

## Rebuilding the Eastern Baltic cod stock under environmental change - a preliminary approach using stock, environmental, and management constraints -

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### Abstract

The population dynamics of the Eastern Baltic cod (*Gadus morhua callarias* L.), unlike many other stocks, shows a strong dependency on environmental conditions. To test the implications of different management policies on the stock and the fishery in a system of global environmental change, we apply a spatially disaggregated, discrete time, age-structured model of the Eastern Baltic cod stock in 50 year simulation analyses. The simulation provides an analysis of stock, yield, and revenue development under various management policies and environmental scenarios. The policy analysis, focusing on different regulations of fishing mortality, is embedded into three environmental scenarios, assuming low, medium, or high climate and environmental change. The environmental assumptions are based on simulation results from a coupled atmosphere-ocean regional climate model, which project salinity in the Baltic Sea to decrease by 7-47% in the period 2071-2100 relative to the reference period 1961-1990. Our simulation results show that a significant reduction in fishing mortality is necessary for achieving high long-term economic yields. Moreover, under the presented environmental scenarios, a stock collapse cannot be prevented. It can, however, be postponed by the establishment of a marine reserve in ICES subdivision 25.

**Keywords:** Baltic cod, climate change, environmental variability, reproductive volume, population dynamics, management, policy, age-structured model, temporal marine reserve

## 1. Introduction

The population dynamics of the Eastern Baltic cod (*Gadus morhua callarias* L.) depends strongly on environmental conditions (e.g. Bagge and Thurow 1994a; MacKenzie *et al.* 2002). As a result of the Baltic Sea's environmental variability, Baltic cod stock abundance has fluctuated widely over time and particularly since the mid-1960s: Spawning stock biomass peaked around 700,000 t in the early 1980s; during the past decade, however, biomass has dropped below the biological limit ( $B_{lim}$ ) of 160,000 t, representing the level below which recruitment is impaired (ICES 2004a). Concomitant to these fluctuations in biomass, landings increased from less than 10,000 t in the early 1900s to approximately 400,000 t during the 1980s (Sparholt 1994), due in part to increases in fishing effort and improved technology (Bagge *et al.* 1994b). In 1992, landings dropped below 100,000 t, and they have remained low since. The sharp decline in stock size since the mid-1980s has been attributed to an interplay between overfishing (high fishing mortality) and unfavourable environmental conditions (MacKenzie *et al.* 2002).<sup>1</sup>

MacKenzie *et al.* (2002, p.184) suggest that “the most important environmental factors for the biota of the Baltic Sea are salinity, oxygen concentration, temperature, and eutrophication”. Unlike other cod populations, cod eggs in the Eastern Baltic are neutrally buoyant in deep water below the permanent halocline<sup>2</sup>. Salinity and oxygen concentrations below the halocline vary relative to major Baltic inflows from the North Sea. They have a direct impact on the development of the Baltic cod eggs, which need a minimum salinity ( $S \geq 11$  psu) and a minimum oxygen concentration ( $c[O_2] \geq 2$  ml/l) to develop (Nissling *et al.* 1994; Wieland *et al.* 1994). The volume of water having these characteristics has been termed the “reproductive volume” (RV) for Baltic cod (e.g. MacKenzie *et al.* 2000; Plikshs *et al.* 1993); it has been applied in the development of Baltic cod stock and recruitment models (Köster *et al.* 2001a, 2001b; Röckmann *et al.* 2005; STORE 2002). Climatic variables directly and indirectly influence the Baltic Sea hydrography, e.g. via precipitation. The reproductive volume and in turn cod population dynamics are thus susceptible to the regional consequences of global climate change (cf. Section 2).

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<sup>1</sup> For a detailed description of the reconstructed historic biomass and landings of Baltic cod before the 1960s, the reader is referred to MacKenzie *et al.* (2002) and Thurow (1999).

<sup>2</sup> The halocline are layers of water where the water's salinity changes rapidly with depth.

In this study, we extend an existing model of the population dynamics of the Eastern Baltic cod (Röckmann *et al.* 2005) to test whether a set of policy options could prevent the stock from collapsing because of climate change. We analyse future stock and yield development, and effects on fishermen's revenues for three environmental scenarios, which are based on simulation results of a coupled ocean-atmosphere regional climate model (RCM) (Meier submitted). Meier's results project an overall decrease in salinity in the Baltic Sea due to global climate change. As a preliminary approach, we develop linear relationships between average salinity in the Baltic Sea and the area-specific size of the reproductive volume in the three subdivisions, serving as the link between climate change and fish population dynamics.

The model of Baltic cod population dynamics is age structured and calculates stock size on a time step of three months explicitly for three subdivisions in the Eastern Baltic Sea. The model includes the migration of mature cod between sub-areas based on theoretical, process-oriented assumptions.

The investigated management policies focus on rebuilding the cod stock via the establishment of a marine reserve (permanent or temporal) in and around a major spawning ground of the Eastern Baltic cod stock. Field studies have illustrated that closed areas can lead to increases in fish biomass, density, and size, and in ecosystem diversity (reviewed by Halpern 2003). Furthermore, marine reserves as a fisheries management tool do not rely on accurate fish stock assessments and are therefore less susceptible to the fallacies of conventional management approaches (e.g. Botsford *et al.* 1997; Walters 2001).<sup>3</sup>

In the next section, we present how climatically driven environmental factors, such as salinity and oxygen, influence Baltic Sea hydrography, and how climate and atmospheric constellations drive these factors. Section 3 provides an outline of the population dynamics model for the Eastern Baltic cod stock combined with the fishery, and describes the environmental scenarios and the selected management policies. The simulation results for the different scenarios are presented and discussed in Section 4. Estimates of stock development, yield development, and the net present value of revenues are shown for the different scenarios. Finally, in Section 5 we conclude the work and point out caveats representing areas where future research is warranted.

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<sup>3</sup> For a discussion of the pros and cons of marine reserves, see Kaiser (2005) and Röckmann *et al.* (2005).

## 2. Baltic Sea hydrography and climate change

Dissolved oxygen concentration is influenced abiotically, partly by wind-induced mixing of the surface water layer, partly by sporadic Major Baltic inflows (MBI) through the Belt Sea, which replenish the deep water layers of the Baltic Sea with saline and well oxygenated North Sea water (e.g. Matthäus and Frank 1992; Schinke and Matthäus 1998). Furthermore, strong cooling at the sea surface results in higher oxygen solubility (Hinrichsen *et al.* 2002b). Additionally, biotic factors alter the dissolved oxygen concentration in the Baltic Sea, as e.g. bacterial degradation and decomposition consume oxygen.

Eutrophication and temperature indirectly impact on the year class strength of Baltic cod. Thurow (1997) assumed “that eutrophication has caused the increase in the Baltic fish stocks since about 1950”, which, when coupled with the high fishing mortality exerted on the cod stock, has resulted in increased predation pressure by sprat and herring on the early life stages of Baltic cod (e.g. Köster and Möllmann 2000). Furthermore, increased primary production as a result of eutrophication leads to an increase in particulate organic matter, which in turn fuels oxygen-consuming demineralisation of organic material during sedimentation. Hence, eutrophication has an indirect effect on the oxygen concentration and the occurrence of hypoxia and anoxia in the bottom water layers.

Similar to eutrophication, an increase in water temperature generally has a stimulating effect on primary production and on metabolic activity of higher organisms. Oxygen concentrations are more likely to decrease in warmer than in colder waters, not only due to increased oxygen-consuming demineralisation of organic material, but also because increasing water temperature reduces oxygen solubility. In a multispecies context, an increase in water temperature favours the reproductive capacity of sprat (MacKenzie and Köster 2004), i.e., sprat reproductive success increases, which may be unfavourable for cod due to a potential increase in predation pressure by adult sprat on the early life stages of cod (Köster and Möllmann 2000). Additionally, the survival of larval cod may become food limited, as the abundance of the zooplankton *Pseudocalanus elongatus*, the main food of cod larvae, decreases with decreasing salinity (Hinrichsen *et al.* 2003).

Salinity conditions in the Baltic Sea are driven by several meteorological and climatic variables, such as temperature, sea ice cover, precipitation, river runoff, atmospheric circulation patterns influencing the occurrence of Major Baltic inflows (MBI) from the North Sea, and by radiation (Hänninen *et al.* 2000; Lehmann *et al.* 2002; Matthäus and Schinke 1999; Omstedt and

Nohr 2004; Winsor *et al.* 2001). Regional climate models (RCM) predict that global climate change results in higher air temperatures and an increase in precipitation and freshwater-runoff over the Baltic Sea drainage area (Döscher and Meier 2004; Omstedt *et al.* 2004; Rutgersson *et al.* 2002). An indirect effect of increased precipitation is the reduction of the impact of major inflows of North Sea water on salinities in the deep layers of the Baltic Sea. The sporadic occurrence of such inflows is triggered by the combination of specific wind speeds and directions (Matthäus and Frank 1992; Schinke and Matthäus 1998). Lehmann *et al.* (2004) investigated effects of remote and local atmospheric forcing on circulation and upwelling in the Baltic Sea. They related the local wind field over the Baltic Sea to the large-scale atmospheric circulation over the North Atlantic, the North Atlantic Oscillation (NAO), by defining a Baltic Sea Index (BSI). Nonetheless, a predictive understanding of the effect of changes in atmospheric circulation on inflow dynamics and the resulting hydrographic conditions in the Baltic Sea is as yet unavailable.

By developing relationships between the seasonal variability of the reproductive volume and environmental factors, MacKenzie *et al.* (1996b) showed that the seasonal decrease in the size of the RV is temperature dependent. Also, existing knowledge concerning the implications of climate change on the Baltic Sea suggest that salinity and oxygen conditions are likely to deteriorate with increasing water temperatures, as we presented above. In summary, the combined effect of climate change and its regional consequences for the Baltic Sea area points at a decrease of the size of the reproductive volume in the future, and hence a deterioration of environmental conditions for Baltic cod recruitment, which has been suggested by MacKenzie *et al.* (1996b).

### **3. Modelling approach and scenario development**

#### *Study area and spatial resolution*

The area modelled, located in ICES area IIIId, is composed of the three ICES subdivisions (SD) 25, 26, and 28 (Figure 1). It is the principle habitat of the Eastern Baltic cod stock (Sparholt *et al.* 1991) and the origin of more than 90 % of the international catch of Eastern Baltic cod (ICES 2000, 2001b, 2002, 2003, 2004a). We neglect the remaining subdivisions, as they do not at this time comprise an important spawning ground for Baltic cod, and cod fishing in subdivisions 27 and 29 to 32 is of minor importance to the commercial fishery.

