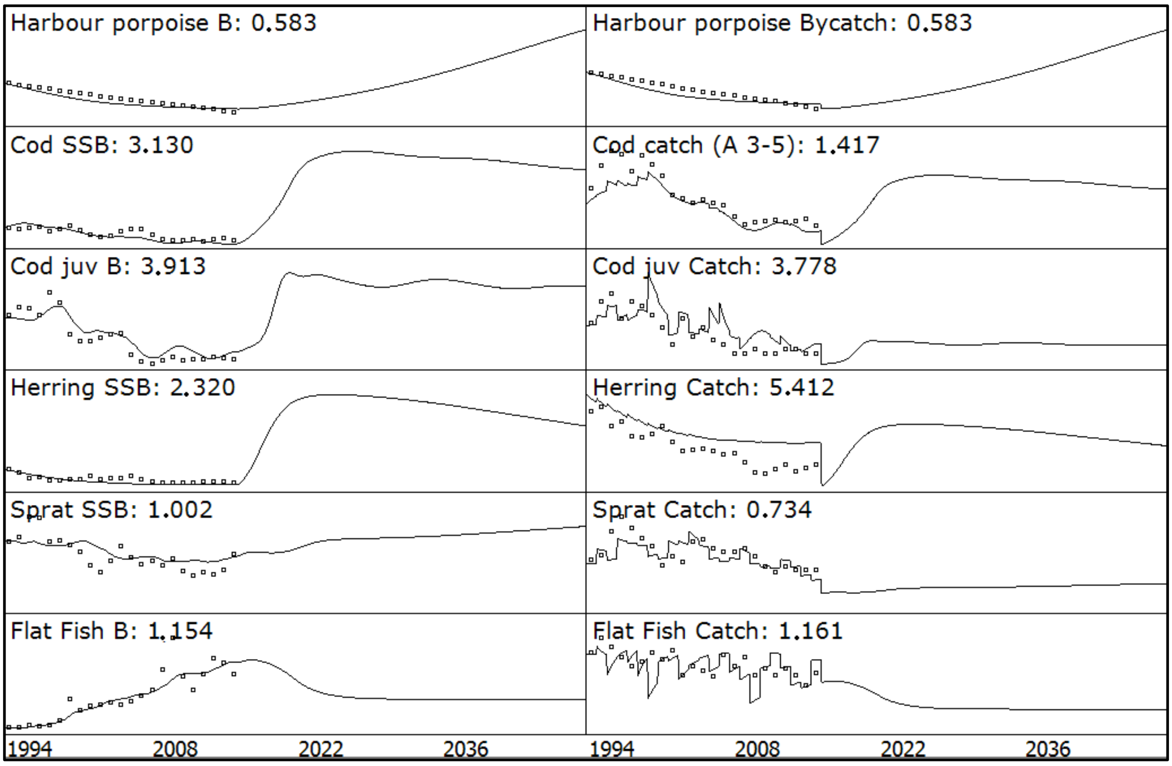

Figure 29*: Scenario EBFM (for the western Baltic Sea):* Herring and sprat fished at ½ F_{msy} and other stocks at 80 % F_{msy}.

The "No fishing" scenario was included to test the robustness of the model, because unrealistic model assumptions typically lead to chaotic developments if the top predator with the highest consumption (here: the combined fisheries) is removed from the system. As can be seen in Fig. 30, none of the modelled groups collapsed or overshot realistic limits of carrying-capacity in the absence of fishing. The main species in the system, cod and herring, are predicted to interact such that herring biomass rebuilds first and fast, leading to a herring dominated regime, followed by a strong recovery of cod such that herring is increasingly controlled and finally balanced by predation pressure.

In summary, the "No fishing" scenario suggests that the parameterization of the model is meaningful and robust.

Note that the model does not predict restoration of sprat to its historically dominant role, presumably because current productivity of sprat in the WBS is low.

The "Business as usual" scenario continues the fishing mortalities of 2016 until the year 2050. Stock biomasses of harbour porpoises, cod, herring and sprat strongly decreased within the previous 23 years (availability of time series). Flat fish biomass in contrast has increased (eventually by occupying abandoned ecological niches). Under this scenario, cod, herring, and sprat stocks remain at the same low 2016 level. Harbour porpoises decline further, only flatfish increases slightly before levelling off. This is the scenario with the overall lowest biomass levels and the highest threat for harbour porpoises (Fig. 31a). Catches of cod, herring and sprat are lowest in this scenario and comparable to catches in 2016 (Fig. 31b). Catches of flatfish are comparable to 2016 but highest of all following fishing scenarios.

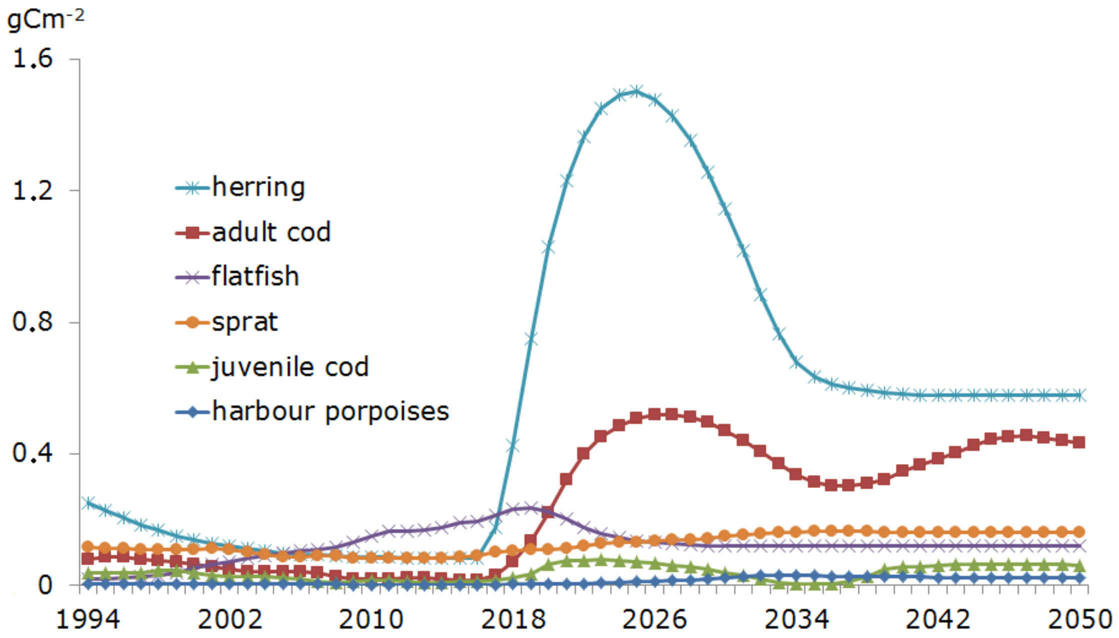

Figure 30: WBS scenario "No fishing". Impact on size (biomass) of selected stocks. Herring and particularly cod as well as seals, seabirds (both not depicted here) and harbour porpoises would be "winners". Indication of a "regime shift" – especially the herring stock would again be controlled top down by its predators, and by cod in particular. *Note different scale of following scenarios.*

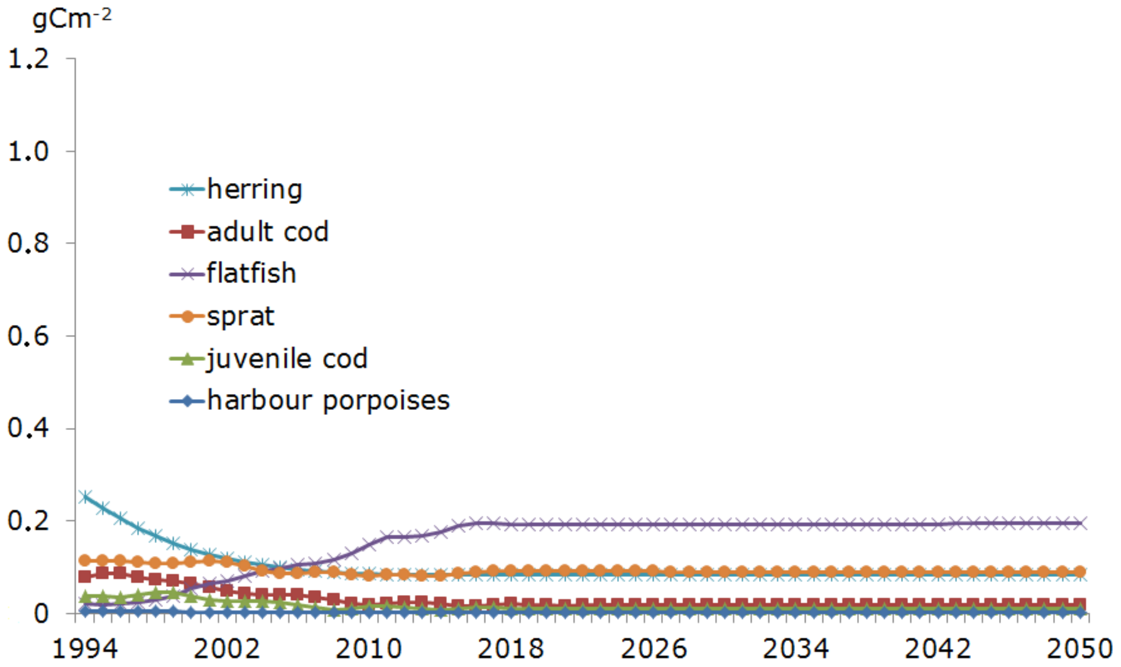

Figure 31a: WBS fisheries scenario "Business as usual". Impact on size (biomass) of selected stocks. Herring and sprat stock remain at the same low level; harbour porpoise and cod stock continue to decline; merely flatfish increases eventually due to free ecological niches. *Note different scales in figures*!

