J. Northw. Atl. Fish. Sci., Vol. 41: 205–220

Environmental Effects on Recruitment and Implications for Biological Reference Points of Eastern Baltic Cod (*Gadus morhua*)

Friedrich W. Köster, Morten Vinther, Brian R. MacKenzie and Margit Eero
Technical University of Denmark, National Institute for Aquatic Resources (DTU-Aqua),
Charlottenlund Castle, DK-2920 Charlottenlund, Denmark.
Emails: fwk@aqua.dtu.dk, mv@aqua.dtu.dk, brm@aqua.dtu.dk and mee@aqua.dtu.dk

and

Maris Plikshs
Latvian Fish Resource Agency, Daugavgrivas str.8,
Riga LV-1048, Latvia,
Email: maris.plikshs@lzra.gov.lv

Köster, F. W., M. Vinther, B. R. MacKenzie, M. Eero, and M. Plikshs. 2009. Environmental Effects on Recruitment and Implications for Biological Reference Points of Eastern Baltic Cod (*Gadus morhua*). *J. Northw. Atl. Fish. Sci.*, **41**: 205–220. doi:10.2960/J.v41.m636

Abstract

The decline of the Eastern Baltic cod (*Gadus morhua*) stock from highest to lowest stock levels on record throughout the 1980s and early 1990s was caused by a combination of recruitment failure and increasing fishing pressure at declining stock sizes. The processes driving the reproductive success are largely understood, but the consequences of these changes for fisheries management are far less evident. This includes doubts about the adequacy of the biological reference points presently used to advise on the stock status, and the need of their revision given that environmental changes have affected stock productivity. Long-term projections suggest that under adverse environmental conditions for reproduction, harvesting at fishing mortality determined as precautionary may not lead to a recovery of the stock to a biomass level considered precautionary. Thus, a revision of either the limit fishing mortality or the limit biomass reference point is indicated. However, an accepted methodology to determine these reference points in situations of changing stock productivity or system carrying capacity does not exist. Environmental conditions affecting recruitment matter not only for the determination of limit reference points, but according to long-term simulations also for target fishing mortalities, being central parts of harvest control rules in several management plans.

Keywords: biological reference points, cod recruitment, management plan, recovery, target fishing mortality

Introduction

The upper trophic levels of the Central Baltic changed from the mid-1980s to mid-1990s from a cod-dominated to a sprat-dominated system. The pronounced decline of the Eastern Baltic cod (*Gadus morhua*) stock from a historic high in the early 1980s to lowest levels on record in the early 1990s (Fig. 1) was caused by a recruitment failure (Bagge *et al.*, 1994) driven mainly by:

i) anoxic conditions in deep water layers of eastern spawning sites causing high egg mortalities (Plikshs *et al.*, MS 1993, MacKenzie *et al.*, 2000),
ii) high egg predation by clupeid predators in the remaining productive spawning area (Köster and Möllmann, 2000), and
iii) reduced larval survival due to the decrease in abundance of the main food item *Pseudocalanus* sp. (Hinrichsen *et al.*, 2002).

Increasing fishing pressure accelerated the decline of the stock, with severe management measures entering into force too late and reducing the fishing mortality only for a short period of time (Fig. 1). Other processes affect stock-recruitment as well, *e.g.* cannibalism is a significant source of mortality in juvenile cod when abundances are high,

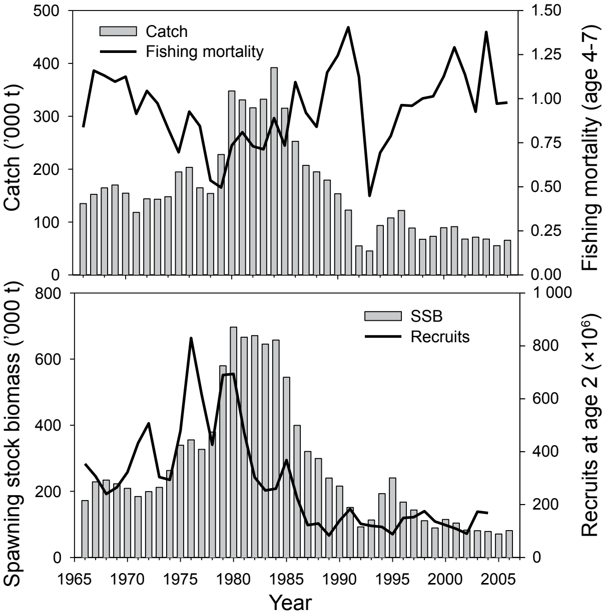

Fig. 1. Catch and fishing mortality and spawning stock biomass and recruitment of Eastern Baltic cod from 1965–2006 as estimated by ICES (2007d).

such as in the early 1980s (Sparholt, 1994). Concurrent to the decline in stock size, other compensatory processes such as changes in growth, maturation and individual egg production were apparent; however, these processes appear to be have limited impact on stock dynamics (Köster *et al.*, MS 2005a).

The decline of the cod stock released sprat (*Sprattus sprattus*) from predation pressure. In combination with high reproductive success, due to in general favourable temperature conditions, this resulted in exceptionally high sprat stock sizes in the 1990s (Köster *et al.*, 2003). Sprat affected cod recruitment negatively by acting as a predator on cod eggs (Köster and Möllmann, 2000) and *Pseudocalanus* sp. adults (Möllmann *et al.*, 2004), reducing the production of *Pseudocalanus* nauplli as food for cod larvae. Also other processes impact on the meso-zooplankton community (Dippner *et al.*, 2000; Hänninen *et al.*, 2000), with the marine copepod *Pseudocalanus* sp. declining in abundance, while standing stocks of the neritic copepod species *Acartia* sp. and *Temora longicornis*, being the major prey of larval sprat, increased. Concurrent changes in the Baltic ecosystem are also apparent on lower trophic levels (ICES, 2007a).

The intensity and significance of all these changes, described as a regime shift (Alheit *et al.*, 2005), are in one way or another steered by both climatic and hydrographic conditions, which were since the late 1980s characterized by prevailing weather with strong westerly winds and mild winters, above normal rainfall, increased river runoff and reduced frequency of major inflows (Matthäus and Schinke, 1994; Hänninen *et al.*, 2000), and by cascading food web effects associated with the decline of the cod stock (Casini *et al.*, 2008; Möllmann *et al.*, 2008). Higher than normal temperatures in the intermediate and bottom waters were recorded, while salinity and oxygen concentrations in the deep Baltic basins utilized by cod as spawning areas declined (Matthäus and Nausch, 2003). Regional prediction scenarios forecast a trend of increasing temperatures and decreasing salinities to continue (Meier, 2006), which threatens cod and favours sprat reproductive success (MacKenzie *et al.*, 2007).

Information on environmental processes affecting Eastern Baltic cod productivity was reviewed by several international working groups, with respect to:

i) implications for stock assessment and management (ICES, 2007b),

ii) determination of biological reference points (ICES, 2007c),

iii) interactions between larval cod and zooplankton (ICES, 2005a), and

iv) species interactions affecting stock recovery (ICES, 2006a).

Based on an estimate of spawning stock biomass (SSB) of 81 000 t in 2006 in relation to the limit biomass reference point (B_{lim}) of 160 000 t, the ICES Advisory Committee on Fisheries Management (ACFM) classified the Eastern Baltic cod stock as suffering from reduced reproductive capacity and based on a fishing mortality (F) of 0.98 in relation to a limit fishing mortality reference point (F_{lim}) of 0.96 as harvested unsustainably (ICES, 2007d). In the absence of an agreed management plan at the time when giving the advice, ACFM (ICES, 2007d) concluded that the exploitation boundaries for this stock should be based on the precautionary limits and as the precautionary biomass (B_{pa}) cannot be reached in 2009 no catch should be taken in 2008. ACFM (ICES, 2007d) further advised that a recovery plan should be implemented as a prerequisite to reopening the fishery.

ACFM (ICES, 2005b) recommended a target annual fishing mortality (F) of 0.3, which would result in a low risk to reproduction and high long-term yields and could form the central part of a harvest control rule. Based on this advice, the EU commission introduced a long-term Baltic cod management in July 2007, which specified the harvest control rule to reduce F by 10% compared to the year before, until a fishing mortality (average of ages 4–7) of 0.3 is reached. Interannual changes in total allowable catches (TAC) should be restricted to ±15%, except if F

is larger than 0.6, in which case the TAC may be reduced by more than 15%.

The simulations conducted by ICES (2005c) formed the basis for advice on a target *F* by ACFM (ICES, 2005b) and considered different stock-recruitment relationships covering time periods with varying environmental conditions and reproductive success. However the present advice with respect to precautionary limits does not take into account any multi-annual changes in stock productivity that potentially can affect the rate of stock decline as well as the rate of recovery.