**Insert Fig. 1 here**

## *Data*

Quarterly data on stock size, natural, predation and fishing mortality of cod for the ICES subdivisions 25, 26, and 28 are employed from an area-disaggregated Multispecies Virtual Population Analysis (MSVPA), covering the time period 1974 to 1999 (ICES 2001a; Köster *et al.* 2001a). Basin-specific data on reproductive volume for the time period 1976 to 1996 are available from MacKenzie *et al.* (2000). Additional data for the years 1997-1999 are taken from ICES (ICES 2005a).

Data for cod weight-at-age in the catch is highly uncertain and of poor quality, partly because of age-reading problems of the otoliths of Baltic cod (ICES 2001c; Reeves 2001), but also because of differences between individual fish, depending on location, food availability, and the time of capture. In general, fish of a similar age from SD 25 are heavier and in a better shape than their cohorts in SD 26 and 28 (H.-H.Hinrichsen, pers.communication). Estimates of average weight-at-age in the stock and in the catch published by STORE (2002) differ by several kg from those published by ICES (2003). In this study, we utilise estimates from the ICES data base, as, within the scope of the standard stock assessments, they provide a long time series of yearly estimates. For the simulation time period 2005 to 2055, we apply the average weight-at-age for the years 2000-2002 (ICES 2003, pp.186-187).

With respect to the Eastern Baltic cod fishery, Polish, Swedish, and Danish fishermen together harvest roughly 70% of the total catch of the Eastern Baltic cod (ICES 2004a). The remainder is shared by Latvia, Russia, Lithuania, Germany, Finland, and Estonia, in decreasing order of catch quantity. In general, ex-vessel prices per kilogram of cod vary by nation as well as over the course of a year and a month. In Denmark, for example, the prices are usually low at the beginning of a month, when each vessel has its full fishing quota and can supply high landings. Towards the end of the month, many vessels have taken their individual vessel quotas, resulting in low landings – hence, prices increase. Price development over the course of a year also reflects accessibility to the resource: In the Baltic Sea, cod fishing has been banned from June till August by the International Baltic Sea Fisheries Commission (IBSFC). Therefore, the monthly average prices of cod increase during the summer months, when supply is restricted, consisting mostly of North Sea or Atlantic cod. In autumn and winter prices decrease again, as continued harvesting in the Baltic Sea delivers additional cod supply (Figure 2; Fiskeridirektoratet 2003).

### **Insert Figure 2 here**

The above descriptions suggest the existence of a local market for Baltic cod where the price is sensitive to local supply. The relationship between price and quantity has, however, not yet been analysed, which would be an interesting extension of our study. In the absence of such an analysis, we use a constant price as a simplification; here, we settle for the 2005 minimum prices of the Danish Fishermen's Producers Organisation (DFPO): Offering a "safety net" for Danish fishermen, the DFPO guarantees minimum payments for cod of quality category E and A, if the affiliated fishermen cannot sell their fish at a certain minimum price (cf. Table 1)<sup>4</sup>. The minimum prices, which we apply, have been confirmed by employees at the Danish fish auctions in Hirtshals and Hanstholm (pers. communication).<sup>5</sup>

### **Insert Table 1 here**

The data reveal that prices depend on the quality and size of the landed fish. For cod, there are six different weight categories and three different quality categories (Table 1). Average prices of cod seem to be determined by external factors; but there is a fairly robust difference in price between small and large specimens. Note that our model deals with separate age groups.

There are substantial differences between the DFPO minimum prices and the three-year average prices: The average prices are recorded on a monthly basis, whereas the minimum prices remain constant over a year. Furthermore, monthly average prices in 2001-2003 were more than 200% greater than the 2005 minimum prices. The minimum prices can therefore be considered a robust minimum estimate. In reality, prices probably do not fall below this target.

#### *The model of population dynamics*

The model of population dynamics for the Eastern Baltic cod, developed by Röckmann *et al.* (2005), consists of an age-structured, area-disaggregated, discrete time model of the Beverton and Holt type. Here, recruitment refers to 0-group cod and occurs at discrete time intervals. Recruits join the parent population two years after spawning at age 2. A similar approach has been used in several applied studies, e.g. for the East Atlantic Bluefin Tuna (Bjorndal and Brasao

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<sup>4</sup> About 70% of the total Danish fishing capacity is affiliated to the DFPO.

<sup>5</sup> We apply prices and calculate revenues in Danish Kroner (Kr.) for two reasons: (1.) The best available economic data on the Baltic cod fishery is collected by the Danish fisheries directorate (e.g. Fiskeridirektoratet 2003). (2.) The existing economic studies and working papers on the Baltic cod fishery are mostly from Denmark (e.g. Kronbak 2003, Andersen 2002, Jørgensen 1988).

forthcoming). Our model is presented in the Appendix. Variables and parameters in model notation are defined in Table 2.

**Insert Table 2 here**

Since Baltic cod is known to have an extended spawning season and feeding migrations (Aro 1989, 2000, 2002), we extended the existing model by accounting for migration of mature Baltic cod between the three subdivisions. We considered two processes:

- (a) spawning migration (S) in spring, with a net migration from the North/Northeast to the South/Southwest
- (b) feeding migration (D) in autumn after spawning, directed mainly from the South/Southwest to the North/Northeast, depending on spatial density differences.

As no quantitative data on cod migration are available at present, the migration patterns used are a stylised representation of those believed to exist, based on the qualitative descriptions by Aro (1989, 2000, 2002). The mathematical functions used to describe these two migration processes (cf. Eq. 3 and 4 below) are different, meaning that fish that migrate from region k to region j to feed, do not necessarily return to region k to spawn. This assumption is in line with the fact, that there is no evidence of homing behaviour of the Eastern Baltic cod stock, “and thus cod may use different spawning grounds in successive years in its distribution area” (ICES 2001b). Egg and larval drift is currently not taken into account in our model, as it is beyond the scope of the present study, requiring for example coupling to a meteorological model which generates spatially and temporally resolved wind fields. Here, we assume that cod of ages 1-8 show the same migration pattern, independent of age.

Spawning migration (S) is calculated in the second quarter as a directional movement from SD 28 into SD 26 and 25, and from SD 26 into SD 25, depending on the size of the reproductive volume in SD 28 and 26, respectively. We are not aware of any study that has investigated migration behaviour of a demersal species, like Baltic cod, in relation to environmental factors. Therefore, we tested three different functional forms – linear (lin), exponential (ex), and logistic (log) (**Equations 1-3**). With respect to the sigmoid form, we set  $RV^{\max}$  at 500 km<sup>3</sup> in all subdivisions, which corresponds to the highest values in the available time series, observed at the beginning of the 1950s (MacKenzie *et al.* 2000).

$$(1) \quad S_{a,y,rj \rightarrow rk}^{lin} = \alpha \cdot N_{a,rj,"q2",y} \cdot (1 - \beta^{lin} \cdot RV_{rj,y})$$

$$(2) \quad S_{a,y,rj \rightarrow k}^{ex} = \alpha \cdot N_{a,rj,"q2",y} \cdot e^{-\beta^{ex} \cdot RV_{rj,y}}$$



$$(3) \quad S_{a,y,rj \rightarrow k}^{log} = \alpha \cdot N_{a,rj,"q2",y} \cdot \left( 1 - \frac{1}{1 + RV_{rj}^{max} \cdot e^{-\beta^{log} \cdot RV_{rj,y}}} \right)$$

with j = SD 28 or 26, k = SD 26 or 25.

Our results are not very sensitive to the three different mathematical approaches. Here, we chose the logistic approach (**Eq.3**). For appropriate parameter choices, this S-shaped curve resembles a step function, which Huse *et al.* (2002) have successfully applied in schooling species, such as herring, to model migration according to the ‘adopted-migrant hypothesis’ (McQuinn 1997). The logistic function is smooth, however.

The coefficient  $\alpha$  is a scaling parameter, accounting for the assumption that a small percentage of cod does not emigrate despite unfavourable hydrographic conditions. This phenomenon of intrapopulation variation in movement is known as partial migration, and there are documented instances of partial migration in a wide array of taxa from insects to fish to birds (Dingle 1996). Here, we arbitrarily set the maximum percentage of mature cod migrants from SD 26 and SD 28 to 70% and 90%, respectively (Table 3).

The coefficient  $\beta$  is chosen such that spawning emigration from SD j into SD k is zero, if the reproductive volume in SD j is close to 200 km<sup>3</sup>, which we assume to be sufficient to allow for successful spawning in SD 26 and 28 (Table 3). Several ecological studies describe comparable inverse relationships between the level of a particular environmental factor, such as soil moisture, precipitation, or temperature, and the frequency and proportion of migrants of a species (Dingle *et al.* 2000, and references herein).

### Insert Table 3 here

The feeding migration (D) after spawning is incorporated as a density-dependent random diffusion process in the fourth quarter (**Eq.4**).

$$(4) \quad D_{a,y,rk \rightarrow j} = \gamma \cdot (N_{a,rk,"q4",y} - N_{a,rj,"q4",y}), \text{ with } j = \text{SD 28 or 26, } k = \text{SD 26 or 25.}$$

Similar to our assumption on spawning migration, we also expect feeding migration to occur only partially. We tested different values for  $\gamma$ . If  $\gamma$  is larger than 0.25, the modelled stock sizes and yields are higher than the historically observed values, i.e., if  $\gamma > 0.25$ , the model does not reproduce the historic data during the validation period 1976-1999 correctly anymore. Here, we choose  $\gamma = 0.2$  for feeding migration between SD 25 and 26, and  $\gamma = 0.1$  for feeding migration between SD 25 and 28 and SD 26 and 28. These values take account of the spatial differentiation

of the three subdivisions, i.e., SD 25 is currently more important as spawning ground but less important as feeding ground than SD 26 and 28.