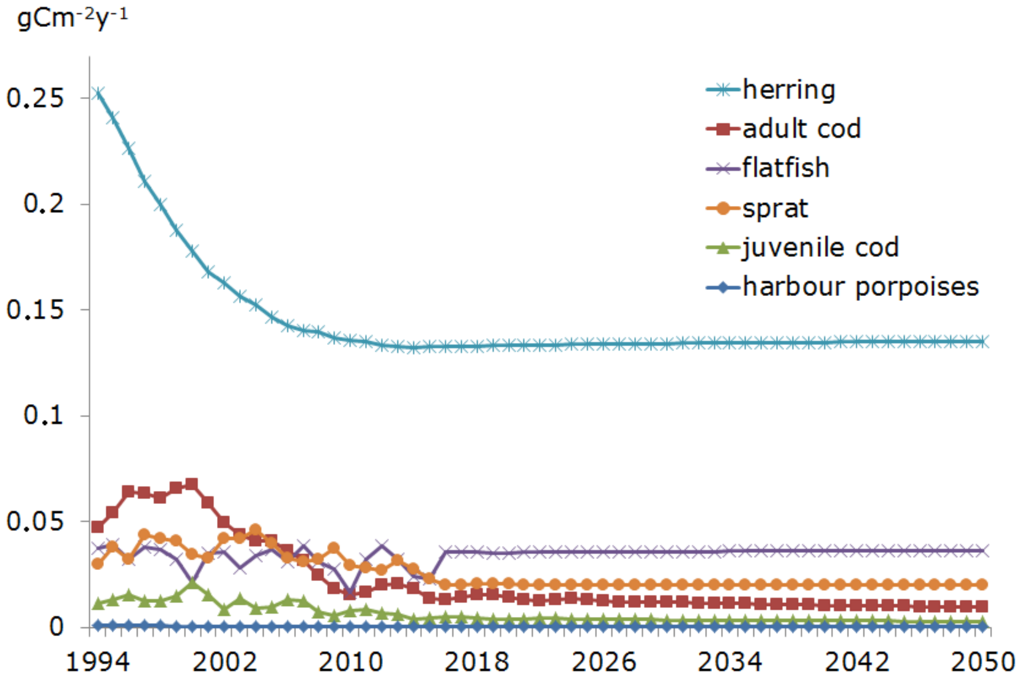

Figure 31b: WBS fisheries scenario "Business as usual". Catches of selected stocks.

The "F_{msy}" scenario (Figure 32a) - despite its maximum sustainable fishing pressure - would be an improvement for the WBS because it ends the previous high rates of overfishing. Biomass of all stocks except flatfish shows increases, up to nine-fold for herring and even more for cod. Catches for herring are predicted to increase almost two-fold and more than four-fold for cod respectively compared to 2016 (Figure 32b).

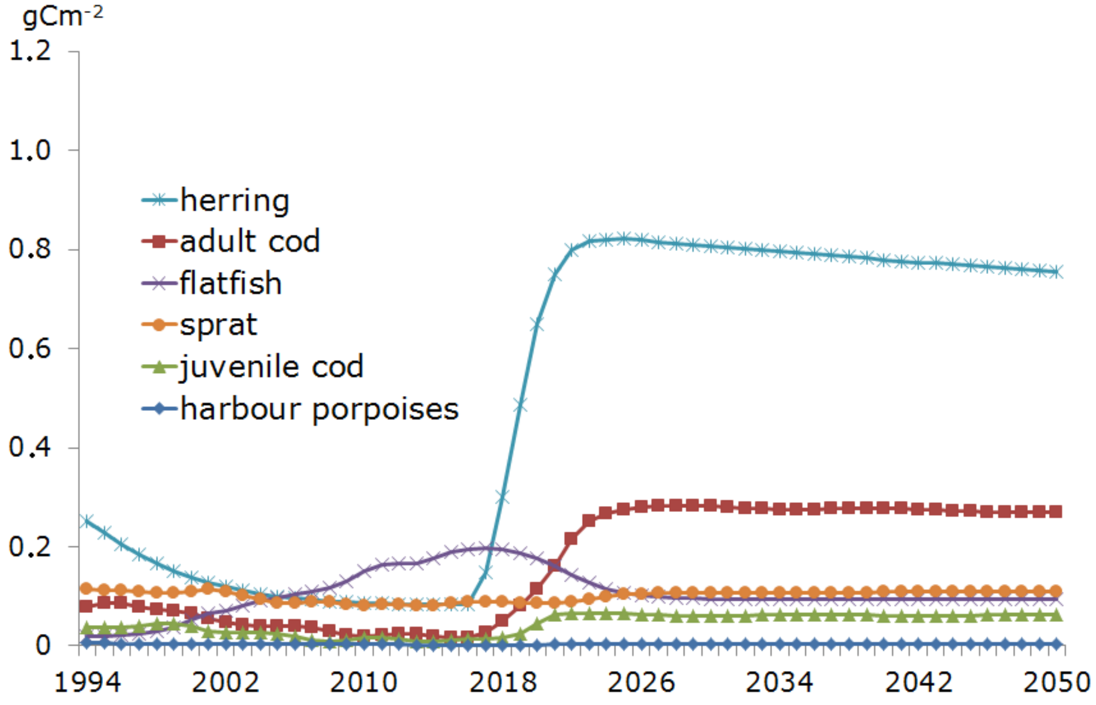

Figure 32a: WBS fisheries scenario "F_{msy}". Impact on size (biomass) of selected stocks.

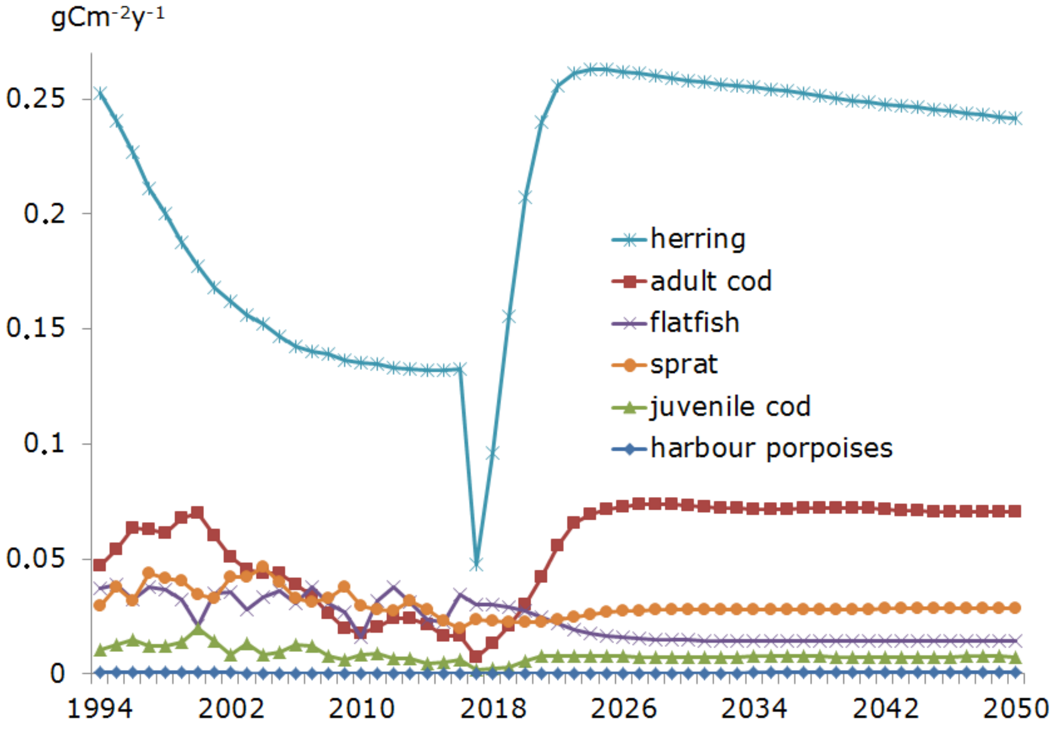

Figure 32b: WBS fisheries scenario "F_{msy}". Catches of selected stocks.

The "½ F_{msy}" scenario (Figure 33a) reduces the maximum sustainable fishing pressure by half and is therefore more precautionary than the F_{msy} scenario. This results in a stronger recovery of stocks and of harbour porpoises in particular. Catches for cod, flatfish, herring and sprat are not as high as under the F_{msy} scenario, but for cod still twice that in 2016 and about equal to 2016 for sprat; herring catch though is predicted to be only 60 % of the 2016 catch (Figure 33b).

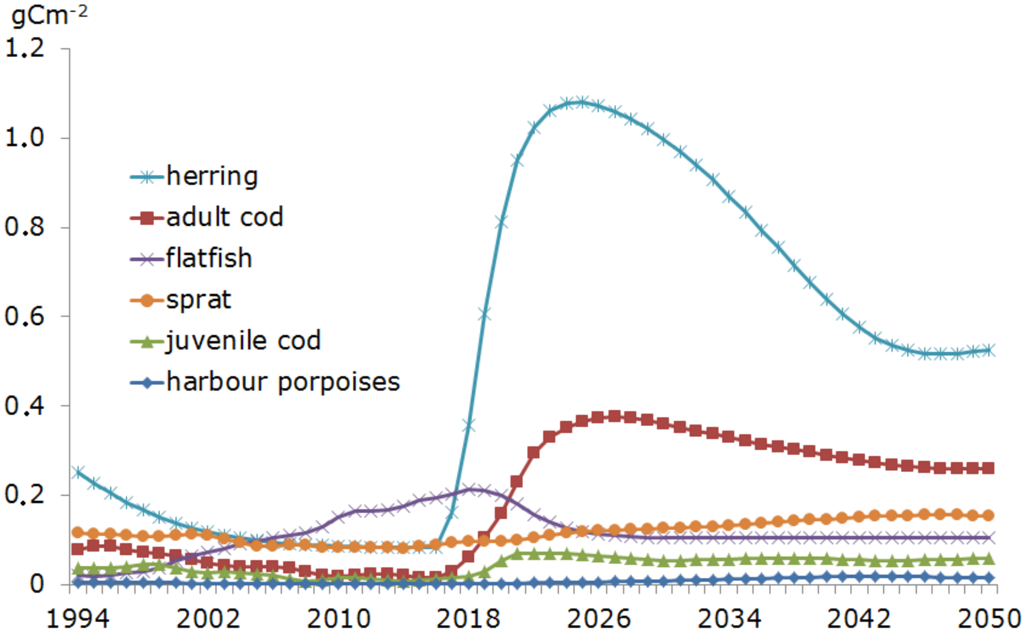

Figure 33a: WBS fisheries scenario "1/2 F_{msy}". Impact on size (biomass) of selected stocks.

