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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

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]). Climactic 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.

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 analyze 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].[3]

oxygen-consuming demineralization of organic material, but also because increasing water temperature reduces oxygen solubility. In a multi-species context, an increase in water temperature favors the reproductive capacity of sprat (MacKenzie and Köster [2004]), i.e., sprat reproductive success increases, which may be unfavorable 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 climactic 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 con-

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. commun.]). 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 utilize 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 to 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,

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 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 (visited June 8, 2005) and from the Yearbook of Fishery Statistics [2001, 2002, 2003] (Fiskeridirektoratet, Ministeriet for Fodevarer, Landbrug og Fiskeri, Kopenhavn).

The model of population dynamics. The model of population dynamics for the Eastern Baltic cod, developed by Röckmann et al. [in press], 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 [forthcoming]). Our model is presented in the Appendix. Variables and parameters in model notation are defined in Table 2.

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, 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 behavior 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^3 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]).

$$(1) \qquad S^{\text{lin}}_{a,y,j\to k} = \alpha \cdot N_{a,j,\text{``}q2\text{''},y} \cdot (1 - \beta^{\text{lin}} \cdot RV_{j,y})$$

$$(2) \qquad S^{\text{ex}}_{a,y,j\to k} = \alpha \cdot N_{a,j,\text{``}q2\text{''},y} \cdot e^{-\beta^{\text{ex}} \cdot RV_{j,y}}$$

$$(3) \qquad S^{\text{log}}_{a,y,j\to k} = \alpha \cdot N_{a,j,\text{``}q2\text{''},y} \cdot \left(1 - \frac{1}{1 + RV_j^{\max} \cdot e^{-\beta^{\text{log}} \cdot RV_{j,y}}}\right)$$

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, equation (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 α is a scaling parameter, accounting for the assumption that a small percentage of cod does not emigrate despite unfavorable 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 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 (equation (5)), with $Z_{a,y,q,r}$ being the total mortality, i.e., the sum of natural, predation and fishing mortality ($Z = M + P + F$).

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

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 ($w_{a,r}$), equation (6).

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

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, equation (7).

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

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, the primary existing spawning ground. Due to regularly returning favorable 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 1976–2055 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:

$$F_{a,r,q,y} = \alpha_r * F_{a,r,q,y}^{\text{average}} + \beta_r * F_{a,\text{``}r25\text{''},q,y}^{\text{average}}. \tag{9}$$

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

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 [forthcoming]).

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 55–65 m 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^2 values.

dependent variable	explanatory variable	Coefficient	Std. Error	Prob. (t-stat)	DW	R^2
RV (SD25)	S_{55-65m}	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_{average}	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_{average}	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		

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 65m 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.

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

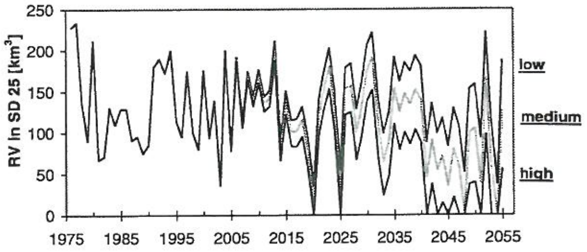

FIGURE 3. Reproductive volume (RV): data until 1999; from 2000 on: estimates derived from salinity as a normally distributed random variable, with its mean decreasing linearly over the 50 year simulation horizon by 7%, 25% and 45%, representing a low, a medium and a high climate change scenario, respectively.

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

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 scenarios, however, are different, as we assume the 34-year historic mean of salinity to decrease by 7%, 25% and

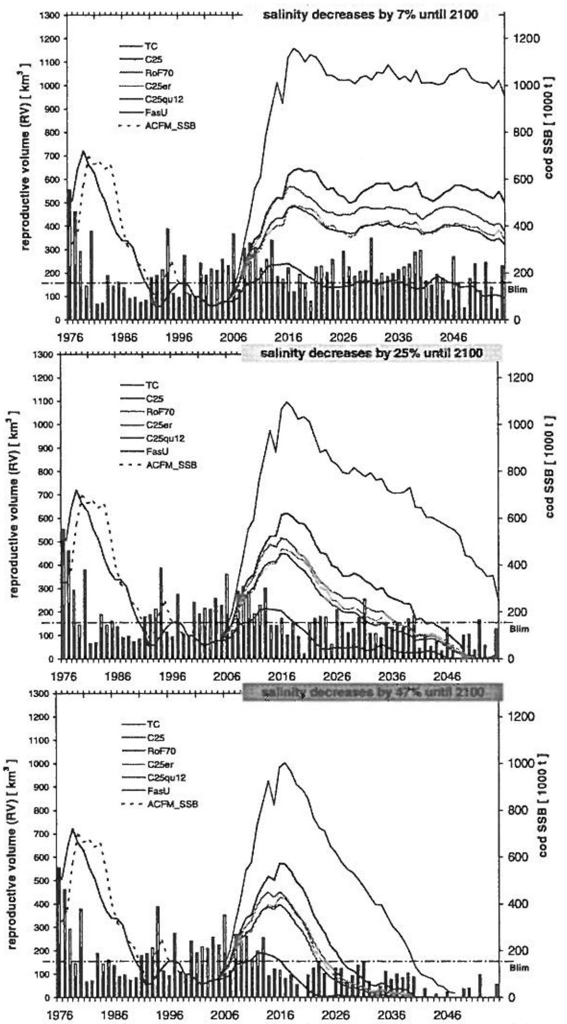

FIGURE 4. Simulated development of SSB (in 1000 t) under the (a) low, (b) medium and (c) high environmental change scenarios for the six different management policies. Bars: reproductive volume [km^3] in SD 25 (black), in SD 26 (white), in SD 28 (grey). Lines represent six different management policies: "**FasU**" = Fishing mortality as usual; "**C25qu12**" = temporal closure of SD 25 in quarters 1 and 2; quarters 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**" = reduction 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.