### *The economic component*

The fish caught during one quarter ( $C_{a,y,q,r}$ ) is calculated for each age-group and for each subdivision according to the Baranov Catch Equation (**Eq.5**), with  $Z_{a,y,q,r}$  being the total mortality total, i.e., the sum of natural, predation, and fishing mortality ( $Z = M + P + F$ ).

$$(5) \quad C_{a,y,q,r} = \frac{F_{a,y,q,r}}{Z_{a,y,q,r}} \cdot (N_{a,y,q,r} - N_{a,y,q+1,r})$$

The corresponding yield ( $Y_{a,y,q,r}$ ), accumulated during one time step (q), is computed by multiplying the age-specific catch with the age- and area-specific estimates of weight-at-age in the catch ( $w_{a,r}$ ) (**Eq.6**).

$$(6) \quad Y_{a,y,q,r} = C_{a,y,q,r} \cdot w_{a,r}$$

The fishermen's yearly total gross revenue (income  $I_y$ ) is calculated by multiplying the age-specific yield with the age-specific minimum price per kg ( $p_a/kg$ ) according to Table 1 and then summing over quarter, subdivision, and age (**Eq.7**).

$$(7) \quad I_y = \sum_{r=1}^3 \sum_{q=1}^4 \sum_{a=2}^8 Y_{a,y,q,r} \cdot \frac{p_a}{kg}$$

Ideally, a cost analysis should be included at this stage to facilitate estimation of profits and present values. However, this would be beyond the scope of this research. Moreover, cost data are not readily available and for this reason it has not yet been investigated how unit costs depend on the quantity harvested and/or on stock size. When referring to a demersal fishery, it is usually assumed – following Schäfer (1957) – that variable unit costs are inversely proportional to stock size, implying a stock elasticity of  $-1$ . Recently, however, an elaborate empirical study by Sandberg (in press) showed that variable unit costs are only moderately sensitive to stock size, with stock elasticities being significantly less than  $-1$  for five Norwegian vessel groups fishing Northeast Arctic cod. Additionally, Sandberg found that unit costs for these five cod fisheries decrease if output, i.e., the quantity harvested, increases. A detailed cost analysis, as part of a bioeconomic analysis, shall be a subject of future research. Here, we limit our analysis to the calculation of revenues and net present value of revenues (i.e., harvests).

The net present value ( $PV$ ) of the cumulative gross revenues earned over the 50 year simulation period is calculated by summing the discounted yearly total revenues over year (**Eq.8**). To

address the uncertainty of future discount rates ( $r$ ), we compare PVs using a basic 4% discounting with PVs from alternative discount rates employing a wide range between 0 and 40%. We tested such a wide range of discount rates because the computational costs are close to zero and we wanted to be sure to include all possible values. Note, however, that we do not expect discount rates for fisheries to be above 10%.

$$(8) \quad PV = \sum_{y=2005}^{2055} \frac{I_y}{(1+r)^{y-2004}}$$

### *Scenario Development*

The objective of our study is an analysis of the biological and economic effects of implementing selected management policies under potential environmental change scenarios. Hence, we need to specify the exogenous variables fishing mortality ( $F$ ) and reproductive volume ( $RV$ ) over the 50 year simulation horizon.

### Management Policies

We investigate the development of the cod stock size, yield and revenues from the Eastern Baltic cod fishery under the following six different management policies:

1. FasU            **F**ishing mortality ‘**as usual**’, applying the average fishing mortality of 1990-1995.
2. C25qu12      temporal closure of SD **25** in **quarter 1** and **2**; quarter 3 and 4 are open to reduced fishing (fishing mortality is reduced by 50%).
3. C25er           permanent closure of SD **25** with fishing effort redistribution from SD 25 into SD 26 or SD 28, i.e., the fishing effort, that had previously been applied in SD 25 is fully redistributed into SD 26 or SD 28.
4. C25             permanent closure of SD **25**, no fishing effort redistribution.
5. RoF70          **r**eduction of fishing mortality  $F$  by **70%** in the Eastern Baltic Sea (corresponding to ACFM advice for 2003).
6. TC              **t**otal closure, i.e. fishing mortality is zero in all three subdivisions (corresponds to current ACFM advice for 2005).

Our scenarios focus particularly on SD 25 with respect to reductions in fishing mortality, because SD 25 comprises the Bornholm Basin, the primary existing spawning ground. Due to regularly returning favourable hydrographic conditions, the Bornholm Basin has turned into the most important spawning ground of Baltic cod during the last decades (e.g. Nissling *et al.* 1994;

Plikshs *et al.* 1993). In contrast, the Gotland Deep in SD 28 and the Gdansk Basin in SD 26 have become less important for cod spawning since 1986. Their location farther East/Northeast makes them less likely to be influenced by inflows and hence, leads to stagnation periods which are much more pronounced and prevail much longer than farther West in the Baltic Sea (e.g. Plikshs *et al.* 1993).

Model runs are performed covering the years 1976-2050 with the different management scenarios initiated in year 2005. Quarterly estimates of fishing mortalities are available from area-disaggregated MSVPA until 1999 (Köster *et al.* 2001a). After 1999, we apply the average fishing mortality of the years 1990-1995 ( $F_{a,r,q,y}^{\text{average}}$ ). We also tested the effect of using other constant fishing mortalities for the simulation period, e.g. averages of the years 1986-1995 and 1974-1999. However, results of these simulations showed only little variation from those using the average fishing mortality of the years 1990-1995. The management scenarios we have chosen are initiated in year 2005 and implemented in our model by the following equation:

$$(9) \quad F_{a,r,q,y} = \alpha_r * F_{a,r,q,y}^{\text{average}} + \beta_r * F_{a,r25,q,y}^{\text{average}} .$$

The coefficient  $\alpha_r$  determines fishing mortality as a fraction of the original 5 year average quarterly fishing mortality in the three subdivisions (r);  $\beta_r$  accounts for the possibility of redistributing fishing mortality from SD 25 into SD 26 or 28. Values for the coefficients  $\alpha_r$  and  $\beta_r$  according to the corresponding selected management policies are given in **Table 4**.

**Insert Table 4 here**

#### Environmental change scenarios

We have depicted that the important exogenous parameter in our model, which is related to climate change and which controls cod recruitment (R) and spawning migration (S), is the reproductive volume (RV). Here, we attempt to project a potential future decrease of the exogenous variable RV based on recent model simulation results, which project average salinity in the Baltic Sea to decrease by 7-47% in the period 2071-2100, relative to the reference time slice 1961-1990 (Meier submitted).

Meier obtained these results by performing a set of four scenarios with a fully coupled atmosphere-ocean RCM for the Baltic Sea area<sup>6</sup> using two global general circulation models

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<sup>6</sup> the Rossby Centre Atmosphere Ocean model

(GCM)<sup>7</sup> and two IPCC forcing scenarios. The two IPCC emission scenarios analysed are the SRES A2 and B2, representing a high and a low scenario of future CO<sub>2</sub> emissions, respectively, which are driven by different societal change (Nakicenovic and Swart 2000). The wide range of the projected decrease in salinity is not very sensitive to the emission scenario, but is, in fact, caused by differences in the two GCMs, which produce the external forcing to the RCM. The lower estimates are obtained when applying the Hadley Center's GCM HadAM3H; the higher estimates are obtained when the RCM is coupled to the ECHAM4/OPYC3. Despite the divergence of the model results, there is agreement on the sign of the change in salinity. It will be negative. Furthermore, Meier argues that the future decrease in salinity will be more pronounced in the deep water layers (Meier submitted).

Quantitative relationships projecting future sizes of the RV have not been published to date due to the complexity of interactions between the size of the RV and determinant environmental factors (cf. Section 2). Research into potential correlations between meteorological variables, major Baltic inflows, and reproductive success of Baltic cod is ongoing, and results allowing us to properly investigate and describe the atmosphere-hydrosphere-biosphere interactions are therefore not yet available. Here, we perform simple linear regression analyses using the average salinity in the second quarter in the Bornholm Basin to explain the variability of the size of the RV in the three subdivisions. With respect to RV in SD 26, and 28, we average salinity over the total depth of the water column. In SD 25, we take the average salinity between 55 and 65 m depth, which improves the correlation. We have checked that average salinity at 55-65m depth is highly correlated to overall average salinity. Also, salinity in the Gotland and Gdansk basin is correlated with salinity in the Bornholm Basin. Regression results are shown in **Table 5**.

#### **Insert Table 5 here**

The developed regression relationships for RV in the three subdivisions with salinity in the Bornholm Basin being the explanatory variable explain 66%, 59%, and 46%, of the variance in RV in SD 25, 26, and 28, respectively. All coefficients are highly significant. The constants of all three regressions are negative, and their absolute values are large. This implies that theoretically the reproductive volume gets negative, if salinity drops below 10 or 9 psu. In our model, we set all computed negative RV estimates to zero. The frequent absence of a reproductive volume in SD 26 and 28 (i.e. RV = 0) accounts partly for the unexplained variance of the regressions, which

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<sup>7</sup> HadAM3H and ECHAM4/OPYC3 the Rossby Centre Atmosphere Ocean model

is particularly high in SD 26 and 28. Additionally, we attribute the unexplained variance to the lack of incorporation of the other environmental variables and artefacts, such as insufficient sampling, different data processing methods, and processes, which have not been identified yet, e.g. patchiness, unusual mixing regimes.

As salinity and the size of the reproductive volume have a high interannual variability, we apply a normally distributed random variable to produce future realisations of salinity. Mean and variance of this random variable are derived from the salinity data of 1966-1999, which we tested for normality. To account for different climate change projections, we test three scenarios, where the mean salinity is assumed to decrease linearly over the 50 year simulation period according to the following three scenarios:

- low change           7% decrease in mean salinity (S) over a period of 100 years,  
                          i.e., 3.5% decrease of S over 50 years
- medium change   25% decrease in mean S over a period of 100 years,  
                          i.e., 12.5% decrease of S over 50 years
- high change       47% decrease in mean S over a period of 100 years,  
                          i.e., 23.5% decrease of S over 50 years.

For simplicity and due to lack of information, we assume that the variance does not change over time (cf. Meier submitted).

As already explained, salinity is not the only factor influencing the size of the reproductive volume. Oxygen also has a direct impact on the RV, and additionally, a number of other environmental factors indirectly affect the Baltic Sea's hydrographic conditions (cf. Section 2). In this study we do not incorporate the dynamics of oxygen in the deep basins, since a predictive understanding of the spatial and temporal dynamics of oxygen renewal and utilisation is as yet unavailable. Hence, our approach, albeit novel, is simplistic. Resolving the effect of changes in atmospheric forcing on inflow dynamics is critical to projecting the reproductive success of Baltic cod in the future. Hence, future research is planned to develop new relationships including the hitherto omitted variables. This will strengthen the reliability of our output. Despite these shortcomings, we believe that including additional factors would not significantly influence our results and conclusions. Rather, the Baltic Sea's hydrographic conditions are expected to become more unfavourable for successful hatching of cod eggs in the future not only due to the expected decrease in salinity, but also due to the continuous deterioration of oxygen concentrations, since eutrophication is still a serious problem in the Baltic Sea (HELCOM 2004).

#### **4. Results and Discussion**

In the first subsection, we show the development of the external forcing of stock development, namely salinity, which, in turn, the reproductive volume depends on. We then present and discuss the results of stock and yield development in the second and third subsection, respectively. In the last subsection, we illustrate results of the net present value of revenues, summed over the 50 year simulation period.