This contribution investigates the effect of environmental variability and changes in stock productivity on the determination and application of biological reference points for fisheries management utilizing the Eastern Baltic cod stock as a case study. The study reviews how the present limit reference points for Eastern Baltic cod have been determined and the strength of evidence that spawning stock biomass influences recruitment, which is a prerequisite for the determination of present biomass limit reference points. Secondly, it investigates by simulations whether present reference points are realistic precautionary limits and whether the adopted target fishing mortality is robust against changes in stock productivity and species interactions.

Biological Limit Reference Points as Signposts for Fisheries Management

According to ICES (2007c) the limit biomass reference point (B_{lim}) is defined as the SSB below which there is a substantial increase in the probability of obtaining reduced (or 'impaired') recruitment. The estimate of B_{lim} should be risk averse, so that when the stock is at B_{lim} the probability that recruitment is substantially impaired is still small, but below B_{lim} that probability increases. The precautionary biomass (B_{pa}) considers uncertainty in determination of stock status relative to B_{lim} and is as such set higher than B_{lim}. The corresponding definition of F_{lim} is the fishing mortality, which in medium- to longer-term will drive the stock size to B_{lim}. F_{pa} considers uncertainties in determination of *F* relative to F_{lim}.

Determination of present reference points

The first attempt to determine B_{lim} and B_{pa} for the Eastern Baltic cod stock was conducted by ICES (1998a) suggesting a B_{lim} equaling to B_{loss} of 79 000 t. B_{pa} and F_{pa} were determined according to Cook (MS 1998) as 140 000 t and 0.81, respectively. Data for 1976–1996 were used, because assessment data prior to 1976 were judged to be of poor quality.

ICES (1998b) did not follow these suggestions, but determined B_{pa} as 240 000 t and B_{lim} as 160 000 t. B_{pa} was derived from a Ricker stock-recruitment relationship (with data covering 1976–1994) as the SSB at which 50% of the maximum recruitment (age-group 2) is originated, following a procedure suggested by Myers *et al.* (1994). B_{lim} was derived from the B_{pa} value as proposed by ICES (1998a) using:

$$B_{lim} = B_{pa} \exp(-1.645\ \sigma),$$

where σ is the standard error of the total biomass estimate from the international bottom trawl survey. A revision of the weight at age and maturity at age was conducted by ICES (1997), as time trends in weight at age and maturity ogives were apparent. F_{pa} was set to 0.65 or 0.75, depending on whether changes in weight at age are considered or not, based on medium-term simulations as the fishing mortality at which there is less than 10% probability of SSB being below B_{lim}. The medium-term simulations applied a Beverton and Holt stock-recruitment relationship fitted to year-classes 1981–1995, thus omitting extraordinarily high recruitment originated in preceding years, assuming log normal error. This period selection was justified by changed environmental conditions leading to on average lower recruitment in the 1980s and 1990s. The underlying SSB was calculated using the updated weight at age and maturity ogives from ICES (1997) and for the simulation part average weight at age for the periods 1992–1996 and 1983–1987 were applied, the latter being lower than the former and thus accounting for a declining trend of weight at age in the 1990s.

ICES (1998c) revisited the F_{pa} determination and based on the same methodology and stock-recruitment relationship, but slightly changed input data for the simulation part, F_{pa} was determined as 0.65 leading to an SSB corresponding to the 10% lower fractile of SSB's above B_{pa}. The simulations utilized an average weight at age, maturity ogive and exploitation pattern determined for the period 1995–1997. ACFM in 1998 finally revised F_{pa} to 0.6 as the 5% percentile of F_{med} derived from a stochastic stock-recruitment relationship covering year-classes 1966–1995 applying updated weight at age in the stock as described above, but period specific maturity ogives (averages over 5 years) up to 1994 and afterwards yearly data. The limit fishing mortality F_{lim} was set to 0.96 determined as F_{med}.

Attempts to revise reference points

ICES (1998b, c) suggested that *F* reference points should be determined with a truncated time series to account for productivity shifts in the Baltic system leading to reduced recruitment success since the first half of the 1980s. The impact of such a truncation of the time series on biomass reference points was explored by ICES (2002) applying segmented regressions: concluding: "The identification of time periods corresponding to 'regimes' is not straightforward, and may be an over-simplification of the true environmental variation. Furthermore, a regime shift that occurs in one direction could presumably be reversed at some time in the future, but this may be very hard to identify or to predict."

ICES (2003a) worked more conceptually on the links between reference points, and the related sources of uncertainty and risk and raised the question of a potentially negative impact of revising biomass reference points downwards in a low productivity regime and remaining fixed to these reference points when changing again to a high productivity regime.

ICES (2003b) developed a framework for the revision of reference points, stating with respect to the Eastern Baltic cod: "The relation between stock and recruitment (and thus B_{lim}) may change if the natural regime changes. … In such cases it could be relevant to limit the analysis to data representing the present regime. Such a procedure should however be implemented with caution because it will be difficult to identify the extent of a regime period and because a precautionary approach should include a consideration that the regime may have changed recently or may do so in the near future."

ICES (2005d) dealt with the necessity to revise the limit reference points for Eastern Baltic cod stating that the stock has been below or close to B_{lim} for 15 years and there are no indications that recruitment has been further diminished due to this low stock size. Instead the indications are that the reduction in recruitment is primarily environmentally driven and that the spawning stock has decreased following the decline in recruitment rather than vice versa. As a result it is difficult to justify the existing B_{lim}, although for similar reasons it is equally difficult to suggest a more appropriate value. Based on the segmented regression approach, ICES (2005d) determined a breakpoint to be approximately 90 000 t, representing a candidate for replacement of B_{lim}.

ICES (2006b) noted that there is a tendency to downplay the role of limit reference points for management advice in favour of target reference points (ICES, 2005c, 2006c), but that limit reference points are likely needed for establishment of future management plans and evaluation of these to be precautionary. While a limit reference point indicates a state of a fishery and/or a resource which is considered to be undesirable and which management action should avoid, a target reference point indicates to a state of a fishery and/or resource which is considered to be desirable and at which management action should aim (Caddy and Mahon, 1995).

Adequacy of present reference points

The present fishing mortality reference points are based on an assessment revised with respect to weight at age and maturity ogives in 1997, while the biomass reference points are based on an older assessment. The biomass reference points are based on the data series from 1976 onwards, while the *F* reference points determined by ACFM in 1998 are based on the entire time series since 1966. Additionally, discards have been included in recent assessments. As such the *F* and biomass reference points are not consistent and the biomass reference points cannot be considered as adequately determined.

These inconsistencies are also obvious from simulations conducted by ICES (2005c, d) suggesting that rebuilding to B_{pa} in the medium-term is impossible when fishing at F_{pa} and that rather a reduction to about half of F_{pa} is required to achieve B_{pa}. These results are further explored in subsequent sections below.

Based on elaboration by ICES (2002, 2003b), the apparent change in productivity should be considered by identifying environmental regimes, either by separating time series into shorter periods of similar environment, but preferably by incorporation of the environmental drivers into stock-recruitment relationships. A determination of biomass reference points for a specific productivity regime requires rules on revision procedures to be invoked if the regime shifts into another state, with indicators how to measure these being in place and monitored. This includes as well rules on related time lines of actions and identification of factors. ICES (2007c) acknowledged this, but was unable to give guidance on methodology to be applied for the determination of limit reference points under shifting environmental conditions.

To carry this discussion forward requires answering two questions. If environmental conditions drive recruitment success and environmental conditions change over time: can we detect a SBB, below which recruitment is impaired and can we rebuild the stock to present biomass reference points or to other levels?

Impact of the Spawning Stock on Recruitment

Inspecting time trends in stock and recruitment, reveals a high reproductive success at intermediate SSB values in the 1970s and declining reproductive success at historically high spawning stocks from 1981 onwards. This stock dynamics leads to a stock-recruitment relationship having two levels with a transition period with reduced recruitment originating from high SSB's in 1980–1982 (Fig. 2). Since 1987 recruitment appears to be largely independent of the SSB. This result also does not change if applying instead of age 2 recruitment from the standard XSA assessment (ICES, 2006b), age 0 or 1 recruitment from MSVPA runs (ICES, 2006d). On the contrary, accounting for cannibalism increases the difference in level between recruitment prior to and after 1982. Additionally, the transition period from high to a low recruitment regime at similar SSB's is also longer, lasting from 1979 to 1983 (Fig. 2). An assessment of the Eastern Baltic cod extending backwards until the 2nd World War (Eero *et al.*, 2007) indicated that stock productivity was higher in the 1950s and 1960s compared to the 1990s, but lower than during the 1970s. Correspondingly, the characteristic two level stock-recruitment relationship still prevails (Fig. 2).