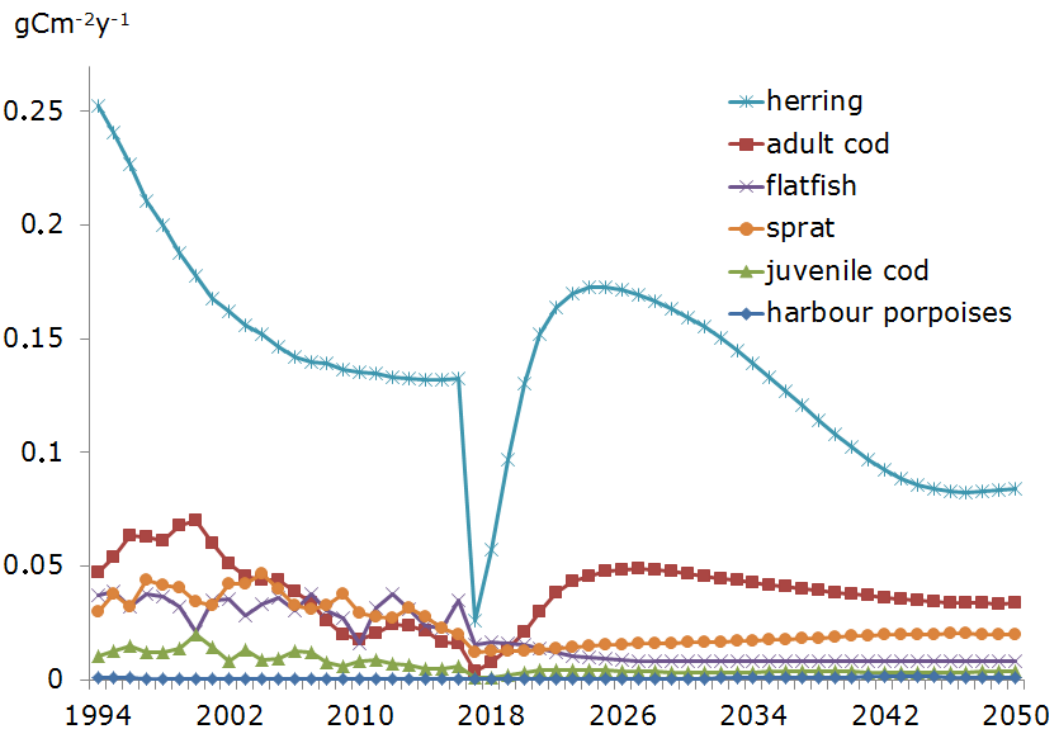

Figure 33b: WBS fisheries scenario "1/2 F_{msy}". Impact on catches of selected stocks.

The optimum scenario for rebuilding and preservation of the majority of stocks in the western Baltic Sea lies between F_{msy} and ½ F_{msy}. Therefore a scenario "Ecosystem Based Fishery Management for WBS" has been modelled. This "EBFM" scenario (Figure 34a) implements general rules of Ecosystem-Based Fisheries Management (Pikitch et al., 2004), such as keeping fishing pressure below the maximum level (here: max 0.8 F_{msy}) and applying especially low fishing pressure (here: 0.5 F_{msy}) to key-stone species such as herring and sprat. As a result, biomass of all groups except flatfish increases, for cod and herring to levels similar to the "F_{msy}" scenario; for sprat intermediate to "F_{msy}" and "½ F_{msy}". Catches for cod and herring are intermediate to the "F_{msy}" and "½ F_{msy}" scenarios and slightly lower than in other scenarios for sprat, i.e. 3.5-fold higher for cod than in 2016 and almost the same as in 2016 for herring and sprat or under the "Business as usual" scenario (Figure 34b). See also Table 11 for a comparison of different fishing scenarios by comparing catches and biomass of selected groups at the start (2016) and end (2050) year.

One reason for implementing EBFM is to balance good fishing yields with stock sizes that enable prey and predators to fulfill their natural roles in the system. Although no hard numbers are available to make such judgement, one would assume that stock sizes larger than two-thirds of the unfished stock would fall into that category. Comparing the predicted stock sizes for cod and herring under the "EBFM" scenario with the respective stock sizes during the herring dominated regime in the "No fishing" scenario, gives a relative stock size of close to two-thirds for cod and of more than four-fifths for herring (see Figures 29 and 33a).

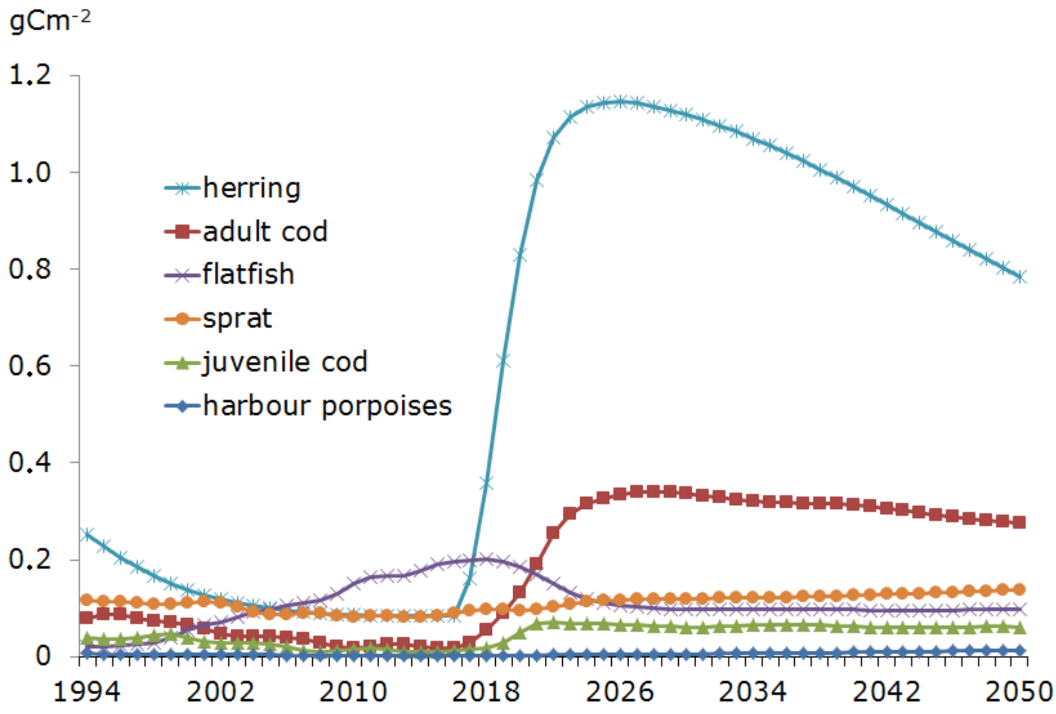

Figure 34a: WBS fisheries scenario "EBFM". Impact on size (biomass) of selected stocks.

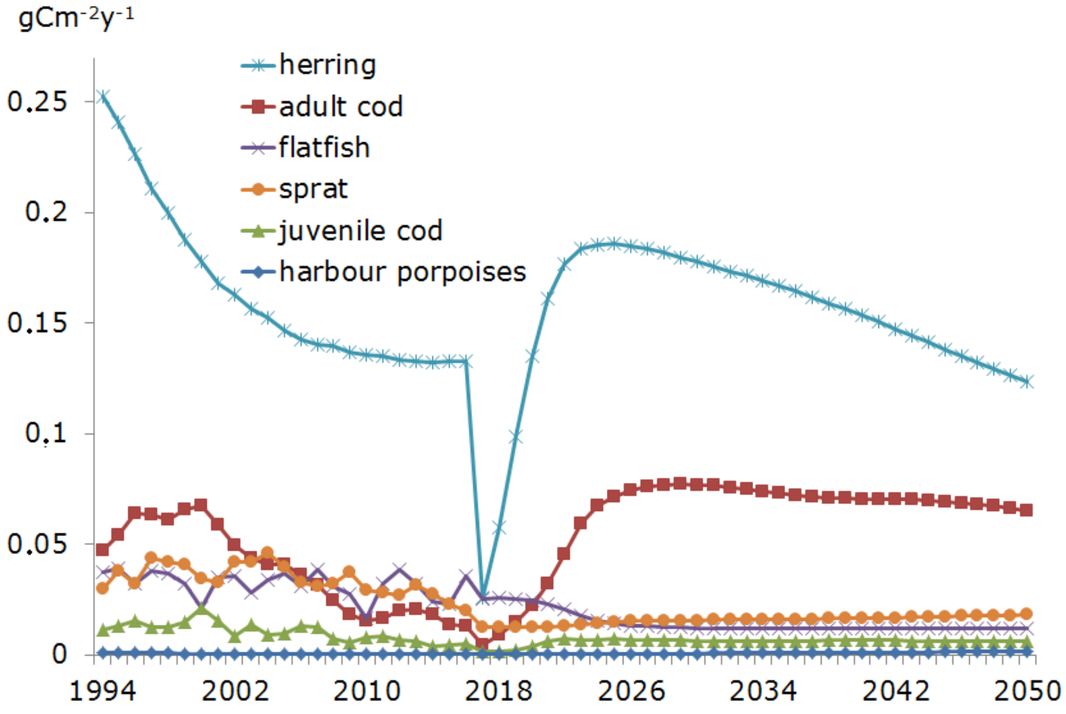

Figure 34b: WBS fisheries scenario "EBFM". Impact on catches of selected stocks.

Another reason for implementing EBFM is the restoration of species that are threatened by extinction or otherwise sensitive to fishing, such as harbour porpoises, seals and birds. Harbour porpoises show the highest biomass increase with the closure of all fishing activities(scenario "No fishing"). A comparison of predicted biomass for harbour porpoises under the four fishing scenarios shows best recovery under the "½ F_{msy}" scenario to about two-thirds of unexploited biomass, followed by the "EBFM" scenario to about half of unexploited. Recovery under the "F_{msy}" scenario is unsatisfactory, to hardly the level of 1994, and with "Business as usual" the species continues to decline towards probable extinction (Figure 35).