For purpose of illustration, the figures plotting RV, stock and yield development are based on only one random choice of salinities. In the tables and when generalising, we present average values and standard errors, derived from 50 random model realisations.

##### ***External forcing – Variation and Change in reproductive volume***

The reproductive volume in SD 25, derived from salinity of one random model run for the three environmental scenarios, is plotted in Figure 3. The variability in reproductive volume for the three climate change scenarios is similar. The absolute values for the low, medium, and high climate change scenario, however, are different, as we assume the 34-year historic mean of salinity to decrease by 7%, 25% and 47% until 2100, respectively. Correspondingly, the decreasing trend over the 50 year simulation period can be observed for the size of the reproductive volume.

**Insert Figure 3 here**

##### ***Change in spawning stock biomass (SSB)***

Figures 4 a-c illustrate the simulated development of the sum of the cod spawning stock biomass (SSB) in subdivisions 25, 26, 28 under the low, medium, and high environmental change scenario. The black, white, and grey bars in the three figures show the size of the reproductive volume in SD 25, 26, and 28, respectively. Each line in the figures depicts one of the six different fisheries management policies. The restrictive management scenarios involving overall reductions in fishing mortality (RoF70, TC) or partial reductions via spatial and temporal closures of SD 25 (C25, C25er, C25qu12) yield the upper lines of SSB development, while the fishing as usual scenario (FasU) forms the bottom line.

The period 1976-1999 serves as validation period: The dotted line (ACFM\_SSB) shows the total spawning stock biomass of the Eastern Baltic cod, i.e., summed over subdivisions 25-32, as estimated by the ICES standard stock assessments. Our model can well reproduce the historic

stock fluctuations with an explanatory power of 0.80. The broken line shows the biological limit biomass  $B_{lim}$  of 160,000 t, representing the level below which recruitment is impaired.

**Insert Figures 4 a-c here**

*Low environmental change*

Under the fishing as usual policy (FasU), the cod stock experiences a slight recovery during the initial ten years of the simulation period due to a period of large reproductive volumes in all three subdivisions (i.e., large black, white, and grey bars). Spawning stock biomass (SSB) increases from less than 100,000 t to approximately 240,000 t. After 2016, following a period of lower reproductive volumes, SSB decreases again to around 160,000 t ( $B_{lim}$ ) and fluctuates around  $B_{lim}$  for the rest of the simulation period. It can be concluded that in the long run the cod stock cannot recover under the ‘fishing as usual’ management scenario.

On the contrary, under the presented five restrictive management policies an enduring stock recovery to SSB levels around and above 400,000 t is possible. Under the total closure scenario, SSB even increases by approximately 100% within the first ten years of the simulation period, yielding a spawning stock size of around 1,000,000 t. Such a high SSB has not been preceded in history and can be regarded as a possible maximum environmental carrying capacity of the Eastern Baltic cod stock, given the environmental conditions of our low climate change scenario. This result, however, should be regarded with caution, because our simulations do not include food-web interactions, such as predation of cod eggs by sprat and herring.

In contrast to achieving an overall reduction of fishing mortality (RoF70), the establishment of a permanent marine reserve in SD 25 (C25) focusses on the protection of a large component of the cod spawning stock to ensure spawning in SD 25 and thus provide for successful recruitment. Our simulation results suggest that the latter policy is indeed more effective in rebuilding the stock, because a permanent closure of SD 25 without fishing effort redistribution leads to an SSB which is roughly 10% higher SSB than SSB under an overall reduction of fishing mortality by 70%. Apart from a higher stability with respect to recruitment, additional stock benefits result from the circumstance that a part of the stock’s habitat is permanently protected. At least a small, less migratory, fraction of the stock is thus allowed to grow older than without this habitat protection (Figure 5). At the end of the simulation period in year 2055, there are 5-15 million more cod of age 4, 5, 6, 7, and 8 under policy C25 than under policy RoF70.

**Insert Figure 5 here**



Stock recovery is also achieved with management policies C25qu12, based on a temporal closure of SD 25 before and during the spawning period, and C25er, the permanent closure of SD 25 allowing for full effort redistribution. Both policies yield very similar results in terms of simulated SSB, which is approximately 20% lower than that achieved under C25 and approximately 10% lower than SSB under RoF70.

#### *Medium and high environmental change*

The simulated SSB results of the six management policies for the medium and high environmental change scenarios follow the same order as those under low environmental change. SSB is lowest under the fishing as usual scenario (FasU), which exerts the highest fishing mortality on the stock. With a fishing moratorium in the entire Eastern Baltic Sea (TC), SSB for both, medium and high environmental change increases to unprecedented high levels. The maximum SSB, reached during the initial 8-10 year recovery phase of high reproductive volumes, is, however, approximately 20% lower for the high environmental change scenario than for the low environmental change scenario.

The main difference between simulated SSBs for the three environmental scenarios is the long-term development, i.e., the trend after the initial decade of stock recovery. For medium and high environmental change, a gradual decrease in SSB starts around 2020 under the five restrictive management policies. The decrease starts already around 2016 under the fishing as usual policy.

For high environmental change, simulated SSBs decrease steadily and steeply, resulting in the extinction of the spawning stock around 2026 under fishing as usual, around 2040 for the marine reserve scenarios, and around 2050 under the total closure scenario. The steadiness of the decrease results from our simplifying assumption to calculate the reproductive volume via salinity estimates only - thus neglecting any future sporadic Major Baltic Inflows which would increase the reproductive volume. According to the model calculations for the high environmental change scenario, the reproductive volumes in SD 26 and 28 disappear completely after 2026 (cf. white and grey bars in Figure 4c, respectively). In reality, however, North Sea inflow events sporadically replenish the Baltic Sea deep water and hence contribute to a sporadic increase in salinity and the re-occurrence of reproductive volumes, despite the general tendency of decreasing salinity due to climate change. Despite these shortcomings, we believe that future reproductive volumes will be smaller and less frequently present. Our model simulations for the medium and high environmental change scenarios both show clearly that the cod stock is threatened by extinction if current fishing effort prevails (FasU). Under medium environmental

change, extinction may set in within the coming 20 years, as SSB remains below 50,000 t from 2026 onwards.

### ***Development of yield***

The curves in figures 6 a-c illustrate the simulated development of the expected annual yield from the Eastern Baltic cod fishery under the low, medium, and high environmental change scenario. Again, the period 1976-1999 serves as validation period: The dotted line (ACFM) shows the total landings of the Eastern Baltic cod, i.e., summed over subdivisions 25-32, as estimated by the ICES standard stock assessments. Our model can well reproduce the historic yield fluctuations with an explanatory power of 0.78.

#### **Insert Figures 6 a-c here**

During the initial decade of the simulation period, which is characterised by favourable hydrographic conditions leading to stock recovery (cf. Figures 4a-c), the yield curves follow the stock development, i.e., yields increase concomitantly to increasing SSB. During these first ten years, the different yield curves follow a similar behaviour under all three environmental change scenarios. Yields increase within the first ten years from less than 100 kt to 190, 200, and 210 kt (minimum) or to 410, 460, and 520 kt (maximum) under the high, medium, and low environmental change scenarios, respectively.

In the first two years of the simulation period, the fishing as usual policy (FasU) reaps the highest annual yields of all presented management policies. In contrast, losses in yield in the first two years characterise the two permanent marine reserve policies (C25, C25er) and the policy with overall reduction of fishing mortality by 70% (RoF70). Yet, already in 2007, i.e., year three of the simulations, yield under the temporal marine reserve policy (C25qu12) exceeds yield under fishing as usual, and in year 2009, also yield under RoF70 exceeds yield under FasU. Even yield under the permanent marine reserve scenario (C25) increases gradually until it exceeds yield under fishing as usual in 2017. There is a turning point in the development around 2015 (a little earlier under high environmental change, a little later under low environmental change), when yields start to decrease. Only with low environmental change, yields under C25 and C25er remain more or less stable around 250,000 and 180,000 t.

Yields decrease steadily under the medium and high environmental change scenarios parallel to the gradual decrease in spawning stock size, starting between 2015-2020. Yields drop to zero around 2050 under the medium environmental change scenario. Under the high environmental

change scenario, this happens already between 2025 and 2040, depending on the management policy.

The order of management policies from lowest to highest yield in year 2025 (representing a long term estimate) for the three environmental change scenarios is presented in Table 6.

**Insert Table 6 here!**

This arrangement clearly shows that annual yield under the first four management policies exceeds yield obtained under “fishing as usual”. This occurs as the reduction in fishing mortality fosters stock recovery. A reduced fishing mortality exerted on a high stock size results in higher yield than a high fishing mortality exerted on a low stock size. Furthermore, this arrangement elucidates that the permanent marine reserve policy allowing for effort redistribution (C25er), does not reduce fishing mortality effectively. Instead, fishing mortality is shifted from SD 25 into SD 26, increasing fishing mortality in SD 26. The overall effect on total fishing mortality reduction is thus only weak. Therefore, we do not consider this management policy very effective in sustaining long-term yields.

According to our simulations, the most effective policy for achieving highest long-term yields is the temporary marine reserve policy (C25qu12). The permanent, thus more restrictive marine reserve policy (C25) results in lower yields, while the SSB is higher than under C25qu12.

***Gross revenues***

Due to our assumption of a constant price, the order of management policies from highest to lowest revenues is the same as for annual yield. We note that, as prices decrease with increasing supply and vice versa, fishing strategies, which increase the quantity of landings, would become less attractive than under the assumption of constant prices.

When calculating the net present value of revenues, the ranking of the management policies persists for discount rates between 0-10%. The attractiveness of the two permanent marine reserve scenarios C25 and C25er, however, decreases relative to the fishing as usual (FasU) scenario, when discount rates greater than 10% are applied. Critical discount rates which would reverse the order of these three least attractive policies (C25, C25er and FasU) are 10/ 13/ 14% and 22/ 23/ 24% under the low/ medium/ high climate change scenario. The FasU policy is shifted up one position, overtaking C25er in the ranking, when applying discount rates of 10-22/ 13-23/ 14-24% under the low/ medium/ high climate change scenario. When discount rates above 22/ 23/ 24% are applied, PVs from FasU also exceed the C25 policy.

Exemplarily, we have presented average net present values of 50 random model realisations, applying a discount rate of 4% in Table 7. Under the three environmental change scenarios, the temporal marine reserve policy with reduced fishing in quarters three and four (C25qu12) yields the highest net present value of revenues over the 50 year simulation period. Table 7 elucidates that for all three environmental change scenarios the net present value of revenues under this temporal marine reserve policy is more than twice as high as under the fishing as usual policy.