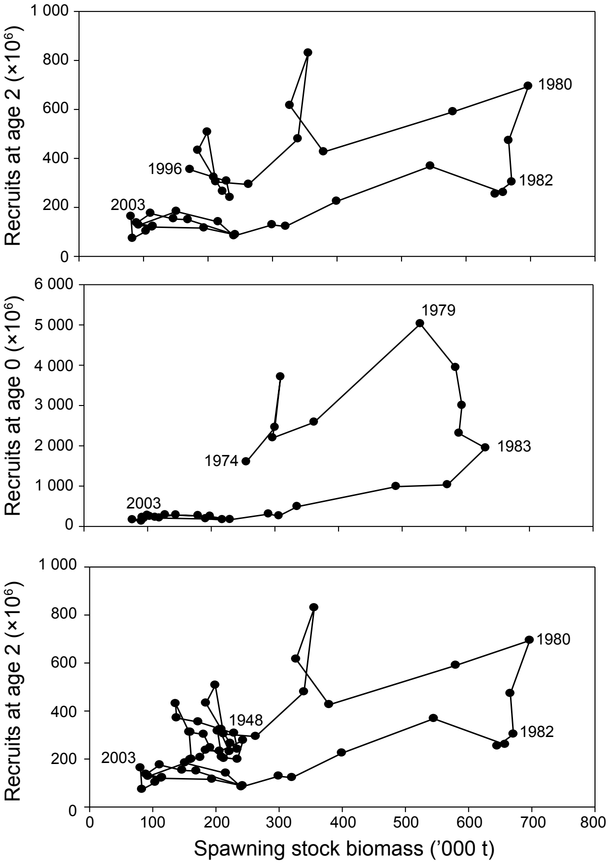

Fig. 2. Stock-recruitment relationship with indicated time line from standard stock assessment (ICES, 2006b) (upper panel), MSVPA (ICES, 2006d) (middle panel) and an extended stock assessment (Eero *et al.*, 2007) (lower panel).

Comparing the distribution of the SSB with the reproductive volume sustaining egg survival (MacKenzie *et al.*, 2000) in the different spawning areas (Fig. 3) indicates a large portion of the egg production in the Gotland Basin in Sub-division (SD) 28 spawned during the late 1970s and early 1980s in unsuitable environments. Since the early 1980s hydrographic conditions were also adverse in the Gdańsk Deep (SD 26), when especially from 1986–1992 virtually no reproductive volume was present (Fig. 3). The only spawning site regularly sustaining successful egg development was the Bornholm Basin (SD 25). This is confirmed by low egg and larval abundances in eastern spawning areas since 1986 as well as low recruitment originating from these areas (Fig. 3). After the major inflow in 1993, oxygen concentrations allowed successful egg development in the Gdańsk Deep in 1993 and 1994, while conditions in the Gotland Basin remained unfavourable as the inflowing water replaced near bottom water layers with eggs developing in the intermediate oxygen depletion zone (Plikshs *et al.*, MS 1999). A similar process is anticipated for the 2003 major inflow, indicating that single major inflow events are in general not sufficient to improve reproductive conditions in eastern spawning areas (ICES, 2004).

Recognizing the decline in reproductive success being caused by losing two out of three effective spawning areas, it is straightforward to assume that the SSB in SD 25 is the only reproducing part of the stock since 1981. Removing the SSB located in eastern spawning areas, derived from an area disaggregated MSVPA (Köster *et al.* (2001a) updated according to ICES (2006d)), from the stock-recruitment relationship after 1980, removes the characteristic time pattern in the stock-recruitment plot and yields an almost linear stock-recruitment relationship (Fig. 4). However, there is still no stock-recruitment relationship apparent since the late 1980s.

A relationship of recruitment per unit of reproductive volume against SSB is significant at high, but not at low reproductive volumes (Fig. 5), indicating that under favourable environmental conditions for egg survival in all three spawning areas, a low SSB is a limiting factor for reproductive success. In turn high spawning stock size in eastern spawning areas without favourable reproductive conditions will likely have only a limited impact on recruitment. However, trawl surveys (Tomkiewicz and Köster, MS 1999) and commercial CPUE data (Lablaika and Lishev, MS 1961) show that spawning migrations

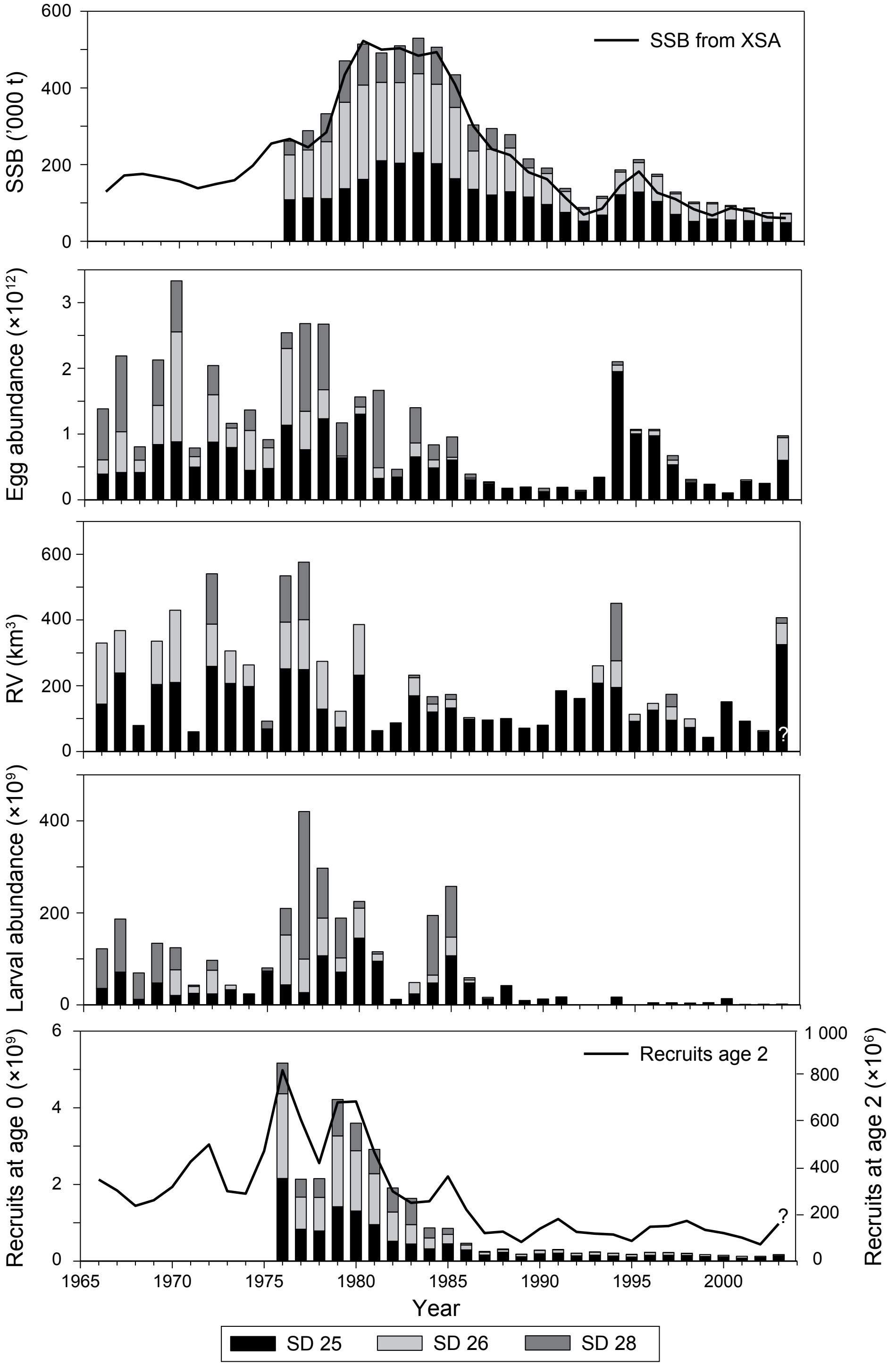

Fig. 3. Time series of spawning stock biomass (SSB) in Sub-division (SD) 25, 26 and 28 (1976–2003) from area dis-aggregated MSVPA (ICES, 2006d) and the entire central Baltic (1966–2003) from standard assessment (ICES, 2006b), egg abundance, reproductive volume at spawning time (RV), larval abundance (data from SD 26 in 1966–1969 missing) and recruitment at age 0 in Sub-division 25, 26 and 28 from area dis-aggregated MSVPA and recruits at age 2 in the entire central Baltic from standard assessment (updated from Köster *et al.*, 2005b).