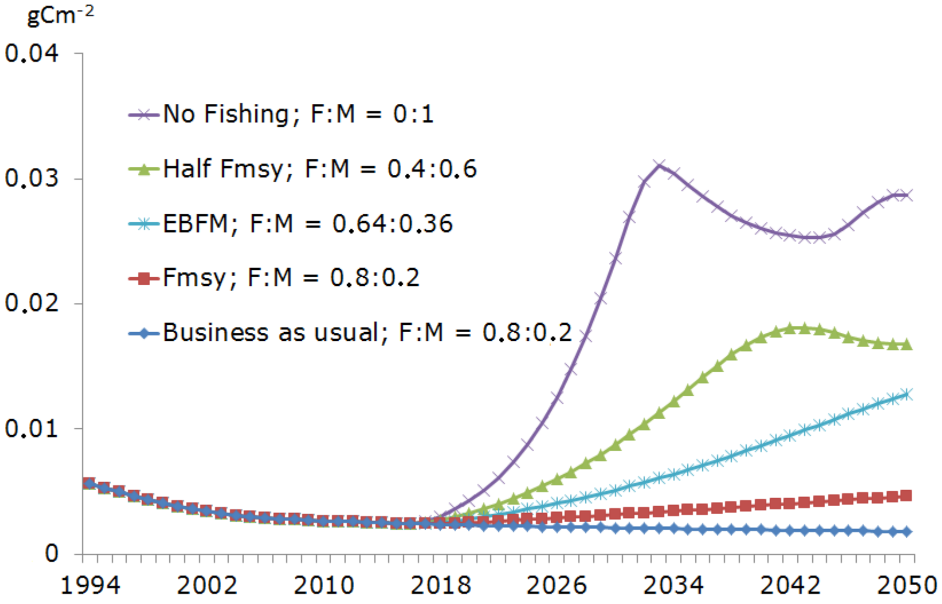

Figure 35: WBS – Impact of different fishery scenarios on the stock size (biomass) of harbour porpoises.

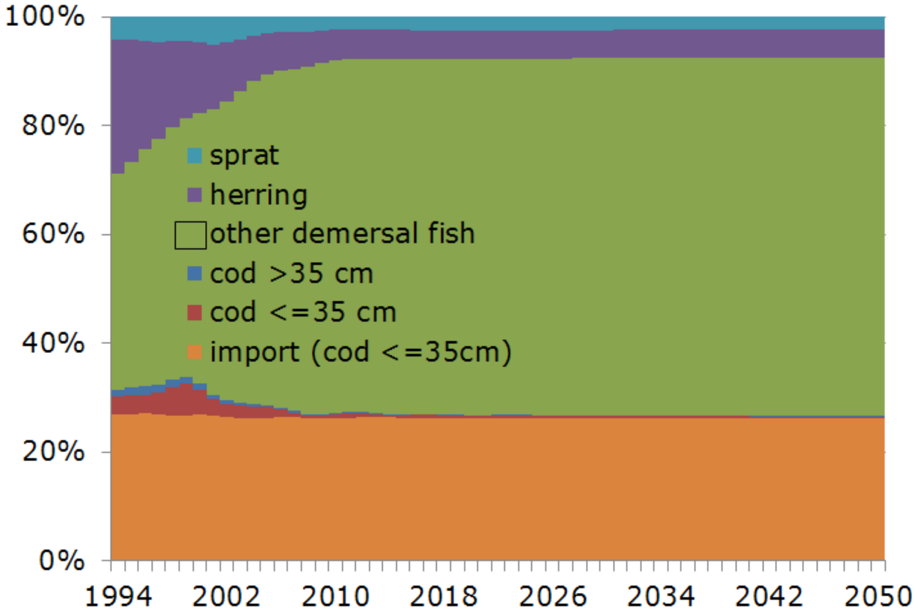

Figure 36a: Diet composition of harbour porpoises under fisheries scenario "Business as usual".

Also, a comparison of predicted diet compositions for harbour porpoises (see Figures 36a,b,c) shows that under the "Business as ususal" scenario the diet consists mostly of other demersal fish because of the lack of herring, whereas under the "EBFM" scenario the diet is very similar to the one in the unexploited scenario and consists mainly of herring.

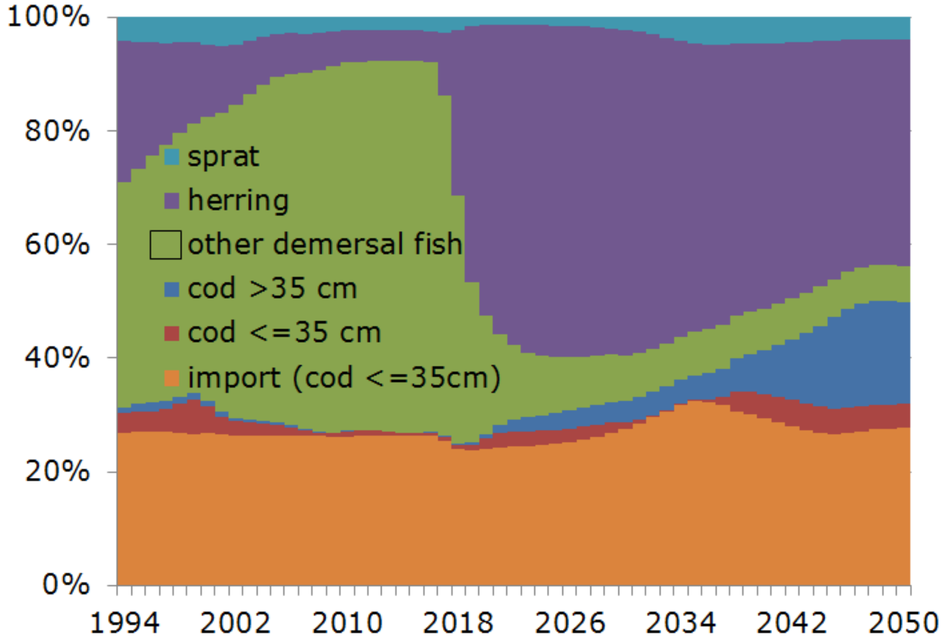

Figure 36b: Diet composition of harbour porpoises under scenario "No fishing".

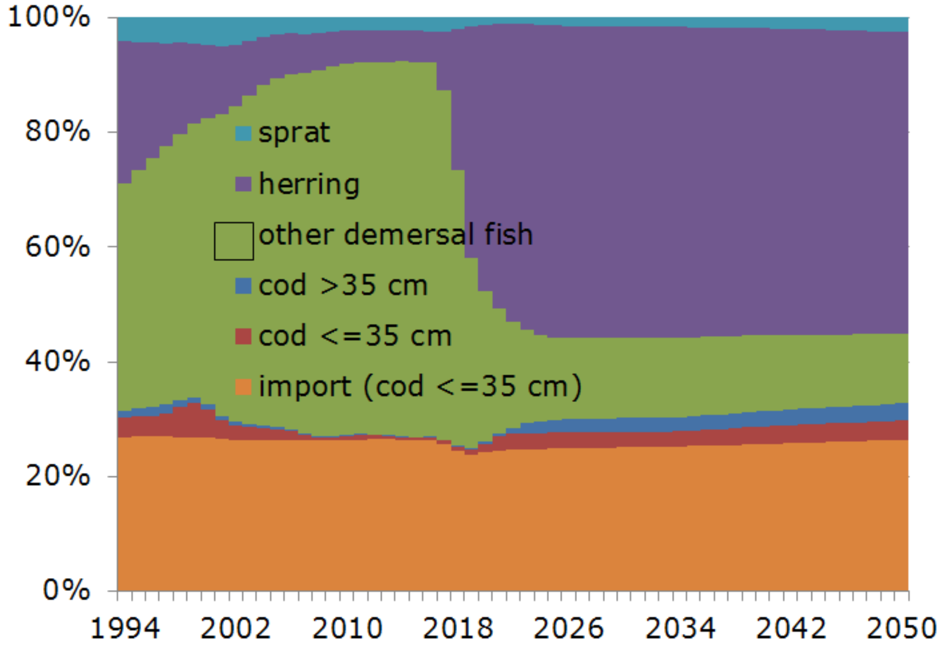

Figure 36c: Diet composition of harbour porpoises under fisheries scenario "EBFM".

The functional resolution of the seabird group is presently not sufficient to explore the impact of the different fishing scenarios at depth, because this group treats fish eaters, omnivores, divers, non-divers, migratory and non-migratory species as a single entity. Nevertheless, preliminary results for seabirds are shown in Figure 37 below. Seabirds are apparently not doing too bad under the present (i.e. "business as usual") fishing regime. After an initial strong increase of biomass in the other scenarios, their biomass falls back to or below the "business as usual" level. This effect may be attributed to feeding competition with other top predators.

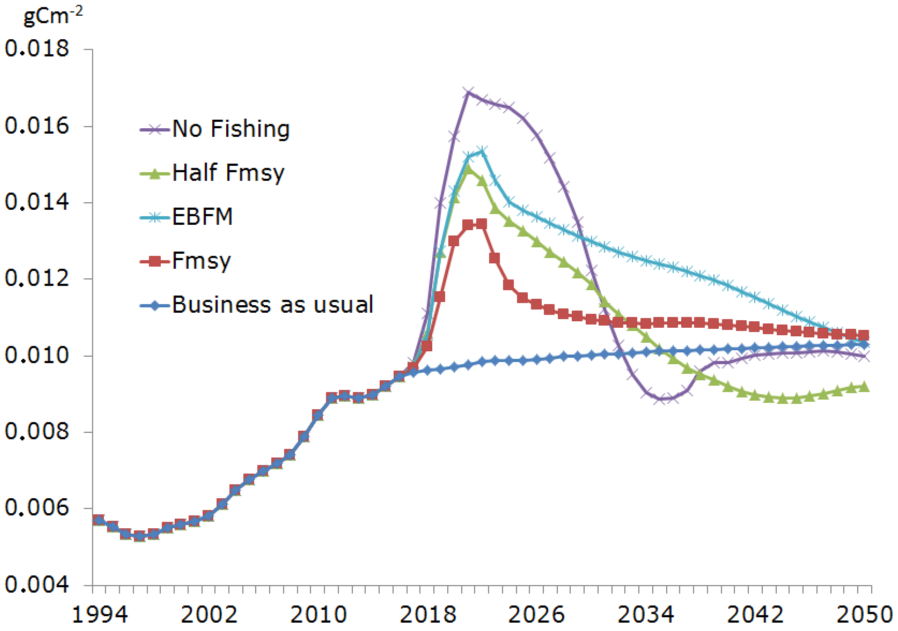

Figure 37: WBS – Impact of different fishery scenarios on the biomass of seabirds.