**Insert Table 7 here!**

We have not included costs into our analysis because of insufficient data availability. The ranking of our results might be altered, once operating costs of fishing are included in the analysis, which then allows the calculation of net present value of profits rather than revenues. An investigation in costs of the Eastern Baltic cod fishery therefore warrants further research. Cost data could be obtained from the administrating national fisheries directorates. Alternatively, a cost analysis could start with applying cost function parameters from other cod fisheries, such as the Northeast Arctic cod fisheries investigated by Sandberg (in press).

In our study, one can hypothesise that harvesting costs per kilogram will be lower than under the fishing as usual policy, if fishing mortality and hence fishing effort is reduced, while at the same time stock size increases. This is the case under policies C25qu12, RoF70, and C25. As, however, the policy C25qu12, which yields highest gross present value in our analysis, does not maintain the highest stock size (cf. Figures 4a-c), policies C25 and RoF70 might be advantageous in terms of economic outcome, once operating costs are included in the analysis.

## **5. Conclusion and outlook**

We can derive some general conclusions from our simulations as to potential impacts of environmental and climate change on the Baltic cod fishery. The implications in the form of a decrease in recruitment, resulting in a decrease in the spawning stock biomass and finally in decreased yield and revenues, will be more severe, the more rapidly climate changes. The results of our simulations under different environmental scenarios show that a future decrease in the size of the reproductive volume caused by a climatically induced decrease in salinity results in extinction of the Eastern Baltic cod stock. Nonetheless, our simulations of stock and yield development under different management policies also elucidate that fisheries management can dampen the negative consequences of climate change for at least 20 years. Such policies should focus on the protection of the spawning stock in SD 25 for at least the six months before and

during the extended spawning period of the Eastern Baltic cod. However, stock collapse cannot be prevented but only postponed with such measures.

In line with advice by the Ad hoc group on long-term management to the European Directorate General for Fisheries (ICES 2005b, p.31), a significant reduction in fishing of the Eastern Baltic cod stock would preserve the stock, unless environmental conditions will become very detrimental. A permanent closure of SD 25 would be even better for the fish. Our simulation results demonstrate that maintaining the spawning stock biomass above  $B_{lim}$  is a prerequisite to achieve high yields in the long term. In terms of stock recovery and conservation, establishing a permanent marine reserve in the Eastern Baltic Sea in SD 25 is more efficient than an overall reduction of fishing effort, and than establishing a temporal/seasonal marine reserve. From the economic point of view, the results are slightly twisted: The establishment of a seasonal marine reserve in SD 25 leads to highest yields and revenues. The second best policy in terms of yields and revenues is the overall reduction of fishing effort, whereas the establishment of a permanent marine reserve ranks third. Closing subdivision 25, at least temporarily for at least six months every year during the cod spawning period, would allow the mature fish to spawn before being caught. Cod reproduction can therefore be ensured to occur at least in SD 25, whereas successful reproduction in SD 26 and 28 cannot be relied on due to the climatically induced deterioration of hydrographic conditions particularly in regions farther East Northeast in the Baltic Sea, which will be more unfavourable for cod reproduction in the future.

An improvement of the stock's age-structure by allowing more fish to grow older is most effectively achieved by permanently closing SD 25. Nonetheless, we conclude from Figure 5 that the crucial factor for improving the stock's age-structure is the reduction of fishing, be it an overall reduction or spatially differentiated by the establishment of marine reserves. In summary, it can be concluded that the establishment of a temporal but also a permanent marine reserve in SD 25 resembles a "win-win" situation for the stock as well as for the fishery. Since larger, older females produce many more and more viable eggs, reproductive success tends to be better if the stock comprises a larger portion of older fish (e.g. Hutchings 2004). As a consequence year classes can get stronger, thus providing a larger harvestable fish stock to the fishery.

The International Baltic Sea Fisheries Commission (IBSFC) has already established a closure of the Bornholm Basin spawning ground and a temporal summer ban for the cod fishery since 1995 in addition to the annual TACs and supplementary technical regulatory measures, such as minimum landing sizes and mesh size regulations (IBSFC 2002). These spatial closures are,

however, too small and too short to effectively reduce fishing mortality on the spawning stock in SD 25. Poor enforcement of management policies moreover aggravates the uncertainty of fish stock assessments and consequently the susceptibility to unbalanced management by TACs, especially if a significant amount of the catch is landed illegally or not reported. In the Baltic Sea, poor management enforcement is a severe problem (ICES 2005a, 2005b) and can render management plans useless, if they assume precise estimates of present stock parameters. Due to these problems, the ACFM was reluctant to give management advice for the Baltic cod fishery in 2005, just recommending “No catch in 2005” (ICES 2004a).

We now point out caveats resulting from critical assumptions, simplifications, or unknown hence omitted processes in our model specifications. All of these aspects represent areas that warrant future research.

As our model is narrowed down to three subdivisions and does not take into account multi-species interactions and density-dependent growth and maturity, the results should only be taken as indicative of the direction of change. To incorporate multispecies and food-web interactions, our model could be coupled to a similar model of sprat and herring population dynamics. This would then account for effects such as the potential increase in predation mortality on juvenile cod by mature sprat due to the projected future increase in water temperature in the Baltic Sea.

As regards the biological compartment of the model, the following model specifications could be improved: The underlying data from area-disaggregated MSVPA is highly uncertain and could be updated, as it is currently only available until 1999. The calculation of migration estimates should be derived from field data. Such data will become available within the next couple of years, because an extensive tagging project of Baltic cod is ongoing (R&D project CODYSSEY). Movement of cod between subdivisions should also include passive wind-induced egg and larval drift. Hydrodynamic models are already available (Hinrichsen and Möllmann 2002; Hinrichsen *et al.* 2002b), but research is needed on meteorological coupling parameters and on the impact of climate change on their future course.

As stressed already, salinity is not the only factor impacting on cod reproductive success. Oxygen is at least of equal importance and is strongly affected by inflow events from the North Sea. Correlations between regional climate change, air and water circulation, and dissolved oxygen should be established and incorporated into the model.

Furthermore, it would be worthwhile to explore potential correlations between the reproductive volume and eutrophication measures, e.g. nutrient concentration. If in the future eutrophication

prevailed, hydrographic conditions were expected to aggravate. On the other side, if eutrophication decreased, then this could improve oxygen conditions, which, to some degree, could counteract or dampen the reproductive disadvantage of a decrease in salinity.

With respect to the economic calculations in our model, future research should focus on including costs in the calculations. As pointed out above, the economic evaluation of our simulation results might be altered, once operating costs of fishing are included in the analysis, because the policy C25q12, which yields highest gross present value in this study, does not maintain the highest stock size. Therefore, policies C25 and RoF70, which sustain a higher spawning stock biomass, might be advantageous in terms of economic outcome, once operating costs are included in the analysis. It is hence desirable to present results of net revenues and net present value of profits in a follow-up study. Finally, the currently static parameter fishing effort should be transferred into a dynamic variable, so that dynamic harvesting policies and an optimal approach can be found.

To summarise, we emphasise that under the present simulations of future climate change a significant reduction in fishing mortality is necessary to achieve high yields from the Eastern Baltic cod fishery in the long term.

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## Appendix: Model of population dynamics

The model calculates stock size (N) for each age-group (a) and for each subdivision (r), accounting for recruitment (R) and mortality due to fishing (F), predation (P) and natural (M) mortality, using an extension of the standard equation of population dynamics (Beverton and Holt 1954). There are three separate equations needed to incorporate recruitment (R), changes in age (a) and year (y), and changes from one time-step (quarter q) to the next (Eq.A1-A3). For definition of symbols, refer to Table 2 in the text.

$$(A1) \quad N_{a+1,r,q=q1,y+1} = N_{a,r,q4,y} \cdot e^{-M_{a,r,q4,y} - P_{a,r,q4,y} - F_{a,r,q4,y}}$$

$$(A2) \quad N_{a,r,q=q2 \vee q4,y} = N_{a,r,q1 \vee q3,y} \cdot e^{-M_{a,r,q1 \vee q3,y} - P_{a,r,q1 \vee q3,y} - F_{a,r,q1 \vee q3,y}}$$

$$(A3) \quad N_{a,r,q=q3,y} = N_{a,r,q2,y} \cdot e^{-M_{a,r,q2,y} - P_{a,r,q2,y} - F_{a,r,q2,y}} + R_{r,y} |_{a=a0}$$

The Eastern Baltic cod in subdivisions 25, 26, and 28 are assumed to be a stock unit composed of age-groups 0-8 with the 8 year old age-group not handled as plus group. The age of entry into the exploitable fishery is age 2. Based on maturity estimates from maturity ogives, we assume that cod of age 2 and older are mature and thus able to spawn (ICES 2002; STORE 2002).

### Natural mortality (M)

Natural mortality was assumed to be 0.2/year, equally distributed over quarters, corresponding to standard MSVPA runs in the Baltic Sea (Sparholt 1991).

### Fishing mortality (F)

As our prime aim is an analysis of selected management policies which constrain fishing mortality (F), F is treated as an exogenous variable. For the period 1976-1999 we apply the quarterly fishing mortalities derived by area-disaggregated MSVPA. For the period 2000-2005, we apply the average fishing mortality of the years 1990-1995. During the simulation period 2005-2055, the average fishing mortalities are modified according to the management policies, as described below.

### Predation mortality (P)

Predation mortality refers to cannibalism by mature cod on the early and juvenile life stages of cod (ages 0, 1, and 2). In accordance with Köster *et al.* (2001b), predation mortality is linearly related to the cod spawning stock size (ssN), i.e. the sum of mature population numbers at ages 2-8, in the corresponding subdivision. For the regression analysis, we applied quarterly data of

predation mortality derived by area-disaggregated MSVPA. Regression parameters and statistics are shown in table A1.

**Insert Table A1 here**

### **Recruitment (R)**

In our approach, recruitment refers to 0-group cod. Here, young of the year enter the model in the third quarter every year, if a spawning stock exists. From then on, these early life stages are subject to predation mortality (as reflected by cannibalism in our model), and to natural mortality. We calculate recruitment in each of the three subdivisions as a function of the basin-specific spawning stock size (ssN) and the size of the basin-specific reproductive volume (RV). We tested several functional forms to combine the two explanatory variables ssN and RV (Röckmann *et al.* 2005). Here, we chose a linear approach (Eq.A4), which gave the best fit in SD 26 and 28 as well as good results in SD 25:

$$(A4) \quad R_{r,y} = a \cdot ssN_{r,q1,y} + b \cdot RV_{r,y} + c$$

The regression parameters of this linear combination of ssN and RV are significant at the 1% level of significance in SD 25 and 26. In SD 28, the level of significance of the explanatory variable “RV” is 24% (Table A2).