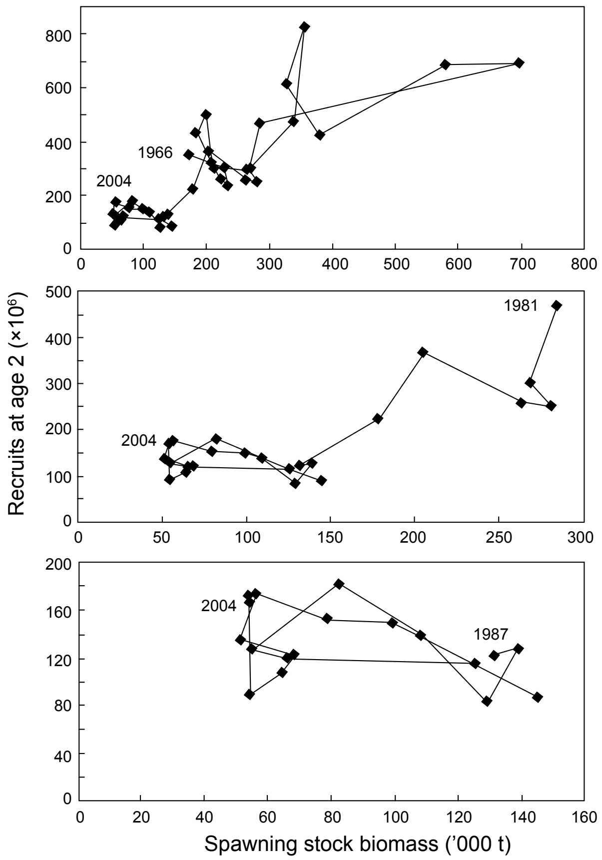

Fig. 4. Stock-recruitment relationship assuming the SSB in Sub-division 25 to be the only reproducing part of the stock since 1981, *i.e.* SSB from Sub-division 26 and 28 excluded from the relationship in 1981–2004.

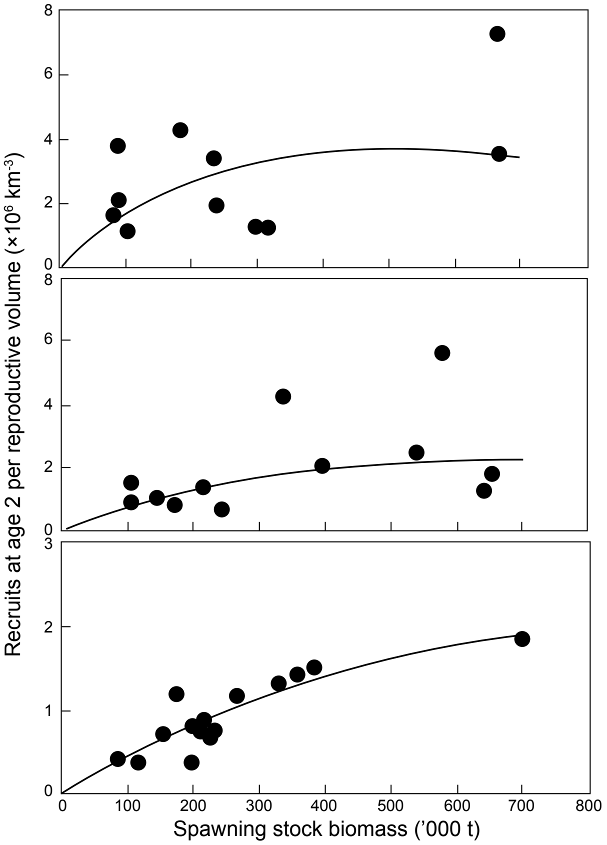

Fig. 5. Recruitment at age 2 per unit of reproductive volume *vs.* spawning stock biomass at low, *i.e.* <100 km^3 (upper panel), intermediate, *i.e.* 100–200 km^3 (middle panel) and high, *i.e.* ≥200 km^3 reproductive volume (lower panel).

by some of the spawners from eastern spawning areas into the Bornholm Basin exist. Thus some of the SSB in eastern spawning areas contributes to recruitment even under unfavourable environmental conditions by moving to and reproducing in more suitable areas. On the other hand, some spawners apparently stay and reproduce in the unfavorable areas as seen by ichthyoplankton data (Fig. 3).

All statistical exploratory analysis conducted for Eastern Baltic cod considering environmental factors, include SSB or potential egg production as a significant variable (Sparholt, 1996, Jarre-Teichmann *et al.*, 2000). This holds also for an analysis revisiting spatially explicit environmentally sensitive stock-recruitment models established by Köster *et al.* (2001b), but now based on enhanced process understanding as well as new and updated time series for all variables. Variables included potential egg production by the spawning stock (PEP), oxygen related egg survival (OES) and in SD 25 the predation related egg survival (PES) as presented by Köster *et al.* (2005b), as well as prey availability for first feeding larvae. The latter was represented by the product of *Pseudocalanus* sp. nauplii abundance during the main spawning time and pursuit success probability, calculated by utilizing a regression model for describing the influence of turbulent velocity on larval feeding success (MacKenzie and Kiørboe, 2000). To account for cannibalism the stock-recruitment relationships were fitted to 0-group abundance from area disaggregated MSVPA output (ICES, 2006d).

PEP was significantly related to 0-group recruitment in all SDs, however in SD 25 it explained only limited variability in recruitment. Utilizing PEP × OES or PEP × OES × PES as an independent variable improved the relationships in SD 25 substantially, while this was not the case in eastern SDs (Table 1). The ln-transformed relationships of PEP and recruitment outperformed linear relationships. A positive effect of including OES was obvious for SD 26 only, otherwise the simplest model, *i.e.* PEP as the only variable, explained variability in recruitment best in the ln-transformed relationship (Table 1).

Representing food availability together with PEP in a multiple linear untransformed regression improved the explained variance in recruitment compared to those obtained when utilizing PEP alone (Table 1). However, PEP was an insignificant variable in SD 25 and SD 26. In the ln-transformed model PEP was significant in SD 26 and 28, but food availability only in SD 25 and SD 26. Including pursuit success as a factor in prey availability always improved the fit, but only marginally.

Modifying PEP for egg survival in the multiple regressions together with food availability, revealed improvements in the un-transformed relationship (Table 1), with surviving egg production and prey availability being always significant variables. The Durban-Watson statistics however indicated serial autocorrelation in residuals for SD 26. The ln-transformed models behaved similar to the un-transformed for SD 25 and SD 26, with complex models having the overall best fit and all variables being significant (Table 1). However, in SD 28 most variability in recruitment was explained by a simple relationship to PEP. A tendency to autocorrelation in the residuals was encountered in all areas.

In conclusion it can be stated that SSB impacts recruitment. The magnitude depends on environmental conditions sustaining egg and larval survival. Environmental conditions vary in time and space, which implies that the distribution of the stock matters as well. However, also stock structure matters, a factor not considered in the above statistical tests. A truncated age structure has a negative effect on offspring survival as larger females produce on average larger eggs, having higher buoyancy and thus being incubated at higher oxygen concentrations (Vallin *et al.*, 1999; Cardinale and Arrhenius, 2000). All of the above indicates that simple biomass limit reference points are not able to account for complex environment and recruitment interactions, confirming doubts about their use in fisheries management (Marshall *et al.*, 2003). Also *F* based reference points based on simple spawning stock biomass considerations are sensitive against neglecting demographic variation in spawning stock characteristics (Murawski *et al.*, 2001).

Simulations

Single- and multispecies long-term simulations were conducted using the SMS package (Lewy and Vinther, MS 2004) which previously has been used to evaluate harvest control rules for blue whiting (*Micromesistius poutassou*) (ICES, 2006e), sandeel (*Ammodytes marinus*) (ICES, 2007e) and Norway pout (*Trisopterus esmarki*) (ICES, 2007f). Methodologically, harvest control rules are evaluated by SMS in a very similar way as by the STPR3 programme used by ICES (2005c) to evaluate harvest control rules for Baltic cod. Like the STPR3 programme, the SMS approach does not simulate the full annual cycle of assessment and projection. Instead, it is assumed that the real stock size can be "observed" with some bias and noise and it is this "perceived" stock that forms the basis for the use of the harvest control rule. The true stock size is assumed to be known in the first projection year and is later updated by recruitment and catches from application of the harvest control rule.

TABLE 1 Explained variation and significance in single and multiple linear regression of recruitment (age 0 from MSVPA 1974–1999) by different variables and combination of variables (PEP: Potential egg production, OES: Oxygen related egg survival, PES: Predation related egg survival, Pp: *Pseudocalanus* sp. nauplii abundance, T: Pursuit success).

Variables	SD 25	SD 26	SD 28
Ln PEP	0.36**	0.53***	0.84***
Ln (PEP•OES•PES)	0.24*	0.70***	0.71***
PEP	0.20*	0.52***	0.62***
PEP•OES•PES	0.42**	0.52***	0.45***
Ln PEP & Ln Pp•T	0.51$^{\text{ns1 \& **}}$	0.63*$^{\text{\& *}}$	0.80***$^{\text{1 \& ns}}$
PEP & Pp•T	0.59 $^{\text{ns \& ***}}$	0.66 $^{\text{ns \& ***}}$	0.67*$^{\text{\& **}}$
Ln (PEP•OES•PES) & Ln Pp•T	0.70***$^{\text{1 \& ***}}$	0.82***$^{\text{1 \& **}}$	0.73**$^{\text{1 \& *}}$
PEP•OES•PES & Pp•T	0.74**$^{\text{\& ***}}$	0.72*$^{\text{1 \& ***}}$	0.67*$^{\text{\& ***}}$

Significance of variables: $^{\text{ns}}$ *p* >0.05, * *p* <0.05, ** *p* <0.01, *** *p* <0.001; Mallows' *Cp* statistics does not suggest exclusion of any variables.