Similarly, the biomass of seals in the WBS is rather small and it is difficult to make meaningful predictions. A preliminary result is shown in Figure 38 below with "EBFM" scenario showing best conditions of all scenarios for a sustainable rebuilding of biomass.

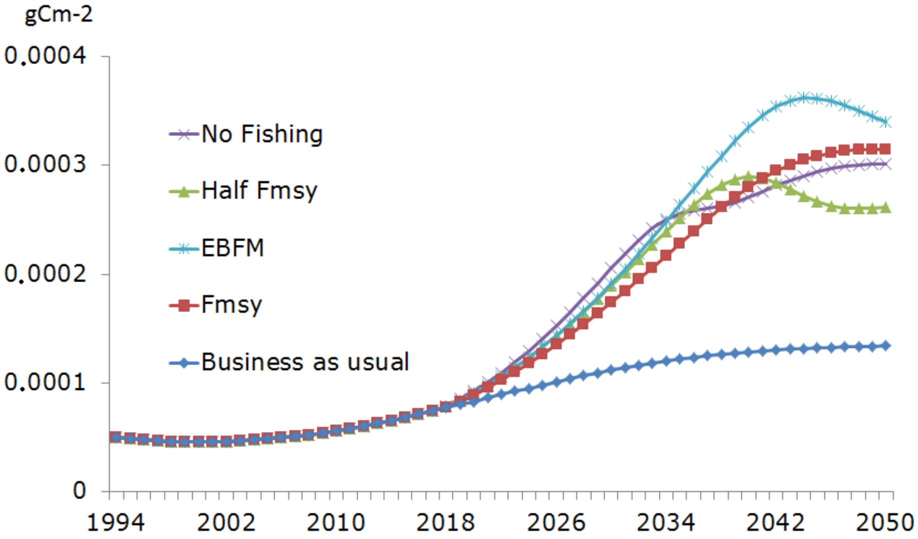

Figure 38: WBS – Impact of different fishery scenarios on the biomass of seals.

Fishers often complain that birds, seals and harbour porpoises are competitors that are responsible for the bad state of the stocks of cod, herring and sprat. However, the data and the predictions for the "Business as usual" scenario show that these groups taken together consume only a small fraction of the amount taken by the fishers (see Figures 39a to 42a). The "EBFM" scenario indicates a potential competition for herring between fisheries and harbour porpoises (see Figure 40b).

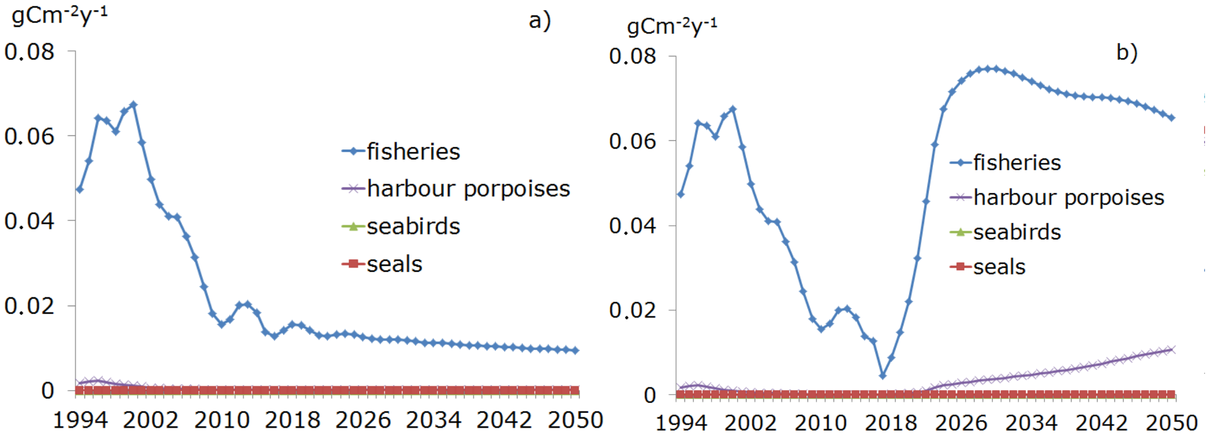

Figure 39 a and b: Annual extraction of adult cod from the WBS ecosystem by fisheries and by top predators such as harbour porpoises, seals and seabirds, viewed frequently by fishermen as competitors for target species such as cod, herring and sprat. a) "Business as usual" scenario; b) "EBFM" scenario.

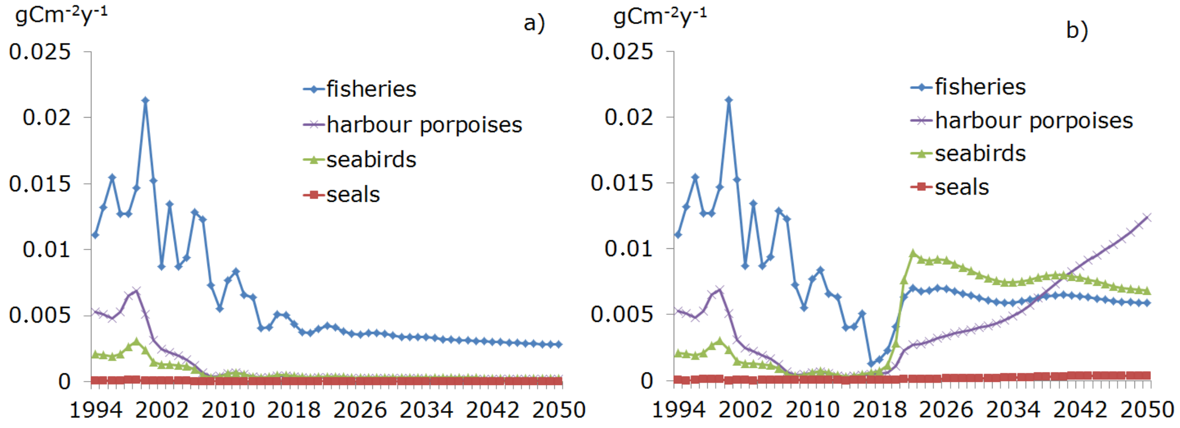

Figure 40 a and b: Annual extraction of juvenile cod from the WBS ecosystem by fisheries and by top predators a) "Business as usual" scenario; b) "EBFM" scenario.

In summary, prediction of future biomass and catches for major ecological groups in the WBS under different fishing scenarios suggests a continuation of low biomass and catches and a decline and potential loss of harbour porpoises under the "Business as usual" scenario.

Fishing at F_{msy} rebuilds all stocks except flatfish, albeit with lower biomass levels compared to the subsequent two scenarios. Fishing all commercial species at half of F_{msy}

shows the best rebuilding of biomass, although to a lesser extent for herring (see Table 11). This may be attributed to an increase in biomass of predators such as harbour porpoises and cod. The "EBFM" scenario accounts for the need to reduce fishery impact on the keystone species herring and sprat and shows good biomass developments similar to F_{msy} for cod and herring (to a lesser extent for sprat) and good catches similar to F_{msy} for cod and flatfish. Herring and sprat catches remain at the 2016 level but with largely reduced fishing effort and thus lower cost of fishing.

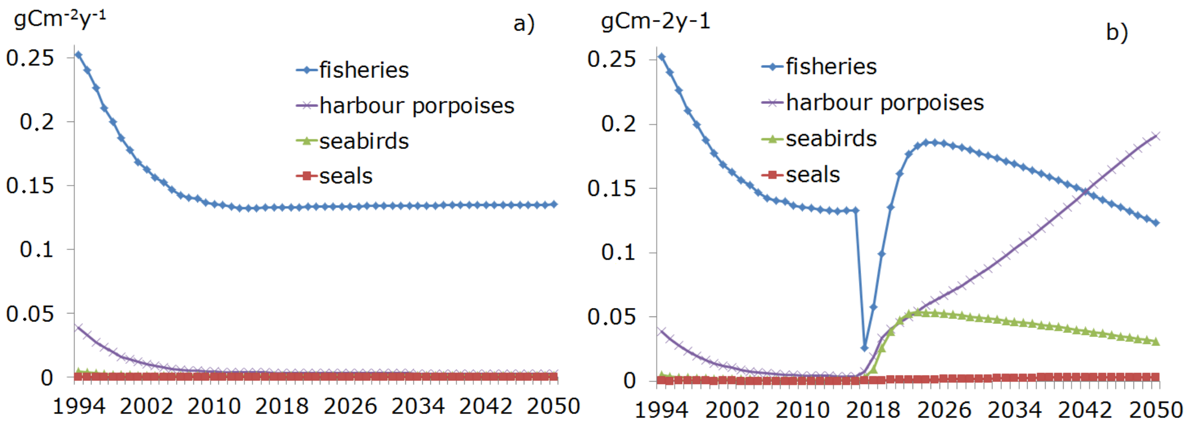

Figure 41 a and b: Annual extraction of herring from the WBS ecosystem by fisheries and by top predators. a) "Business as usual" scenario; b) "EBFM" scenario.