**Insert Table A2 here**

**Table A1.** Results of regression analyses of linear relationship between quarterly predation mortality due to cannibalism of cod at age 0, 1, and 2 and cod spawning stock size (ssN) in SD 25, 26, and 28 ( $P_{a,r,q,y} = a \cdot ssN_{r,q,y} + c$ ): parameter estimates and  $R^2$  values.

region	age	quarter	a	c	$R^2$
SD 25	0	3	0.0021	0.1996	0.53
SD 25	0	4	0.0007	0.0445	0.31
SD 25	1	1	0.0002	0.0069	0.51
SD 25	1	2	0.0002	0.0017	0.56
SD 25	1	3	0.0001	0.0210	0.48
SD 25	1	4	0.0001	0.0089	0.30
SD 26	0	3	0.0009	0.0591	0.57
SD 26	0	4	0.0006	0.0340	0.62
SD 26	1	1	0.0003	0.0050	0.71
SD 26	1	2	0.0002	0.0036	0.80
SD 26	1	3	0.0004	0.0179	0.68
SD 26	1	4	0.0001	0.0044	0.69
SD 28	0	3	0.0015	0.0072	0.81
SD 28	0	4	0.0024	0.0376	0.66
SD 28	1	1	0.0004	0.0145	0.51
SD 28	1	2	0.0006	0.0028	0.84
SD 28	1	3	0.0010	0.0007	0.76
SD 28	1	4	0.0002	0.0030	0.62

Time series: 1974-1999

**Table A2.** Results of regression analyses ( $R_{r,y} = a \cdot ssN_{r,q1,y} + b \cdot RV_{r,y} + c$ ) of linear stock-recruit relationships for SD 25, 26, and 28: parameter estimate, standard error, individual and joint significance level of parameter estimates, Durbin Watson statistics, and  $R^2$  values.

Sub-division	Parameter	Std.Error	p(t-stat.)	p(F-stat.)	DW	$R^2$ $R^2_{adjusted}$	
SD 25	a =	0.769131	0.236851	0.0078	0.002	1.97	0.76
	b =	1.372792	0.325873	0.0015			0.68
	c =	-163.2885	98.77706	0.1265			
	ar(1) =	0.762269	0.240958	0.0090			
	ar(2) =	-0.629696	0.263016	0.0356			
SD 26	a =	0.974694	0.192394	0.0001	0.000	1.67	0.83
	b =	2.119031	0.612369	0.0035			0.80
	c =	-72.00417	56.83591	0.2245			
SD 28	a =	1.396162	0.151571	0.0000	0.000	1.73	0.85
	b =	0.718526	0.588287	0.2408			0.83
	c =	-42.42439	24.15914	0.0995			

## Tables

**Table 1.** Quality categories, weight categories and respective age-groups, DFPO minimum prices for 2005, and average Danish exvessel prices for cod in 2001-2003.

Quality	Description
Quality E	New fish, first quality
Quality A	Ordinary fish
Quality B	Bad quality

Sorting category	Weight classes (kg)	Corresponding age-group	Danish PO Minimum price for quality categories E and A [DKK/kg]	3-year average exvessel price for cod in Denmark [DKK/kg]
0	> 10		9.25	
1	7 – 10		9.25	33.65
2	4 – 7	Age 8 and older	9.25	26.46
3	2 – 4	Age 6, 7	8.73	21.88
4	1 – 2	Age 5	6.94	15.55
5	0.3 – 1	Age 2, 3, 4	4.88	12.41

Based on information from [http://www.dfpo.dk/danish\\_fishermens\\_po.htm](http://www.dfpo.dk/danish_fishermens_po.htm) (visited June 8, 2005) and from the Yearbook of Fishery Statistics 2001, 2002, 2003 (Fiskeridirektoratet, Ministeriet for Fødevarer, Landbrug og Fiskeri, København).

**Table 2.** Variables, parameters, and indices used in our model.

variables and parameters		indices/ subscripts	
N	Eastern Baltic cod stock size in number of fish	r	region (r25, r26, r28)
ssN	spawning stock size in number of fish	a	age-group (a0 – a8)
R	recruitment	q	quarter (q1 – q4)
M	natural mortality	y	year (1976-2055)
P	predation mortality		
F	fishing mortality		
Z	total mortality		
RV	reproductive volume		
S	spawning migration		
D	feeding migration		
w	Eastern Baltic cod weight-at-age in the catch		
p	price of Baltic cod per kg, in Danish Kroner (DKK)		
C	catch		
Y	yield		
I	gross revenue (income)		
r	discount rate		
PV	net present value of yield (revenues)		

**Table 3.** Coefficient estimates applied in equations 3-6, describing spawning and feeding migration.

<b>Spawning Migration</b>	<b>26 → 25</b>	<b>28 → 25</b>	<b>28 → 26</b>
<b>from SD j → into SD k</b>			
Coefficient $\alpha$	0.7	0.5	0.4
Coefficient $\beta_{\text{lin}}$	0.005	0.006	0.006
Coefficient $\beta_{\text{ex}}$	0.01	0.01	0.01
Coefficient $\beta_{\text{log}}$	0.1	0.1	0.1
<b>Feeding Migration</b>	<b>25 → 26</b>	<b>25 → 28</b>	<b>26 → 28</b>
<b>from SD j → into SD k</b>			
Coefficient $\gamma$	0.43	0.08	0.25

**Table 4.** Coefficients  $\alpha_r$  and  $\beta_r$ , defining management scenarios 1-6 via Equation 11.

Management Scenario	$\alpha_{SD\ 25}$	$\alpha_{SD\ 26}$	$\alpha_{SD\ 28}$	$\beta_{SD\ 25}$	$\beta_{SD\ 26}$	$\beta_{SD\ 28}$
“FasU”	1	1	1	0	0	0
“C25qu12”	quarter 1&2: 0 quarter 3&4: 0.5	1	1	0	0	0
“C25er”	0	1	1	0	1	0
“C25”	0	1	1	0	0	0
“RoF70”	0.3	0.3	0.3	0	0	0
“TC”	0	0	0	0	0	0



**Table 5.** Results of linear regression analyses, using salinity in the Bornholm Basin in the second quarter as explanatory variable for explaining the variance of the reproductive volume (RV). For RV in SD 25, we apply the mean salinity from 55-65m depth. For the RV in SD 26 and 28, we apply the salinity averaged over the whole water column. Table presents parameter estimates, standard error, significance level of parameter estimates, Durbin Watson statistics, and R<sup>2</sup> values.

dependent variable	explanatory variable	Coefficient	Std. Error	Prob. (t-stat)	DW	R <sup>2</sup>
RV (SD25)	S <sub>55-65m</sub>	56.5794	6.3261	0.000	1.84	0.66
	constant	-503.9241	74.1344	0.000		
	AR(1)	0.5364	0.1572	0.002		
RV (SD26)	S <sub>average</sub>	105.2018	16.6747	0.000	2.08	0.59
	constant	-1028.6720	172.1346	0.000		
	AR(1)	0.2898	0.1443	0.054		
RV (SD28)	S <sub>average</sub>	53.5814	11.3237	0.000	1.95	0.46
	constant	-533.1376	116.5172	0.000		
	AR(1)	0.2576	0.1726	0.147		
	AR(2)	-0.3737	0.1727	0.039		

**Table 6.** Yield in 1000 tons in year 2025 under the low, medium, and high environmental change scenario. Values are averages  $\pm$  the standard deviation of 50 random model runs.

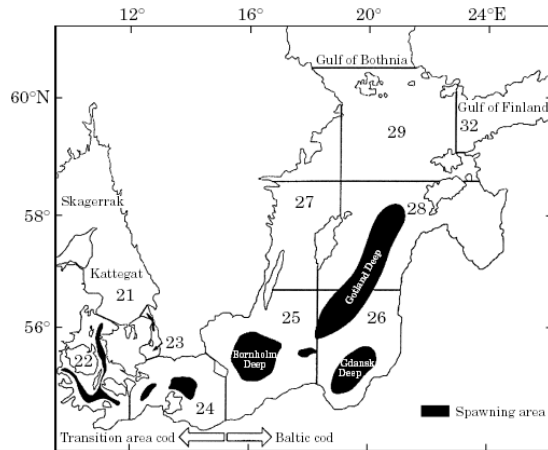
Yield in 2025	FasU	C25er	C25	RoF70	C25qu12
Low	124 $\pm$ 48	154 $\pm$ 29	203 $\pm$ 33	265 $\pm$ 46	316 $\pm$ 64
Medium	47 $\pm$ 33	84 $\pm$ 34	127 $\pm$ 40	154 $\pm$ 57	175 $\pm$ 75
High	15 $\pm$ 16	33 $\pm$ 22	56 $\pm$ 34	59 $\pm$ 41	65 $\pm$ 47

**Table 7.** Net present value of revenues in Billion Danish Kroner [DKK] under the low, medium, and high environmental change scenario, discounted over the 50 year simulation period (2005-2055) applying a discount rate of 0.04. Values are averages  $\pm$  the standard deviation of 50 random model runs.