[1] Durbin Watson statistics suggest autocorrelation of residuals.

The SMS model was not only applied in long-term simulations, but also used to estimate historical stock sizes, fishing mortality and recruitment. It uses a maximum likelihood technique for fitting observations of catch at age, CPUE at age, SSB and recruitment as well as stomach contents in multispecies runs. In multispecies runs, changes in cannibalism intensity and their effect on stock dynamics were explored. Decadal changes in cod cannibalism have been described by Uzars and Plikshs (2000). During 1963–1979 the distributions of young and adult cod were widespread, but separated in time and space, resulting in overall low cannibalism. When the biomass of clupeids decreased in the late 1970s, competition for food increased as did cannibalism. In the late 1980s, unfavourable oxygen conditions in the bottom water affected the benthic community negatively, and cod shifted from a benthic to a more benthopelagic mode of life utilizing mysids and sprat as a food resource (Uzars and Plikshs, 2000). This distribution pattern is believed to have reduced cannibalism pressure substantially, which is confirmed by recent stomach content sampling (Because, 2007). A pronounced time trend in cod cannibalism is as well apparent from MSVPA runs (ICES, 2003c) applying the 4M model (Vinther, 2001). On average 50% and 30% of the 0-group and 1-group cod were removed from the stock by cannibalism during the 1970s and early 1980s, respectively. During the 1990s the corresponding values were below 20% and 10%, respectively.

To test for the effects of changes in cannibalism, SMS runs were performed with the entire stomach content data set (1977–1993) as well as the dataset reflecting the period of high (1977–1986) and low cannibalism (1987–1993). SMS was also used to conduct runs with a constant natural mortality with time and age as used by most ICES assessments. In the single species model, a residual mortality of 0.2 per year was assumed for all age groups.

For comparison of model performance in the simulations, five different recruitment models were defined and

TABLE 2. Eastern Baltic cod stock-recruitment relationships derived from SMS runs with different combinations of time spans and cannibalism scenarios; with α for the hockey stick function: slope of the ascending limb and β: inflection point (recruitment = exp(α)*min (SSB, β)); for geometric mean recruitment exp(α) gives the mean; std: standard deviation of the estimated log (recruitment). In the SMS runs, maximum likelihood *a priori* weights on SSB/R "observations" were down-weighted by setting the value to 0.1, except for all hockey stick stock-recruitment functions fitted with inflection point at 160 000 t; here the *a priori* weight was set to the default 1.0 to avoid too large of standard deviations on the SSB/R parameter estimates. The error distribution for stock-recruitment relationships is log-normal with no bias correction.

Model type	α	β	std
Single species hockey stick 1974–2005	0.626	160 000	0.59
Single species hockey stick 1987–2005	0.538	92 000	0.24
Single species hockey stick 1987–2005	0.257	160 000	0.40
Single species geometric mean 1974–2005	12.444		0.64
Single species geometric mean 1987–2005	11.945		0.24
Multispecies hockey stick 1974–2005	1.297	160 000	0.89
Multispecies hockey stick 1987–2005	0.932	92 000	0.19
Multispecies hockey stick 1987–2005	0.653	160 000	0.33
Multispecies geometric mean 1974–2005	13.334		1.22
Multispecies geometric mean 1987–2005	12.340		0.20
High cannibalism hockey stick 1974–2005	1.234	160 000	0.86
High cannibalism hockey stick 1987–2005	0.891	92 000	0.19
High cannibalism hockey stick 1987–2005	0.597	160 000	0.26
Low cannibalism hockey stick 1974–2005	0.953	160 000	0.68
Low cannibalism hockey stick 1987–2005	1.586	92 000	0.30
Low cannibalism hockey stick 1987–1994	1.051	160 000	0.24

combined with the above mentioned four configurations of cannibalism, which mimic possible combinations of recruitment and species interaction regimes (Table 2). "Hockey stick" stock-recruitment relationships with breakpoints of 92 000 t and 160 000 t were fitted to recruitment at age 0 including year-classes 1987–2005 and 1974–2005. When applying the entire data series 1974–2005, only a breakpoint of 160 000 t was used. There are some differences to the simulations conducted by ICES (2005c). Using age-group 0 instead of 2 restricts data availability backwards to 1974, as multispecies stock assessments do not cover prior periods. Secondly, for the extended time series only an inflection point of 160 000 t was used. Applying an inflection point of 356 000 t (ICES, 2005c) resulted in a poor fit to the data.

While SSB values are almost identical in our different stock-recruitment relationships, recruitment varies over a wider range; refer to Fig. 6 for the combined impact of truncating the time series and choosing different levels for the inflection point. As a further alternative, the geometric mean recruitment from respective time periods 1987–2005 and 1974–2005 was used, assuming recruitment to fluctuate independent of SSB. In multispecies predictions, recruitment of herring is drawn from a Ricker stock-recruitment at age 0 relationship, fitted to the whole time series (1974–2005), while sprat recruitment at age 0 is estimated as a geometric mean over the years 1990–2005.

Start populations in the beginning of 2006 were derived from SMS assessments using the specified year range for SSB per recruit data and optional stomach contents data for multispecies runs. Exploitation patterns were derived by averaging *F* in the period 1996 to 2005. Other input data were taken from ICES (2006d), *i.e.* mean weight

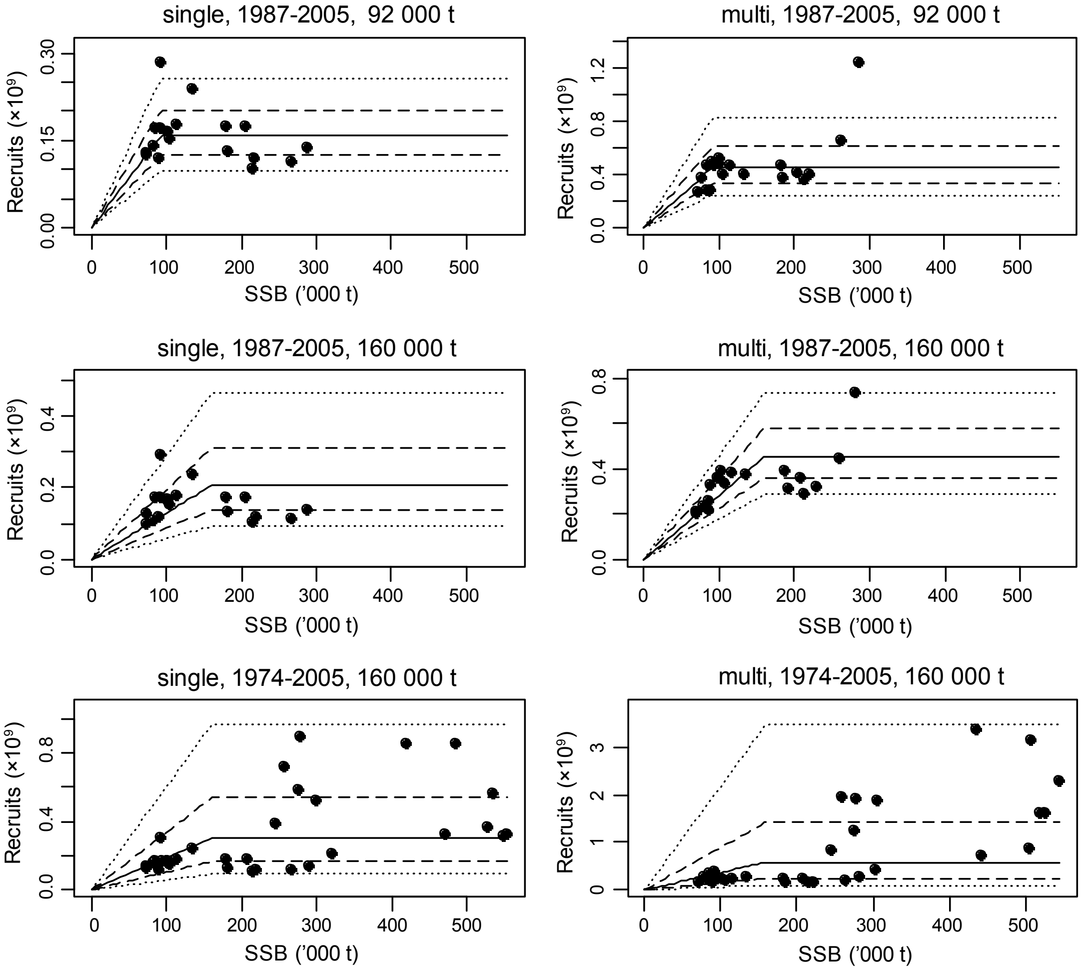

Fig. 6. Stock-recruitment relationships for Eastern Baltic cod derived by SMS run in single- and multispecies model fitted to data for the period 1987–2005 with an inflection point of 92 000 t and 160 000 t, as well as for the entire data series 1974–2005 with an inflection point of 160 000 t. The lines show the mean value and ±1 and ±2 standard deviations.

in the sea and food rations averaged from 1995–2004 and maturity ogives kept as in the 2006 assessment by ICES (2006b). Due to a highly fluctuating cod stock in some multispecies scenarios, the simulations were conducted until 2059 with an assumed equilibrium condition being reached after 2055. In all these simulations, no assessment or implementation errors or retrospective bias were applied.