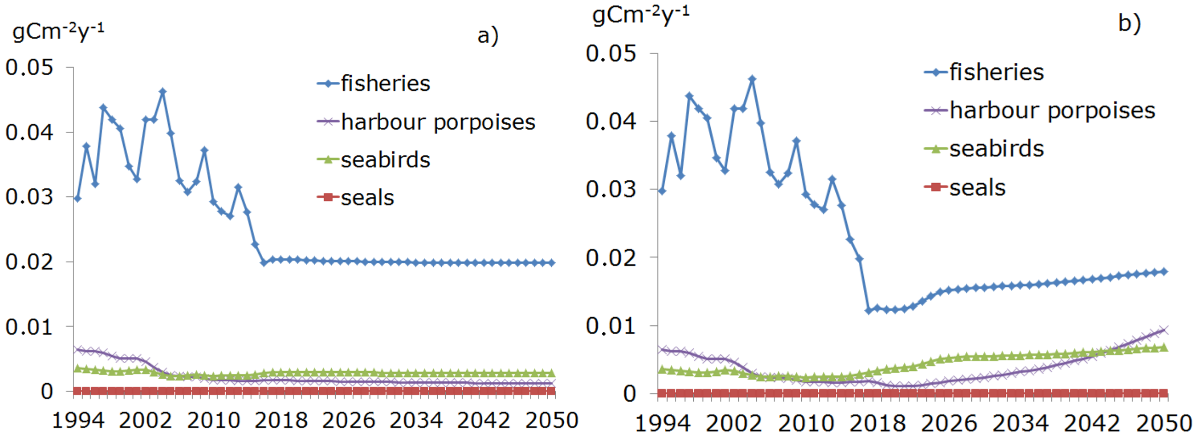

Figure 42 a and b: Annual extraction of sprat from the WBS ecosystem by fisheries and by top predators. a) "Business as usual" scenario; b) "EBFM" scenario.

Table 11: WBS – catches and biomass of selected groups. Comparison between start (2016) and end (2050) year of fishing scenario.

Catches

Scenario & Year	Seals	Seabirds	Harbour porpoises	Adult cod	Juvenile cod	Flatfish	Other demersal fish	Herring	Sprat	Other pelagic fish
2016	6.74E-07	0.00332243	0.00034449	0.01631765	0.00606282	0.03476003	0.05924343	0.1324693	0.01996916	0.03351641
BAU 2050	1.27E-07	0.00357161	0.00025094	0.01750204	0.00477384	0.03457306	0.06112008	0.1347418	0.01986405	0.02771048
FMSY 2050	2.99E-06	0.00380614	0.00066232	0.07030026	0.00751273	0.01440437	0.04362851	0.2413727	0.02870844	0.03896908
1/2 FMSY 2050	2.49E-07	0.00331583	0.00119262	0.03366883	0.00362198	0.0082061	0.03268419	0.08421213	0.02005404	0.05728422
EBFM 2050	3.22E-06	0.00376318	0.0014609	0.05748585	0.00593889	0.01197222	0.03803905	0.1255077	0.0178611	0.04497729
BAU x-fold	0.2	1.1	0.7	1.1	0.8	1.0	1.0	1.0	1.0	0.8
FMSY x-fold	4.4	1.1	1.9	4.3	1.2	0.4	0.7	1.8	1.4	1.2
1/2 FMSY x-fold	0.4	1.0	3.5	2.1	0.6	0.2	0.6	0.6	1.0	1.7
EBFM x-fold	4.8	1.1	4.2	3.5	1.0	0.3	0.6	0.9	0.9	1.3

Biomass

Scenario & Year	Seals	Seabirds	Harbour porpoises	Adult cod	Juvenile cod	Flatfish	Other demersal fish	Herring	Sprat	Other pelagic fish
2016	0.000071	0.00931583	0.00239226	0.01648248	0.01315145	0.1952811	0.3788283	0.0838944	0.08954781	0.4435655
BAU 2050	0.0001342	0.01001451	0.00174262	0.01767883	0.0103554	0.1942307	0.3908284	0.08533365	0.08907646	0.3667281
FMSY 2050	0.00031446	0.01067212	0.00459942	0.2703856	0.06208868	0.09353486	0.2789797	0.7542896	0.1104171	0.5157275
1/2 FMSY 2050	0.00026197	0.00929734	0.01656417	0.2589911	0.05937662	0.1065727	0.2089969	0.5263258	0.1542619	0.7581153
EBFM 2050	0.00033939	0.01055167	0.01270349	0.2763743	0.06122568	0.09655013	0.2432382	0.7844234	0.1373931	0.5952418
NoFish 2050	0.00030109	0.01006032	0.02297375	0.4345959	0.06234723	0.1189618	0.203954	0.5796351	0.162356	0.7761386
BAU x-fold	1.9	1.1	0.7	1.1	0.8	1.0	1.0	1.0	1.0	0.8
FMSY x-fold	4.4	1.1	1.9	16.4	4.7	0.5	0.7	9.0	1.2	1.2
1/2 FMSY x-fold	3.7	1.0	6.9	15.7	4.5	0.5	0.6	6.3	1.7	1.7
EBFM x-fold	4.8	1.1	5.3	16.8	4.7	0.5	0.6	9.4	1.5	1.3
NoFish x-fold	4.2	1.1	9.6	26.4	4.7	0.6	0.5	6.9	1.8	1.7
EBFM/NoFish	1.13	1.05	0.55	0.64	0.98	0.81	1.19	1.35	0.85	0.77

Primary Production Required (PPR) in the WBS ecosystem

Decreasing values of PPR/TotPP (%) from 1994 to 2016 and later under management scenario “Business as usual” indicate an increasing missmatch between primary production available and use by system elements nourishing the hypothesis that due to increasing release of non-point source polluters and / or shrinking fish stocks - provoked mainly through overfishing, particularly LTL species herring and sprat, - eutrophication in the western Baltic Sea ecosystem is increasing. Under fisheries management scenario “EBFM” model results show to what extent the situation may be reversed compared to the starting situation in 1994 (see Tables 12a-d).

Table 12a: PPR - Primary production required in the WBS ecosystem in **1994**

Group name	No. of paths	TL	PPR (PP)	PPR (Det)	PPR	Catch	PPR/ catch	PPR/TotPP (%)	PPR/u. catch
seals	429	4.39	0.00773	0.017	0.025	1E-06	52000	0.00182	38.35
(sea-) birds	460	3.73	0.405	0.986	1.391	0.00204	681.8	0.103	0.503
harbour porpoises	603	4.4	5.916	14.08	20	0.00052	38376	1.475	28.3
cod >35 cm	412	3.52	7.343	19.83	27.17	0.0584	465.4	2.004	0.343
cod <=35 cm	123	3.19	2.042	5.893	7.935	0.0114	693.6	0.585	0.511
flatfish	209	3.22	5.431	15.5	20.93	0.0377	554.7	1.544	0.409
other demersal fish	42	3.42	6.695	16.28	22.97	0.0447	514.5	1.694	0.379
herring	13	3.4	5.483	8.331	13.81	0.234	58.93	1.019	0.0435
sprat	13	3.4	0.474	0.164	0.639	0.0324	19.71	0.0471	0.0145
other pelagic fish	42	3.48	2.674	2.523	5.197	0.0434	119.6	0.383	0.0882
benthic macrofauna	8	2.01	0.111	0.362	0.472	0.0355	13.3	0.0348	0.0098
Total	2354	3.31	36.58	83.97	120.5	0.501	240.8	8.89	0.178

Table 12b: PPR – Primary production required in the WBS ecosystem in **2016**

Group name	TL	PPR (PP)	PPR (Det)	PPR	Catch	PPR/ catch	PPR/ TotPP (%)	PPR/u. catch
seals	4.37	0.0448	0.123	0.168	1E-06	249206	0.0124	183.9
(sea-) birds	3.86	1.014	2.719	3.733	0.00332	1123	0.275	0.829
harbour porpoises	4.35	4.779	12.51	17.29	0.00035	50168	1.276	37.02
cod >35 cm	3.66	2.689	7.532	10.22	0.0161	635.1	0.754	0.469
cod <=35 cm	3.18	1.332	3.939	5.271	0.00612	861.2	0.389	0.636
flatfish	3.36	4.18	11.86	16.04	0.0348	461.3	1.183	0.34
other demersal fish	3.35	8.375	22.09	30.47	0.0592	514.4	2.248	0.38
herring	3.4	1.606	2.399	4.005	0.132	30.24	0.296	0.0223
sprat	3.41	0.261	0.0902	0.351	0.02	17.56	0.0259	0.013
other pelagic fish	3.49	2.12	2.183	4.303	0.0335	128.3	0.318	0.0947
benthic macrofauna	2.01	0.11	0.361	0.471	0.0354	13.3	0.0347	0.0098
Total	3.27	26.51	65.81	92.32	0.341	270.5	6.812	0.2

Table 12c: PPR - Primary production required in the WBS ecosystem in **2050** under management scenario "Business as usual".

Group name	TL	PPR (PP)	PPR (Det)	PPR	Catch	PPR/ catch	PPR/ TotPP (%)	PPR/u. catch
seals	4.38	0.0505	0.14	0.191	1E-06	149802	0.0141	110.5
(sea-) birds	3.88	1.091	2.971	4.062	0.00357	1137	0.3	0.839
harbour porpoises	4.34	3.484	9.318	12.8	0.00025	51004	0.945	37.64
cod >35 cm	3.67	2.984	8.452	11.44	0.0175	653.4	0.844	0.482
cod <=35 cm	3.18	1.067	3.184	4.251	0.00477	890.5	0.314	0.657
flatfish	3.39	4.317	12.33	16.64	0.0346	481.4	1.228	0.355
other demersal fish	3.33	8.303	22.38	30.68	0.0611	502	2.264	0.37
herring	3.41	1.637	2.432	4.07	0.135	30.21	0.3	0.0223
sprat	3.41	0.252	0.0871	0.339	0.0199	17.06	0.025	0.0126
other pelagic fish	3.5	1.881	1.925	3.806	0.0277	137.3	0.281	0.101
benthic macrofauna	2.01	0.11	0.361	0.471	0.0354	13.31	0.0347	0.0098
Total	3.27	25.18	63.58	88.75	0.339	261.4	6.55	0.193

Table 12d: PPR - Primary production required in the WBS ecosystem in **2050** under management scenario "EBFM".