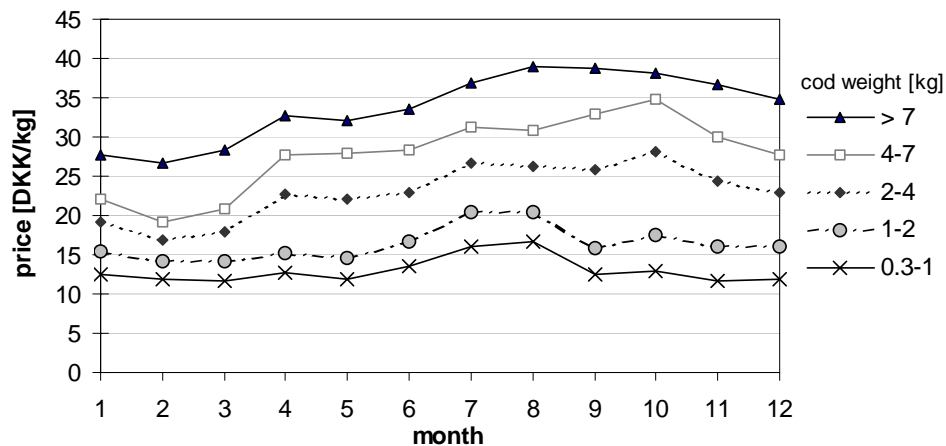
Climate change	FasU	C25er	C25	RoF70	C25qu12
Low	14 $\pm$ 3.2	18 $\pm$ 3.1	24 $\pm$ 3.6	31 $\pm$ 5.1	37 $\pm$ 6.2
Medium	9 $\pm$ 2.7	11 $\pm$ 3.2	15 $\pm$ 4.2	19 $\pm$ 5.6	23 $\pm$ 6.6
High	6 $\pm$ 2.1	8 $\pm$ 2.7	11 $\pm$ 3.7	13 $\pm$ 4.7	17 $\pm$ 5.5

## Figures

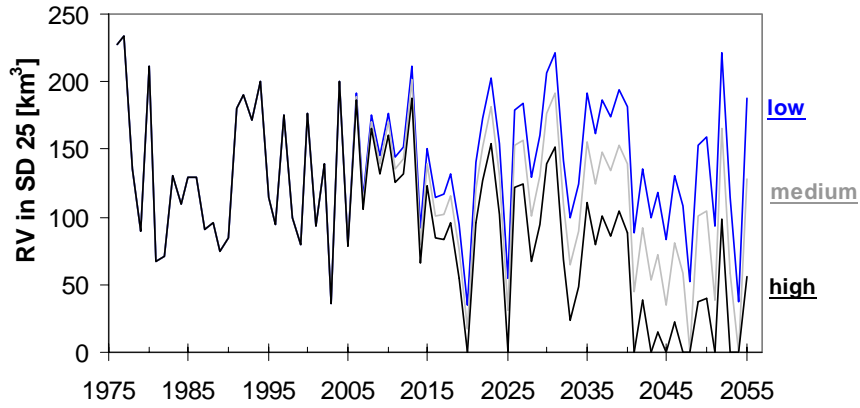
**Figure 1.** Chart of the Baltic Sea, showing ICES subdivisions and important spawning grounds of Baltic cod. Source: after Bagge *et al.* (1994b).



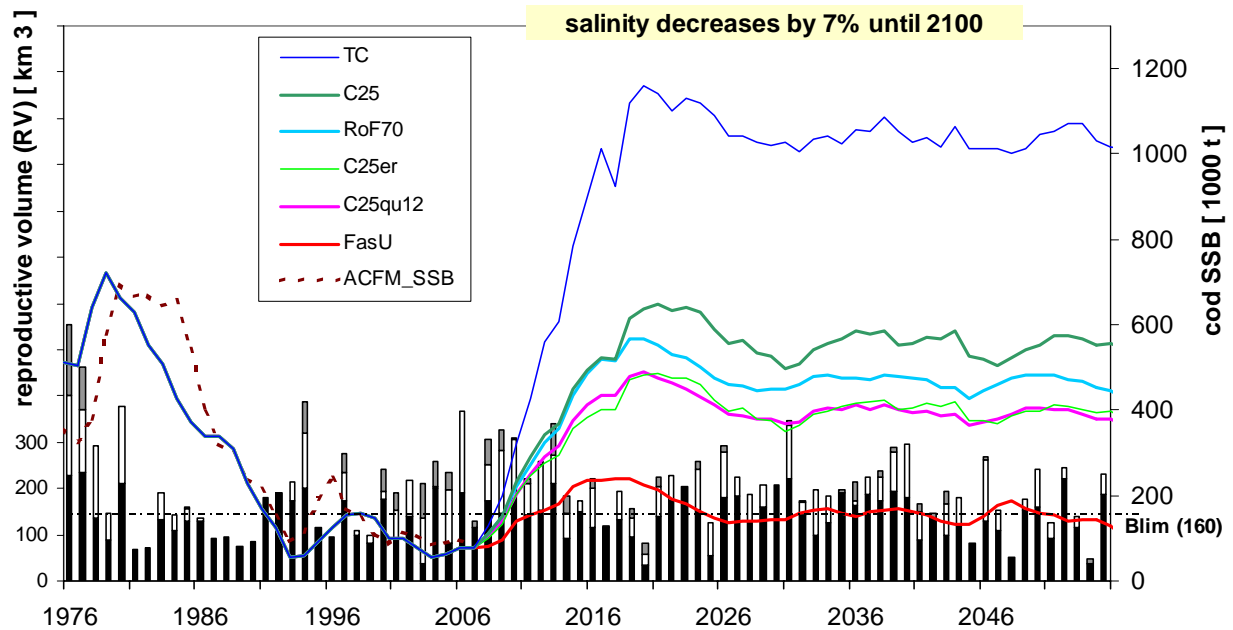
**Figure 2.** Monthly variability of exvessel prices for 5 size categories (1-5) of Baltic cod in Denmark; 3-year (2001-2003) averages. For details on the size categories, see Table 1.

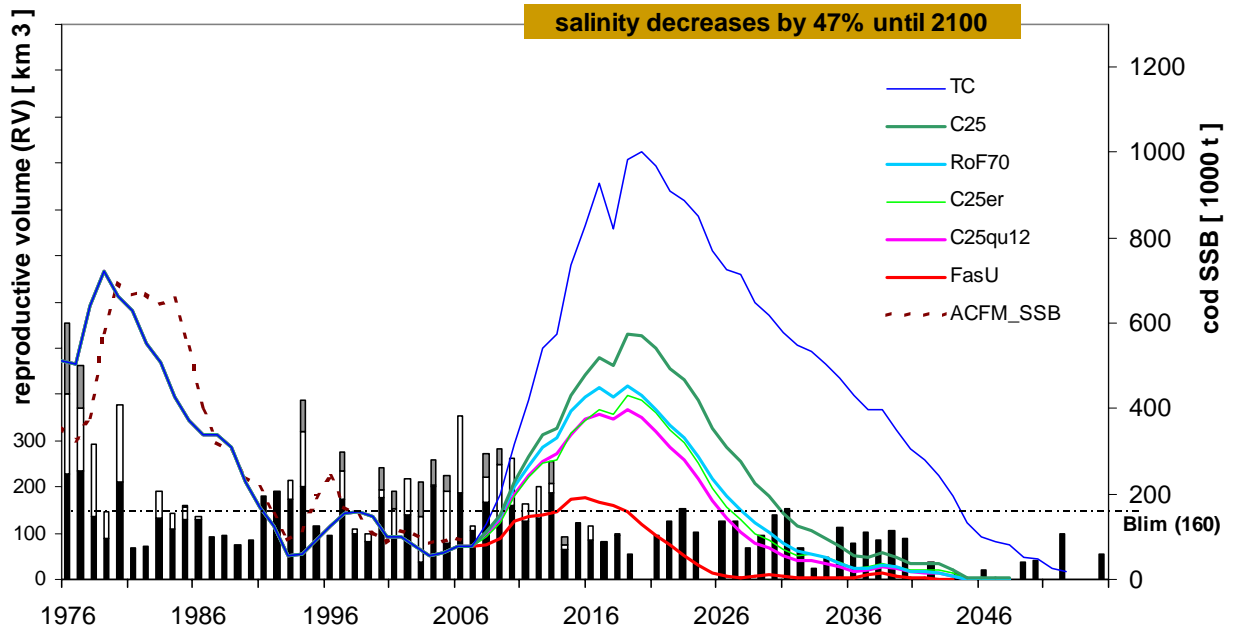
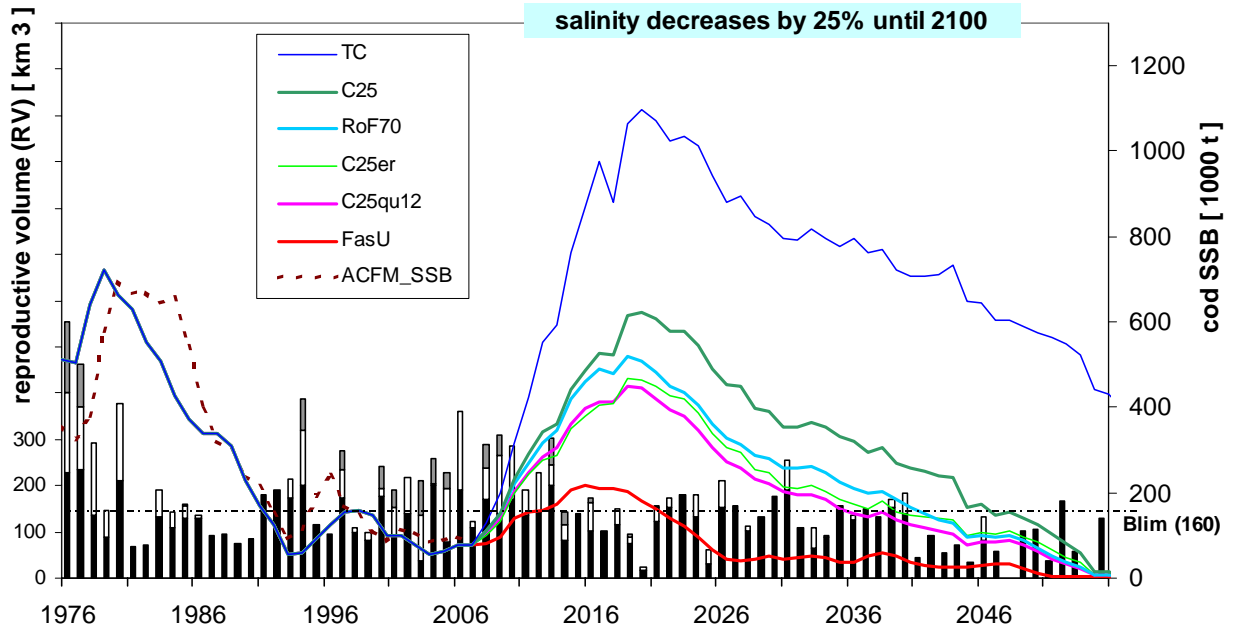


**Figure 3.** Reproductive volume (RV): data until 1999; from 2000 on: estimates derived from salinity as a normally distributed random variable, with its mean decreasing linearly over the 50 year simulation horizon by 7%, 25% and 45%, representing a low, a medium, and a high climate change scenario, respectively.