The results from the long-term simulations suggest that there is a less than 5% probability of SSB being below B_{lim} at F of 0.55 even under low recruitment scenarios (time period 1987–2005, inflection point of 92 000 t). Recovery to B_{pa} (less than 5% probability of SSB below B_{pa}) requires F below 0.4 (Fig. 7). Whether one assumes a stock-recruitment relationship with breakpoint at 92 000 t or geometric mean recruitment derived from the same period hardly affects the simulation results. As an inflection point of 92 000 t is relatively low and stock sizes will fall below this inflection point only at high F, recruitment is basically log-normally distributed around the average recruitment at the plateau for low to mid-level F. Assuming cannibalism or not makes a difference only for the F at which the stock recovers to B_{pa}, for recovery to B_{lim} it is insignificant (Fig. 7), because of the relatively low adult stock size.

Simulation results from applying a 160 000 t inflection point for fitting a stock-recruitment relationship to data from the period 1987–2005 suggests F up to 0.6–0.65 to be robust against B_{lim} (Fig. 7). Simulations including cannibalism are somewhat less optimistic, especially with respect to recovery to B_{pa}, which requires F of below 0.35 compared to the single species simulation which suggests that a F below 0.45 is sufficient.

Assuming high recruitment allows rebuilding to B_{lim} at F of 0.75 to 0.83, with applying a stock-recruitment relationship sustaining higher F than applying a geometric mean (Fig. 7). Whether one assumes cannibalism or not has only very limited impact on the simulation results. For rebuilding to B_{pa} however, the assumption about cannibalism matters. F of 0.54 and 0.63 are sufficient to rebuild to B_{pa} in the single species scenario, while it is only 0.44 and 0.54 in the multispecies scenario. At higher F, the risk of SSB being below B_{pa} increases more rapidly with increasing F in the single species than in the multispecies scenario, *i.e.* multispecies probability curves are in general flatter. The compensatory mechanism of cannibalism gives more stability against high F, however it requires lower F to reduce the risk of being below B_{pa} (Fig. 7). Assuming a geometric mean recruitment requires lower F to avoid the biomass limit reference points than assuming a stock-recruitment relationship.

The simulated SSB at equilibrium shows independent of the recruitment model a steeper decline with fishing mortality in the single species compared to the multi-

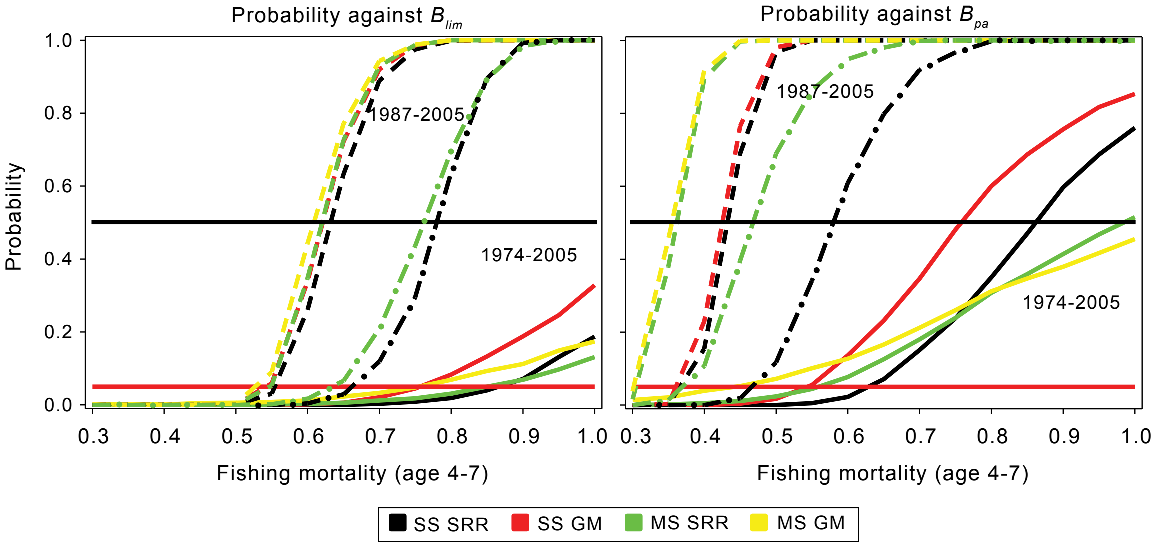

Fig. 7. Probability of spawning stock size being at or below B_{lim} and B_{pa} at different fishing mortalities, assuming single (SS) or multispecies (MS) interactions and different recruitment models fitted to different time periods with low recruitment (1987–2005, stock recruitment relationships (SRR) with inflection points 92 000 t as dashed lines and 160 000 t as dashed lines with points both black and green, geometric mean recruitments (GM) as dashed lines in red and yellow) and the entire time series (1974–2005, stock recruitment relationships (SRR) with inflection points 160 000 t as solid lines in black and green, geometric mean recruitments (GM) as solid lines in red and yellow); horizontal lines represent the 5% (red) and 50% (black) percentile, respectively.

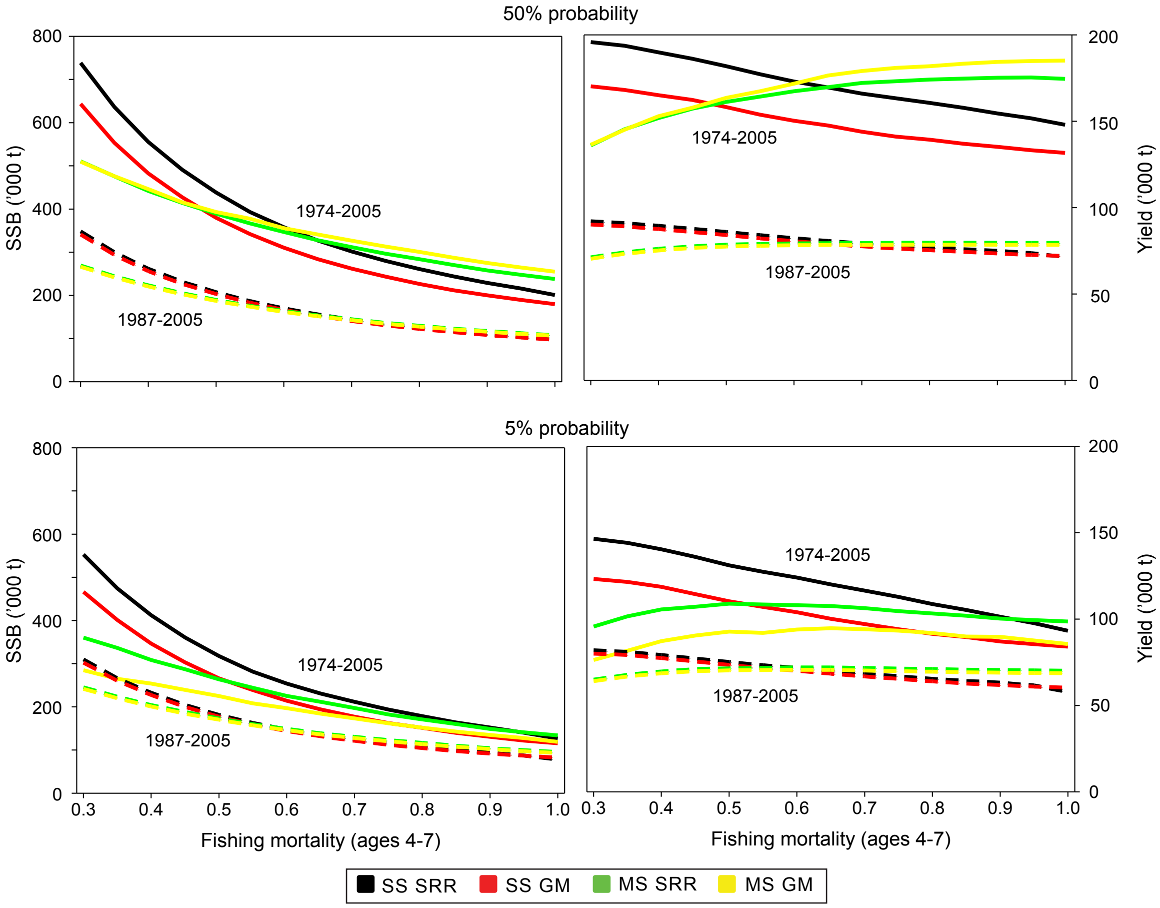

Fig. 8. Equilibrium spawning stock size (50% and 5% percentile) and corresponding yield at different fishing mortalities in single (SS) and multispecies (MS) simulations with stock-recruitment models fitted to different time periods with low recruitment (1987–2005, stock recruitment relationships (SRR) with inflection point 92 000 t as dashed lines in black and green, geometric mean recruitments (GM) as dashed lines in red and yellow) and the entire time series (1974–2005, stock recruitment relationships (SRR) with inflection point 160 000 t as solid line in black and green, geometric recruitments (GM) as solid lines in red and yellow).

species simulations (Fig. 8). Using a stock-recruitment relationship or a geometric mean recruitment creates only limited differences in the low recruitment scenario, but also in the multispecies high recruitment scenario the differences are marginal. Clearly, the largest differences are caused by using different time periods to fit the recruitment model. From comparison of the 5% and 50% percentile (Fig. 8) it is obvious that the probability distributions of both SSB and yield are considerably narrower in the low recruitment scenario. Single species simulations result in a steeper decline in SSB with increasing *F* and a decline in yield with increasing *F* (in the range of *F* from 0.3 to 1.0 considered). In contrast, multispecies simulations show increasing catches with increasing *F*, at least up to an *F* of 1.0. However, the probability distribution of the yield flattens, *i.e.* the 5% percentile declines at *F* above 0.5 to 0.6.