Group name	TL	PPR (PP)	PPR (Det)	PPR	Catch	PPR / catch	PPR / TotPP (%)	PPR /u. catch
seals	4.35	0.0321	0.0739	0.106	3E-06	32867	0.00781	24.22
(sea-) birds	3.92	0.6	1.395	1.995	0.00377	529.8	0.147	0.39
harbour porpoises	4.41	11.12	23.76	34.88	0.00146	23905	2.57	17.61
cod >35 cm	3.8	11.22	29	40.21	0.0575	699.3	2.963	0.515
cod <=35 cm	3.26	0.647	1.806	2.453	0.00594	412.8	0.181	0.304
flatfish	3.19	0.943	2.696	3.639	0.012	304	0.268	0.224
other demersal fish	3.47	5.667	13.01	18.68	0.0381	490.8	1.376	0.362
herring	3.4	2.427	3.677	6.103	0.126	48.58	0.45	0.0358
sprat	3.4	0.24	0.0832	0.323	0.0179	18.11	0.0238	0.0133
other pelagic fish	3.48	2.84	2.57	5.41	0.045	120.4	0.399	0.0887
benthic macrofauna	2.01	0.111	0.361	0.472	0.0355	13.3	0.0348	0.0098
Total	3.34	35.84	78.43	114.3	0.343	333.5	8.42	0.246

Discussion

Quality of the 1994 Model

The Ecopath model for 1994 is the first model that combines all living components of the WBS ecosystem and quantitatively connects them via their diet.

In summary, the WBS food web in 1994 may be characterized as a system under stress. Ecotrophic efficiency values >1 or near 1 for all fish species / groups indicated that these groups were "overused", i.e. annual consumption (to a larger extent by fisheries and to a lesser one by natural predators) exceeded annual production. In some cases, e.g. for flatfish, this result may be aggravated by reporting biases. Important commercial stocks such as western Baltic cod and western Baltic spring spawning herring were suffering from overfishing. Particularly for herring and juvenile cod the demand could only be balanced assuming immigration from and coverage of dietary needs of predators in neighbouring areas.

One may argue "why should one have confidence in a model where more is used than is available"?

The western Baltic sea is not a closed system; instead there is inflow and outflow of waters and organisms swimming and floating therein. And there are organisms that can actively search for food, shelter, and suitable mating and hatching sites in nearby ecosystems. Thus, there is considerable exchange of energy and matter with those neighbouring ecosystems.

In the Ecopath base model year 1994 important fish stocks such as herring, and sprat were already overfished and in the decent and stocks did not produce "sufficient" biomass to satisfy extraction by predators and fishery on a balanced level. Thus, the lack of a certain food item may be balanced by shifting to more abundant food items within the model area or by assuming import or immigration of the scarce food item. We opted for the latter approach because the first one makes single contributions from different scarce food items indiscernible. Conclusion is that system resources – are being or "overused" or "predation pressure shifted down to lower trophic levels".

One of the rules in Ecopath is that the exchange of matter with neighbouring systems per unit of time should not exceed the production of matter within the model system. Summary statistics for the model area show, that total system production was 632 $gCm^{-2}y^{-1}$. In comparison only 0,4 $gCm^{-2}y^{-1}$ (excluding detritus) or 232 $gCm^{-2}y^{-1}$ (including detritus) were exported out of the model system, and 0,18 $gCm^{-2}y^{-1}$ (excluding detritus) or 213 $gCm^{-2}y^{-1}$ (including detritus) entered the system by import of food through mobile organisms (e.g. harbour porpoises, birds) or by immigration (herring, sprat, flatfish). It should be noted in this context that detritus is not a producer but more a source / sink of matter.

Prior qualitative knowledge about the WBS suggested that herring was a LTL (Low Trophic Level) keystone species (Essington & Plagányi, 2013) and of more importance to higher trophic levels than sprat. This may be attributable quantitatively to the size of the herring stock and related flows. Herring had the highest stock biomass in the WBS system (the sprat stock – although being more productive per unit of biomass - was only half the size of the herring stock) and transported the highest amount of matter from lower trophic levels (mostly zooplankton) to a large number of predators at higher and highest trophic levels. The model showed that herring served more predators and more herring was consumed by predators than sprat. Figure 42 shows the strength of impact of trophic groups on the food web using a measure named Keystone Index no. 1 (Libralato et al. 2006). Herring shows the highest value as a single fish species transporting matter from low trophic levels to predators high in the food web.

With reference to the quality of input data (for a quality ranking of input data see Table 5 above) there is a strong need for better inputs particularly for top predators such as harbour porpoises (B, P/B), seals (all inputs), and seabirds (all inputs).

Quality of the EwE Fitting and Predictions

For the 1994 Ecopath model, the biomass of seals was actually too low to properly qualify for a group of their own and would normally have been lumped with harbour porpoises into one marine mammals group. Nevertheless, this species was treated as a group of its own because harbour porpoises in the WBS are threatened by extinction and thus of special concern in the context of EBFM. Furthermore, harbour porpoises and seals have different dietary needs. Porpoises are particularly dependent on energy-rich food and must eat constantly to meet their high metabolic energy demands (Read & Hohn, 1995, Wisniewska et al. 2018). Similarly, seabirds are a group that spans several trophic levels (from benthic macrofauna eaters such as ducks to fish eaters such as sea gulls and cormorants (*Phalacrocorax carbo))* and includes migratory and non-migratory birds (ICES JWGBIRD, 2016c). For these reasons, the EwE for seals and seabirds are considered to be only partially representative and are not discussed further.

Traditionally, the quality of a model is validated by comparing model results with independent (sets of) data, i.e. with external data not used during the modelling procedure (Joergensen & Bendoricchio, 2001). In this study, model predictions of catch and biomass for years 1994-2016 matched input values for catch and biomass remarkably well and only some adjustments to the fishing mortality before 2000 were needed for adult cod to improve fits in these early years. There are indications in nature – particularly for cod – for immigration and mixing of adjacent populations. Hüssy et al. (2015) noted eastern Baltic cod invasions into the western Baltic since 2008, i.e. the area west of Bornholm comprising a mixture of both stocks. While SD 22 is utilized soley by the western cod stock and SD 25 utilized soley by the eastern cod stock, SD 24 north of Rügen is the main mixing zone, with 9 to 90 % eastern stock occurring in the said area. According to Hüssy et al. (2015) invading cod from the eastern Baltic do not spawn in the western part. Only occasionally do eastern juvenile cod invade the western part.

ExplR for WBSS in ICES SDs 22+24 was fitted to estimated SSB time series of 50 % of total stock area since biomass and F data were only available for the entire area covered by the herring stock throughout the year (ICES SDs 20-24). The approximation of the best fit for ExplR obtained during the fitting process suggested an increase of fishing pressure within the model area along the time axis in contrast to a decrease of F for the entire stock area (ICES SDs 20-24). The cause for this phenomenon is not quite clear but it would explain to some extent why the herring stock is not rebuilding properly despite of reducing quotas and thus fishing pressure lately. Provided that the assumption of 50% SSB inside the model area holds true, results suggest that fishing pressure on herring inside the model area has not been reduced along the years but has increased compared to data of F published by ICES for the entire WBSS herring stock.

Plaganyi & Butterworth (2004) published a thorough analysis of advantages and shortcomings of the EwE software packages II to VI. They state that "ECOPATH constraints act as a rigorous analytical framework (in contrast to an *ad hoc* type model)", as well as "given good input data, EwE has utility to provide a first-order perturbation analysis." Plaganyi & Butterworth (2004) explicitly welcomed the introduction of the foraging arena concept into EwE expressed through a vulnerability parameter (V) of prey towards its predators. This has the effect of "dampening the unrealistically large population fluctuations usually predicted by the Lotka-Volterra formulation". Because they state that vulnerability parameters are difficult to estimate, we used the default V = 2 for all predator-prey combinations.

The foraging arena concept in EwE expressed through a vulnerability parameter (V) of prey towards its predators has the effect of "dampening the unrealistically large population fluctuations usually predicted by the Lotka-Volterra formulation" (Plaganyi & Butterworth, 2004). These vulnerability parameters are usually difficult to estimate. Trial runs using the vulnerability routine during the fitting process yielded unrealistically high values for a great part of predator / prey combinations. Therefore the default V = 2 for all predator-prey combinations was used.

Another routine in EwE (see e.g. Heymans et al., 2016, for a thorough compilation of model result evaluation routines in EwE) for addressing uncertainty of inputs is by running input parameters through Monte Carlo simulations. This showed only a negligible difference of SS before (25.19) and after (24.68) applying the routine to the calibrated WBS model (start value before calibration >100).

These good fits increased confidence in the model predictions of future biomass and catch for 2017 until 2050.

Another routine in EwE (see e.g. Heymans et al., 2016, for a thorough compilation of model result evaluation routines in EwE) for addressing uncertainty of inputs is by running input parameters through Monte Carlo simulations. Doing this showed only a negligible difference of SS before (25.19) and after (24.68) applying the routine to the calibrated WBS model (start value before calibration >100).

(1) The groups of juvenile and adult cod are treated as development “stanzas” (life history stages) in EwE and are interdependent in the model. Figure 43 shows the relationship between juvenile and adult cod biomass, which resembles a hockey-stick stock-recruitment relationship (SR), as expected for cod. This SR is not an input to but an output of the modelling process, and thus confirms the ability of the model to produce reasonable results.

(2) Most ecosystem models enter states where groups crash or explode in size when left unchecked for an extended period of time. This is, however, not the case for this WBS model, where no group crashed or increased indefinitely, but rather, when modelled without fishing, all groups reached and fluctuated around levels that seem to be reasonable representations of carrying capacity, suggesting that biomass in 2016 represented about 4% of carrying capacity for cod and about 15% for herring.

(3) Köster & Möllmann (2000) postulate two stable states for the Baltic ecosystem, one that is herring-dominated and the other, cod-dominated. The model predictions without fishing indeed show two such stable states and suggest that, under such conditions, a herring-dominated state would establish first (because increase in herring biomass is faster), followed later by a cod-dominated state (because other herring-eating groups increase even slower than cod but help switch the system once the joined consumption equals or exceeds annual production of herring*)*.