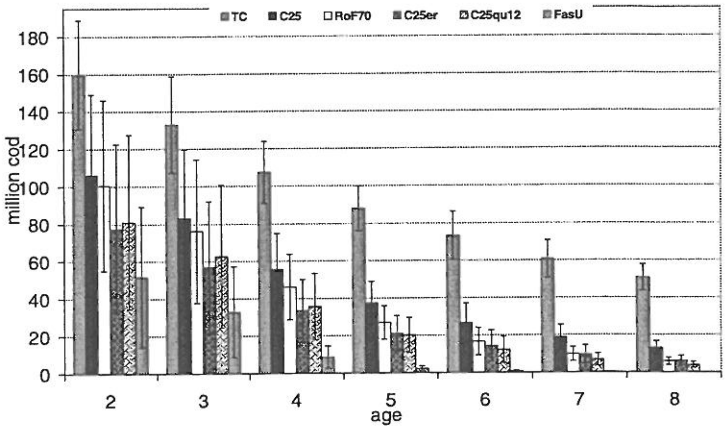

FIGURE 5. Age structure of the spawning stock in year 2055 under the low environmental change scenarios for the six different management policies (average of 50 model runs and standard deviation).

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 4 (c), respectively. In reality, however, North Sea inflow events

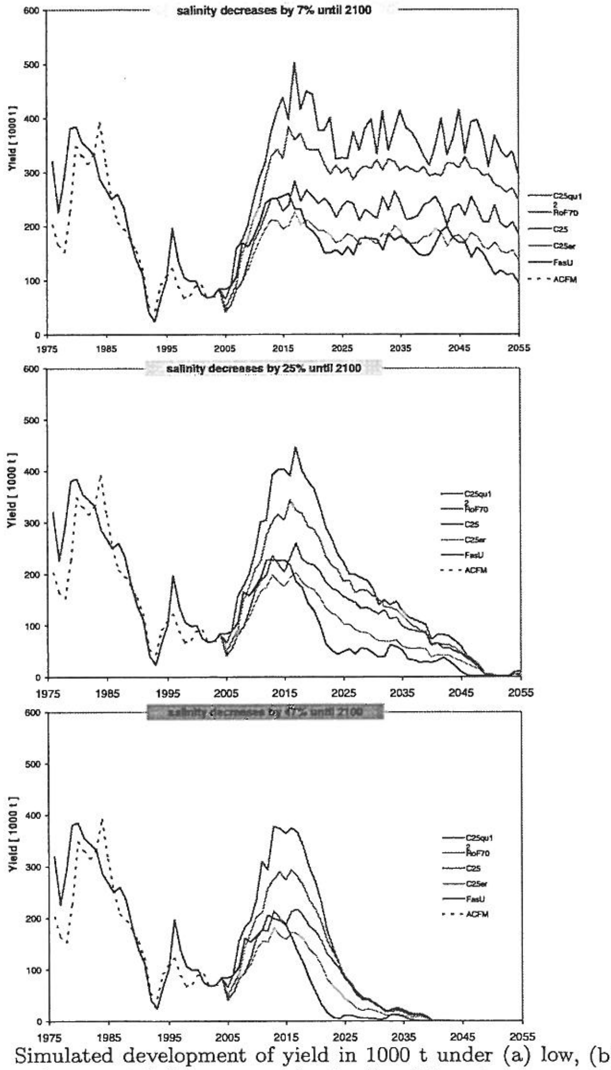

FIGURE 6. Simulated development of yield in 1000 t under (a) low, (b) medium and (c) high environmental change scenarios for five different management policies: "**FasU**" = Fishing mortality as usual; "**C25qu12**" = temporal closure of SD 25 in quarters 1 and 2; quarters 3 and 4 are open to reduced fishing; "**C25er**" = permanent closure of SD 25 with fishing effort redistribution from SD 25 into SD 26; "**RoF70**" = reduction 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.

TABLE 6. Yield in 1000 tons in year 2025 under the low, medium and high environmental change scenario. Values are averages ± the standard deviation of 50 random model runs which differ in the external forcing by salinity. This translates into differences in reproductive volume and finally in different population dynamics of the 50 model runs.

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

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.

As an example, we have presented average net present values of 50 random model realizations, applying a discount rate of 4% in Table 7. Under the three environmental change scenarios, the seasonal 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 seasonal marine reserve policy is more than twice as high as under the fishing as usual policy.

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 unfavorable 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 madisaggregated 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 C25qu12, which yields highest gross presented 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 summarize, we emphasize that under the present simulations of future climate change a significant reduction in fishing mortality is

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.

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 morality (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

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			

SD 28, the level of significance of the explanatory variable "RV" is 24% (Table A2).

ENDNOTES

1. 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].

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

3. For a discussion of the pros and cons of marine reserves, see Kaiser [2005] and Röckmann et al. [2005].

4. About 70% of the total Danish fishing capacity is affiliated to the DFPO.

5. 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].

6. The Rossby Centre Atmosphere Ocean model.

7. HadAM3H and ECHAM4/OPYC3.

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