Assuming high or low cannibalism, *i.e.* recruitment based on SMS runs using stomach content data from the period 1977–1986 and 1987–1993, respectively shows only limited impact on the equilibrium SSB and yield (Fig. 9). The simulation results are more sensitive against the choice of the data period for fitting the stock-recruitment relationship. Applying an inflection point of 160 000 t for the time series 1987–2005 results in slightly higher SSB and yields than when using an inflection point of 92 000 t until an *F* of 0.8. At higher *F*, the simulation run with the higher inflection points shows drastically reducing SSB and yield, which can be explained by the

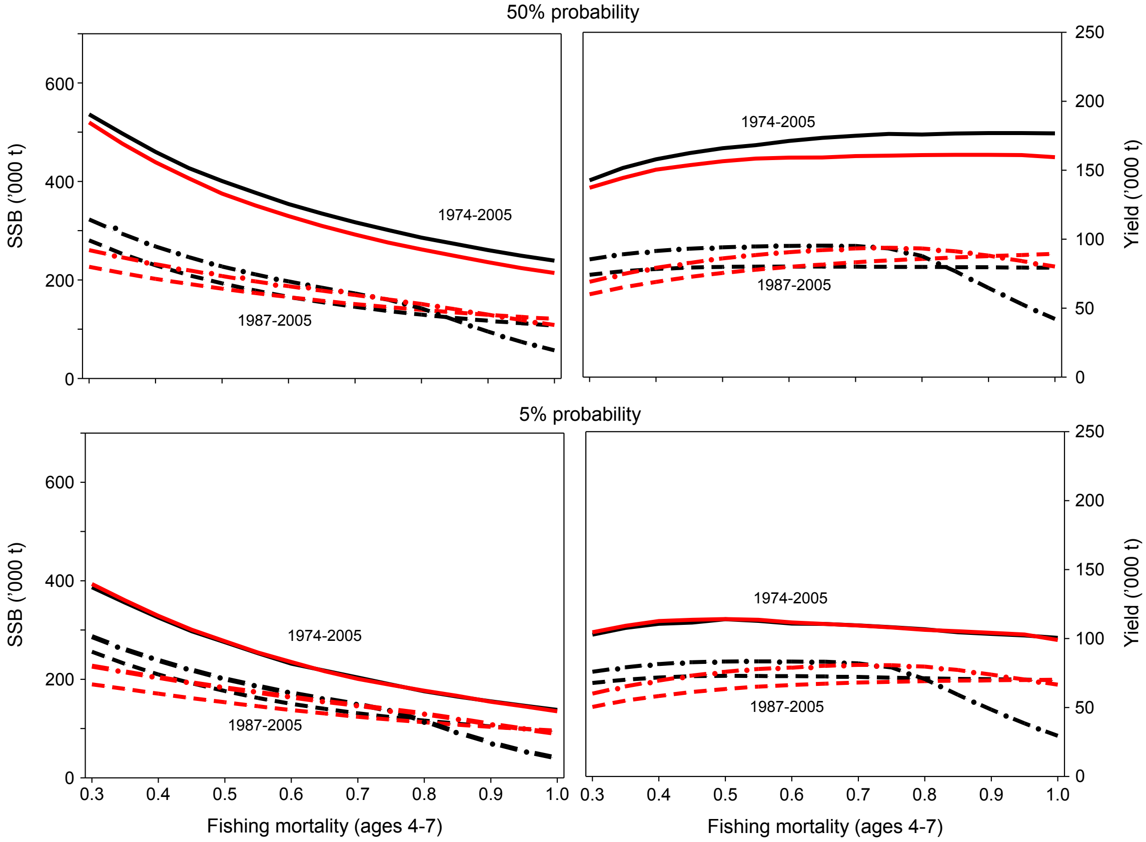

Fig. 9. Equilibrium spawning stock size (SSB, 50% and 5% percentile) and corresponding yield at different fishing mortalities, assuming high (stomach content 1977–1986, black lines) or low cannibalism (stomach content: 1987–1994, red lines) and stock-recruitment relationships fitted to different time periods with low recruitment (1987–2005, inflection point 92 000 t as dashed line and 160 000 t as dashed line with points) and the entire time series (1974–2005, inflection point 160 000 t as solid line).

fact that SSB is getting below the inflection point invoking a real dependence of recruitment on stock size. High recruitment and high cannibalism as well as low recruitment and low cannibalism, *i.e.* the most likely combination of scenarios, result in the steepest yield increases with fishing mortality.

These results indicate that target *F*'s are sensitive to environmental changes affecting the reproductive success of fish stocks. The form of the stock-recruitment relationships matters, with hockey stick stock-recruitment relationships and geometric means behaving very similar as long as the biomass is above the inflection point. Thus, the choice of the inflection point is important when applying a hockey stick model. Utilizing an inflection point corresponding to B_{lim} of 160 000 t results in F of 0.62 to 0.65 maintaining the stock with a 95% probability above B_{lim}, compared to 0.55 when applying an inflection point of 92 000 t. The corresponding F for avoiding B_{pa} is around 0.35–0.45 and 0.3–0.35, depending on whether cannibalism is considered or not.

Conclusions

Present limit reference points for the Eastern Baltic cod stock are not determined adequately. Biomass and fishing mortality reference points are based on two different stock and recruitment time series covering periods with quite different reproductive success. The assessment input data have been substantially revised before determining fishing mortality reference points, while an older assessment output was used for the determination of the biomass reference points. Additional changes in the assessment input were introduced since then, without revision of the reference points.

The dependence of recruitment on environmental conditions and the fluctuation of recruitment at low levels apparently independent of the size of the spawning stock or the magnitude of egg production since 1987, does not imply that the spawning stock biomass has no significant impact on recruitment. All statistical analyses that consider environmental factors, include SSB or potential egg production as significant variables.

Removing the spawning stock biomass located in eastern spawning areas in years with unfavourable conditions from the stock-recruitment relationship, removes the characteristic two level time pattern in the stock-recruitment plot and yields an almost linear stock-recruitment relationship. Similarly, stock-recruitment relationships utilizing recruitment per unit of reproductive volume as a measure of reproductive success indicate that a low spawning stock biomass is likely a limiting factor for recruitment under favourable environmental conditions.

Long-term simulations suggest that fishing at F_{pa} of 0.6 may not rebuild the stock, neither to B_{pa} when applying a hockey stick stock-recruitment relationship based on data covering a period of low reproductive success (1987–2005) with an inflection point of 160 000 t, nor to B_{lim} when applying the same data and an inflection point of 92 000 t. Applying a geometric mean recruitment instead of using a stock-recruitment relationship, yields in general more conservative stock and yield trajectories, but the differences are limited for the low recruitment scenario as long as SSB stays above the inflection point. Including cannibalism in the simulations makes a difference only for stock recovery to B_{pa}; for recovery to B_{lim} it is of very limited importance, because of the relatively low adult predator stock size.

In contrast, the present F_{pa} may be sustainable in a high productivity system as indicated by single species simulations. Including cannibalism results in somewhat less optimistic trajectories, with a 10% probability of stock size being below B_{pa} when fishing at F_{pa}. At higher F, the risk of SSB being below B_{pa} is increasing faster with increasing F in singles species simulations, *i.e.* the compensatory mechanism of cannibalism gives more stability against high F, however, it requires lower F to reduce the risk of being below B_{pa}.

Simulated SSB and yield at equilibrium depend mostly on the time span used to fit the recruitment model, of next importance being the choice of the inflection point defining the SSB below which there is a relationship between SSB and recruitment. Assuming low inflection points (or geometric mean recruitment) creates in multispecies simulations increasing yield curves with F, which is counter-intuitive and is also not the case in multispecies simulations using stock-recruitment relationships with higher inflection points. Choosing different stomach content data, representing periods of high and low cannibalism has only limited impact on the simulation results.