(4) Based on an earlier published ecosystem model by Harvey et al. (2003), Hansson et al. (2007) explored possible effects of different management scenarios for the central and eastern Baltic Sea. Scenarios included a strong increase of seals (marine mammals), oligotrophication of the system, and impact of different fishing intensities on stock size and catches of cod, herring, and sprat. They simulated a large number of scenario combinations for the period 2001 to 2100 (we simulated scenarios for years 2017 to

2050). They ran simulations with three different fishing intensities named SQ (status quo conditions), PA (precautionary approach as defined by ICES), and ½ PA. SQ resembles "Business as usual" in our modelling and ½ PA would roughly correspond to F_{msy}. Similarly to our model (numbers in parentheses), both herring and cod biomass dropped by 80% (77%) and 85% (80%) respectively during the "calibration" period 1974 to 2000 (1994 to 2016). In contrast to Hansson et al.´s (2007) findings of 80% sprat biomass in WBS dropped only by slightly over 20%. This may be attributed to the fact that the Baltic sprat stock is concentrated in the eastern part of the Baltic Sea and in WBS stock biomass is only half the size of the herring stock. Thus, the ecological role (e.g. main LTL species) and pattern of interaction differs from the eastern Baltic situation. Hansson et al.´s (2007) simulations for years 2001 to 2100 predicted a continued and drastic decrease of the herring and cod populations and an increase of the sprat stock for continued SQ fishing intensities. For PA levels herring and cod stocks would thrive but the sprat stock would be drastically reduced (PA level for sprat was higher than SQ level). Despite decreased fishing intensities for cod and herring, catches would be substantially higher than during the SQ fishing regime and similar to average catches for the calibration period. Sprat catches, however, would decrease drastically due to increased predation by cod. The highest catches were obtained when sprat was fished at ½ PA and cod and herring where fished at PA level. This combination and the resulting catches compare to some extent to our "EBFM" scenario with herring and sprat fished at ½ F_{msy} and other fish (including cod) at 80% F_{msy}. Simulations of increased selection and without catches of juveniles had only a very marginal impact on stock size.

Correction of Misconceptions

A number of misconceptions exist about the trophic relations in the WBS. One of these predicts that an increase in adult cod would increase the rate of cannibalism on juvenile cod (ICES, 2013). However, our model shows that if fishing pressure on herring is reduced and thus herring biomass is allowed to increase, then cannibalism on juvenile cod plays a minor, not increasing role. This is evident in the stock-recruitment relationship (Figure 43) where, after an early peak, the number of juvenile cod should continuously decline with increase in biomass of cannibalistic adults, which is clearly not the case.

Another misconception is that birds (especially cormorants) consume a large fraction of the biomass of cod and herring. The model shows that the combined consumption by birds, seals and harbour porpoises on cod, herring, and sprat is negligible compared to extraction by current fisheries (Figures 38a to 41a). But the model shows also that a big increase of fish-eating marine mammals may create competition with fisheries particularly for juvenile cod (a bycatch product of the adult cod fishery) and herring as demonstrated in the "EBFM" scenario (Figures 39b and 40b). Nevertheless, a drastic increase in fish eating marine mammals will not devastate fish stocks, as suggested by Hansson et al. (2007) for the central and eastern Baltic Sea.

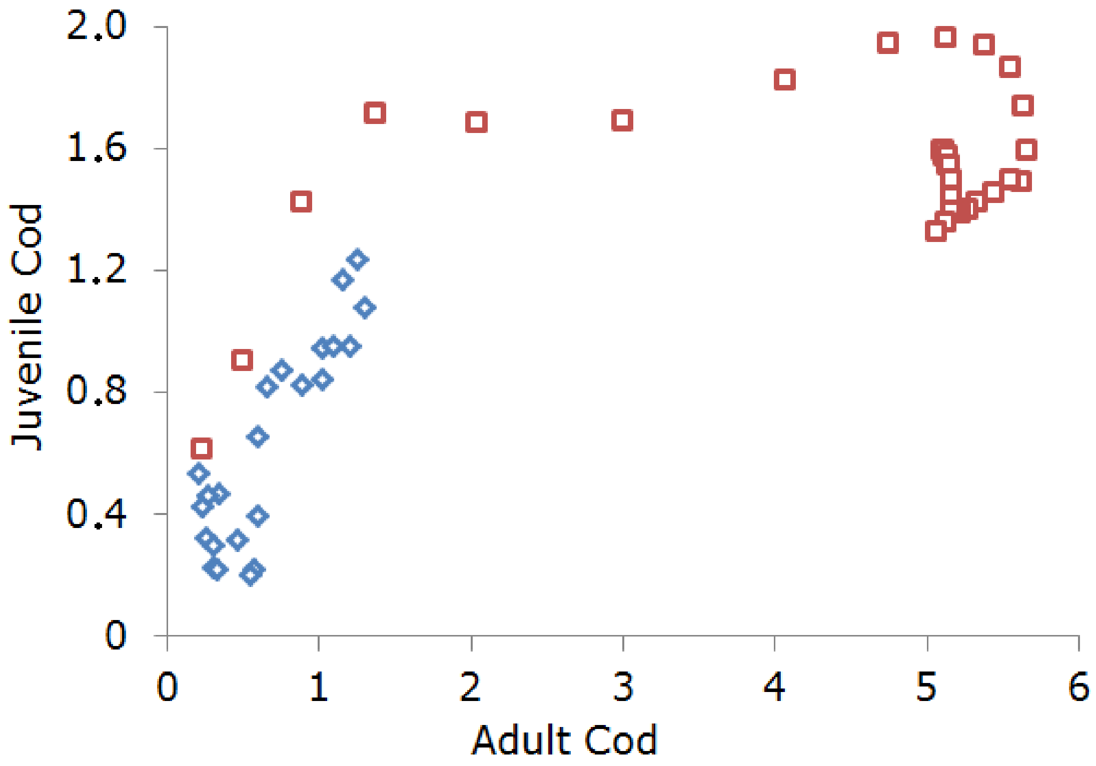

Figure 43: Stock / recruitment relationship of cod in the WBS Ecosystem 1994 to 2016 (in blue) and 2017 to 2050 (in red) under fisheries scenario "EBFM".

The third and often repeated misconception is that the productivity of the WBS is actually limited by lack of nutrients needed for primary production. Hansson et al. (2007) state that the overall primary production in the Baltic Sea in the early 1900s has been estimated to approximately 35% of its current level. Due to a rise in primary production and presumably to the extensive culling of seals all over the Baltic Sea fishery yields have increased five to ten fold during the past century. Our model suggests that less than 10% of the primary productivity is required for the current catches taken from the system. This is a very low number, compared to the usual 24-35% found in other coastal systems (Pauly & Christensen, 1995) and suggests that the biomass of herring and sprat is too low to transport more energy from the zooplankton level to the upper trophic levels and to the fisheries.

The ratio of PPR to total PP (Tables 12a to d) shows decreasing values from 1994 (8.9 %) to 2016 (6.8 %) and furtheron under management scenario "Business as usual" (6.6 %

in 2050). This indicates an increasing missmatch between PP available and use by system elements nourishing the hypothesis that due to increasing release of non-point source polluters and / or shrinking fish stocks - provoked mainly through overfishing, particularly LTL species herring and sprat, - eutrophication in the western Baltic Sea ecosystem is increasing. Under fisheries management scenario "EBFM" model results show (8.4 % in 2050) to what extent the situation may be reversed compared to the starting situation in 1994. It should be noted though, that for the 2050 "EBFM" scenario, the model predicts a considerable lack of juvenile cod – possibly due to strongly increased feeding pressure by strongly increased biomass of harbour porpoises and adult cod.

EBFM for the WBS

The CFP (2013) and the MSFD (2008, 2017a,b) of the EU call for Ecosystem-Based Fisheries Management in European seas where negative impacts of fishing are minimized and the biological wealth and the natural functioning of the ecosystem are safeguarded, and where multiannual management plans shall take into account knowledge about the interactions between fish stocks, fisheries and marine ecosystems. While enabling a sustainable use of marine goods and services, priority should be given to achieving and maintaining good environmental status in European seas. With these obligations from the MSFD, the entire spectrum of species and habitats in Europe's seas must be included in management decisions (Kreutle et al. 2016). The WBS model addresses most of these legal requirements and allows, for the first time, a comprehensive assessment of MSFD criteria D4C, referring to the undisturbed diversity, abundance and balance of trophic guilds.

While common sense implementations of EBFM have been proposed (Pikitch et al., 2004, Froese et al., 2016), such as fishing all stocks below F_{msy} and reducing fishing pressure even further for forage fish such as herring and sprat (Pikitch et al., 2012), few studies compared such fishing to alternative scenarios. This model shows for the first time for the WBS, that without changes to the present fishing regime low biomass and catches and a decline and potential loss of harbour porpoises will continue as demonstrated by the "Business as usual" scenario. Fishing at F_{msy} would rebuild all stocks except flatfish, albeit with lower biomass levels compared to the subsequent two scenarios. Fishing all commercial species at half of F_{msy} shows the best rebuilding of biomass for most groups (to a lesser extent for herring) due to increased predation pressure by enlarged stocks of harbour porpoise and cod. The "EBFM" scenario accounts for the need to reduce fishery impact on herring and sprat and shows good biomass developments similar to F_{msy} for cod and herring (to a lesser extent for sprat) and good catches similar to F_{msy} for cod and flatfish. Herring and sprat catches remain at the 2016 level but with largely reduced fishing effort and thus lower cost of fishing.

Conclusions

The trophic model presented here shows for the first time the "big picture" of the WBS food web by quantifying structure and flows between all trophic elements. The model may be viewed as a preliminary but thermodynamically viable hypothesis of the WBS food web subject to more refined results along with the availability of more up-to-date data particularly for top predators such as marine mammals and seabirds.

Results from our model show that the fishing pressure presently exerted on the WBS forces not only top predators such as harbour porpoises and seals, but also cod and other demersal fish to heavily compete for fish as food and to cover their dietary needs by shifting to organisms lower in the trophic web, mainly to benthic macrofauna and / or search for suitable prey in adjacent ecosystems such as Kattegat, Skagerrak, central Baltic Sea and North Sea.

Simulations show that a "Business as usual" scenario would perpetuate low catches from depleted stocks in an unstable ecosystem where endangered species may be lost. In contrast, the "EBFM" scenario allows the recovery of all stocks (to a lesser extent for sprat) with strongly increased catches close to the maximum for cod and flatfish and catches similar to the 2016 level for herring and sprat.

Acknowledgements

The German Federal Agency for Environmental Protection (Bundesamt für Naturschutz BfN) provided financial support. ECOLAB (FTZ Büsum, DE) provided information on marine mammals and sea birds in WBS, and M. Zettler (IOW, Warnemünde, DE) helped with quantitative information on benthic macro- and meiofauna in the WBS ecosystem. C. Garilao provided valuable technical support and a thorough final review of the manuscript.

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