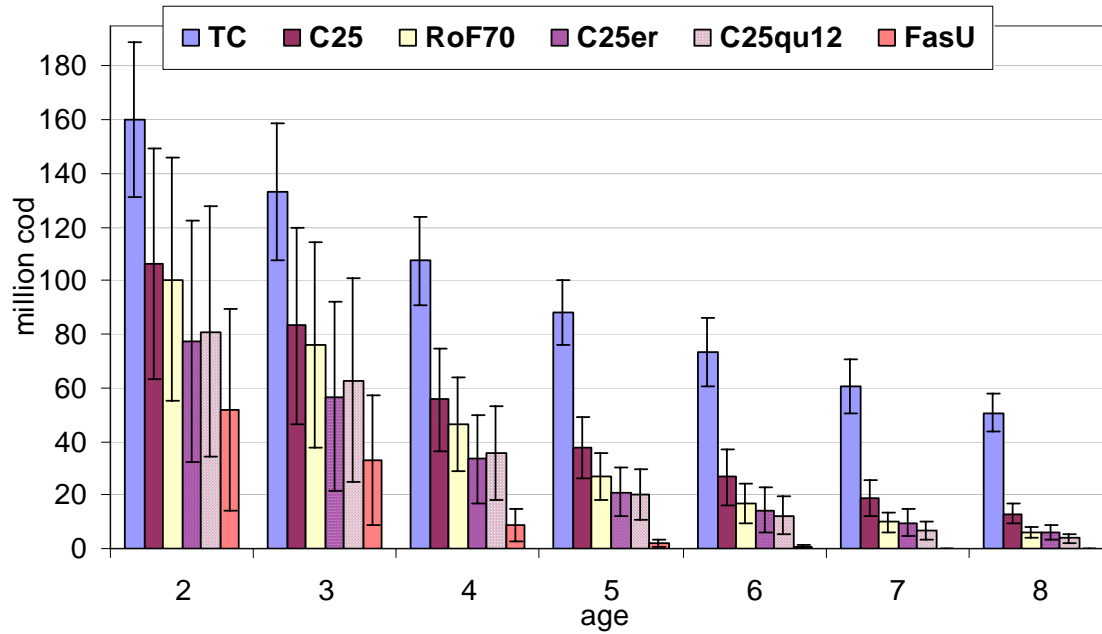


**Figures 4 a-c.** Simulated development of SSB (in 1000 t) under the (a) low, (b) medium, and (c) high environmental change scenarios for the six different management policies. Bars: reproductive volume [ $\text{km}^3$ ] in SD 25 (black), in SD 26 (white), in SD 28 (grey). Lines represent six different management policies: “**FasU**” = **F**ishing mortality **as usual**; “**C25qu12**” = temporal closure of SD **25** in **quarter 1** and **2**; quarter 3 and 4 are open to reduced fishing; “**C25er**” = permanent closure of SD **25** with fishing effort redistribution from SD 25 into SD 26; “**RoF70**” = **r**eduction of fishing mortality **F** by **70%** in the Eastern Baltic Sea; “**C25**” = permanent closure of SD **25** without fishing effort redistribution; “**TC**”= total closure. “**ACFM\_SSB**” shows standard stock assessment estimates from 1976-1999 for model validation. See text for further explanation.

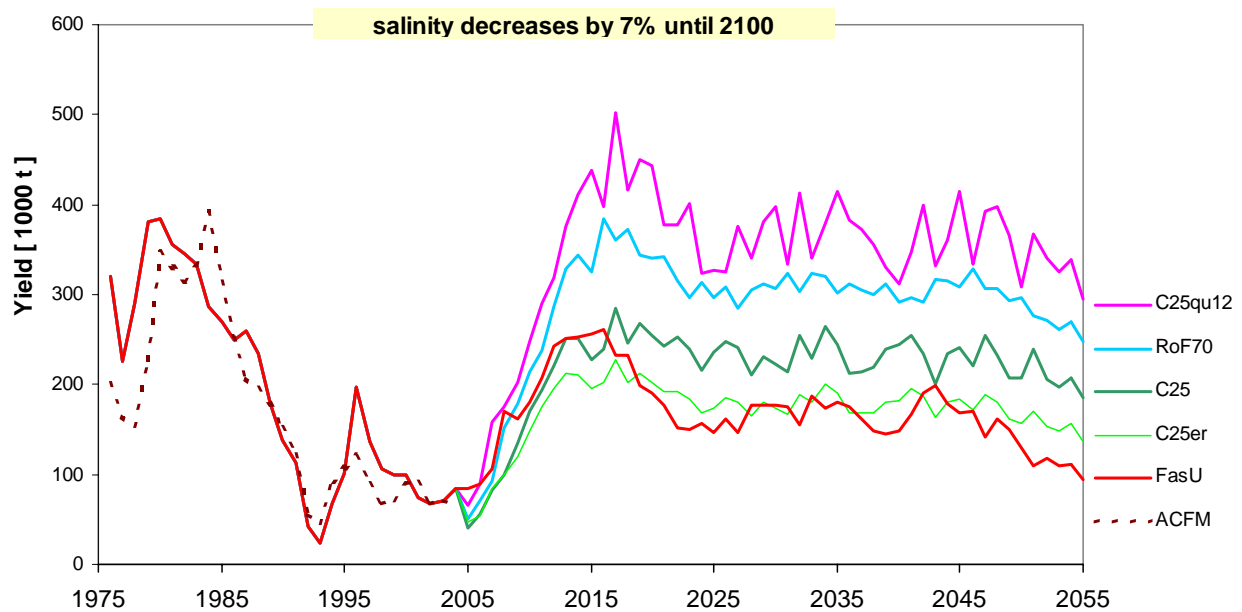




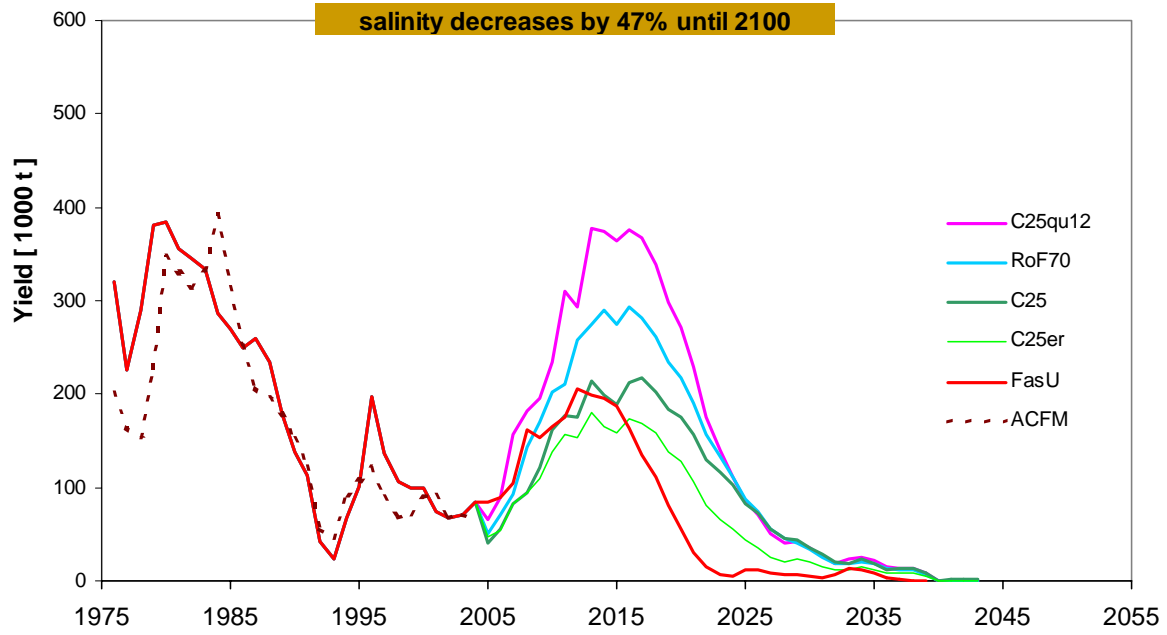
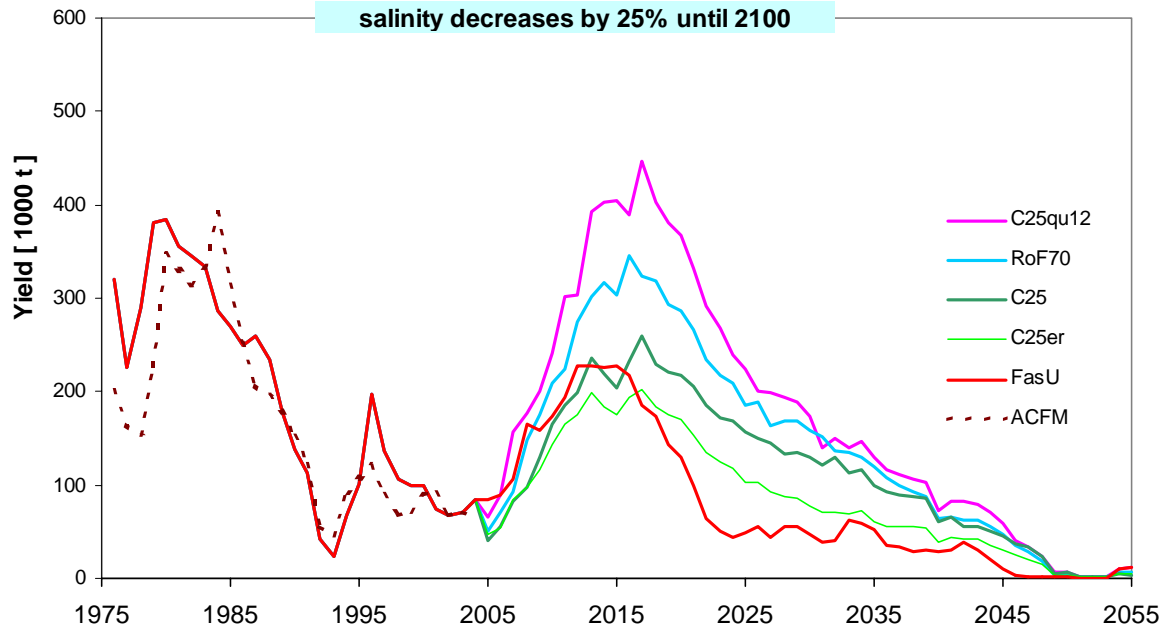
**Figure 5.** Age structure of the spawning stock in year 2055 under the low environmental change scenarios for the six different management policies (average of 50 model runs and standard deviation).



**Figures 6 a-c.** Simulated development of yield in 1000 t under (a) low, (b) medium, and (c) high environmental change scenarios for five different management policies: “**FasU**” = **F**ishing mortality **as usual**; “**C25qu12**” = temporal closure of SD **25** in **quarter 1** and **2**; quarter 3 and 4 are open to reduced fishing; “**C25er**” = permanent closure of SD **25** with fishing effort redistribution from SD 25 into SD 26; “**RoF70**” = **r**eduction of fishing mortality **F** by **70%** in the Eastern Baltic Sea; “**C25**” = permanent closure of SD **25** without fishing effort redistribution. Broken line “**ACFM**” shows actual ACFM landing estimates from ICES for comparison.







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