In conclusion, any projection of biomass and yield trajectories requires quantification of the impact of SSB on recruitment. Simulations without having this information may be highly misleading, both on an absolute scale, *i.e.* biomass and yield, but to a lesser extent also on relative scale, *i.e.* the F at which high long-term yield and stable stock size are sustained. The present target F is at the lower end of potential candidates and, thus can be assumed to be robust against these uncertainties, as well as against limited assessment errors and bias.

To optimize fisheries, changes in stock productivity need to be considered when defining harvest control rules, either by constructing time series reflecting similar productive states or by direct inclusion in environmentally sensitive stock-recruitment relationships. The latter would relieve the scientific community and managers from discussing how to adapt our management procedures and goals to shifting regimes, but at present no methodology exists to be applied for the determination of limit and target reference points under shifting environmental conditions.

Acknowledgements

The present study is based on results of the EU FP6, TP 8.8 Specific Targeted Research Project 022717 (UNCOVER), and contributes to the FP6, TP 8.8 Specific Targeted Research Projects 044133 (RECLAIM) and 044227 (IMAGE). Contributions from participants of these projects are acknowledged here. We also acknowledge the helpful comments made by two referees in improving an earlier draft of the manuscript.

References

ALHEIT, J., C. MÖLLMANN, J. DUTZ, G. KORNILOVS, P. LÖWE, V. MOHRHOLZ, and N. WASMUND. 2005. Synchronous ecological regime shifts in the North and Central Baltic Sea in 1987–88. *ICES J. Mar.*, **62**: 1205–1215.

BAGGE, O., E. THUROW, E. STEFFENSEN, and J. BAY. 1994. The Batlic cod. *Dana*, **10**: 1–29.

BECAUSE. MS 2007. Critical interactions between species and their implications for a precautionary fisheries management in a variable environment - a Modelling Approach. Final report EU project SSP8-CT-2003-502482.

CADDY, J. F., and R. MAHON. 1995. Reference points for fisheries management. FAO Fisheries Technical Paper. No. 347. Rome, FAO. 83p.

CASINI, M., J. LOEVGREN, J. HJELM, M. CARDINALE, J.-C. MOLINERO, and G. KORNILOVS. 2008. Multilevel trophic cascades in a heavily exploited open marine ecosystem. *Proc. R. Soc. Lond., Ser. B: Biol. Sci.*, **275** (1644): 1793–1801.

CARDINALE, M., and F. ARRHENIUS. 2000. The influence of stock structure and environmental conditions on the recruitment process of Baltic cod estimated using a generalized additive model. *Can. J. Fish. Aquat. Sci.*, **57**: 2402–2409.

doi:10.1139/cjfas-57-12-2402

COOK, R. M. MS 1998. Glossing over the ICES stocks: some suggested limit values. Working Document to ICES C.M. 1998 / Assess:10.

DIPPNER, J. W., G. KORNILOVS, and L. SIDREVICS. 2000. Long-term variability of mesozooplankton in the Central Baltic Sea. *J. Mar. Sys.*, **25**: 23–32. doi:10.1016/S0924-7963(00)00006-3

EERO, M., F. W. KÖSTER, M. PLIKSHS, and F. THUROW. 2007. Eastern Baltic cod (*Gadus morhua callarias*) stock dynamics: Extending the analytical assessment back to the mid-1940s. *ICES J. Mar. Sci.*, **64**: 1257–1271.

HÄNNINEN, J., I. VUORINEN, and P. HJELT. 2000. Climatic factors in the Atlantic control the oceanographic and ecological changes in the Baltic Sea. *Limnol. Oceanogr.,* **45**: 703–710.

HINRICHSEN, H.-H., C. MÖLLMANN, R. VOSS, F. W. KÖSTER, and G. KORNILOVS. 2002. Biophysical modelling of larval Baltic cod (*Gadus morhua* L) growth and survival. *Can. J. Fish. Aquat. Sci.*, **59**: 1858–1873. doi:10.1139/f02-149

ICES 1997. Report of the Baltic Fisheries Assessment Working Group. ICES CM 1997/Assess:12.

1998a. Report of the Study Group on the Precautionary Approach to Fisheries Management. ICES CM 1998/ Assess:10.

1998b. Report of the Study Group on Management Strategies for Baltic Fish Stocks. ICES CM 1998/ ACFM:11.

1998c. Report of the Baltic Fisheries Assessment Working Group, Copenhagen. ICES CM 1998/ ACFM:16.

2002. Study Group on the Further Development of the Precautionary Approach to Fisheries Management. ICES CM 2002/ACFM: 10.

2003a. Report of the Study Group on the Precautionary Approach to Fisheries Management. ICES CM 2003/ ACFM:09.

2003b. Study Group on Precautionary Reference Points for Advice on Fishery Management. ICES CM 2003/ ACFM:15.

2003c. Study Group on Multispecies Assessment in the Baltic. ICES CM 2003/H:03.

2004. Report of the Study Group on Closed Spawning Areas of Eastern Baltic Cod. ICES CM 2004/ACFM:17.

2005a. Report of the Workshop on the Impact of Zooplankton on Cod Abundance and Production. ICES CM 2005/C:08.

2005b. ICES Advice, book VIII.

2005c. Report of the ad hoc Group on Long Term Advice. ICES CM 2005/ACFM:25.

2005d. Report of the Baltic Fisheries Assessment Working Group. ICES CM 2005/ACFM:19.

2006a. Report of the Workshop on the Decline and Recovery of Cod Stocks throughout the North Atlantic, including trophodynamic effects. ICES CM 2006/OCC:12.

2006b. Report of the Baltic Fisheries Assessment Working Group. ICES CM 2006/ACFM:24.

2006c. Report of the Study Group on Management Strategies. ICES CM 2006/ACFM:15.

2006d. Report of the Study Group on Multispecies Assessment in the Baltic. ICES CM 2006/BCC:07.

2006e. ICES Advice, book IX

2007a. ICES/HELCOM Working Group on Integrated Assessments of the Baltic Sea. ICES CM 2007/BCC:04.

2007b. Report of the Workshop on the Integration of Environmental Information into Fisheries Management Strategies and Advice. ICES CM 2007/ACFM:25.

2007c. Report of the Workshop on Limit and Target Reference Points. ICES CM 2007/ACFM:05.

2007d. ICES Advice, book VIII.

2007e. Report of the ad hoc Group on Sandeel. ICES CM 2007/ACFM:38.

2007f. Report of the Ad Hoc Group on Real Time Management and Harvest Control Rules for Norway Pout in the North Sea and Skagerrak. ICES CM 2007/ACFM:39.

JARRE-TEICHMANN, A., K. WIELAND, B. R. MACKENZIE, H. H. HINRICHSEN, M. PLIKSHS. and E. ARO. 2000. Stock-recruitment relationships for cod (*Gadus morhua callarias* L.) in the central Baltic Sea incorporating environmental variability. *Arch. Fish. Mar. Res.*, **48**: 97–123.

KÖSTER, F. W., and C. MÖLLMANN. 2000. Trophodynamic control by clupeid predators on recruitment success in Baltic cod? *ICES J. Mar.Sci.*, **57**: 310–323. doi:10.1006/jmsc.1999.0528

KÖSTER, F. W., C. MÖLLMANN, S. NEUENFELDT, M. A. ST. JOHN, M. PLIKSHS, and R. VOSS. 2001a. Developing Baltic cod recruitment models. I. Resolving spatial and temporal dynamics of spawning stock and recruitment for cod, herring and sprat. *Can. J. Fish. Aquat. Sci.*, **58**: 1516–1533. doi:10.1139/cjfas-58-8-1516

KÖSTER, F. W, H.-H HINRICHSEN, M. A. ST. JOHN, D. SCHNACK, B. R. MACKENZIE, J. TOMKIEWICZ, and M. PLIKSHS. 2001b. Developing Baltic cod recruitment models. II. Incorporation of environmental variability and species interaction. *Can. J. Fish. Aquat. Sci.,* **58**: 1534–1556. doi:10.1139/cjfas-58-8-1534

KÖSTER, F. W., C. MÖLLMANN, S. NEUENFELDT, M. VINTHER, M. A. ST. JOHN, J. TOMKIEWICZ, R.VOSS, H. H. HINRICHSEN, G. KRAUS, and D. SCHNACK. 2003. Fish stock development in the Central Baltic Sea (1976–2000) in relation to variability in the physical environment. *ICES Mar. Sci. Symp.*, **219**: 294–306.

KÖSTER, F. W., C. MÖLLMANN, J. TOMKIEWICZ, and B. R. MACKENZIE. 2005a. Spawning and life history information for North Atlantic cod stocks – *Baltic. Coop. Res. Rep.*, **274**: 19–32.

KÖSTER, F. W., C. MÖLLMANN, H.-H. HINRICHSEN, J. TOMKIEWICZ, K. WIELAND, G. KRAUS, R. VOSS, B. R. MACKENZIE, D. SCHNACK, A. MAKARCHOUK, M. PLIKSHS, and J. E. BEYER. 2005b. Baltic cod recruitment – the impact of climate and species interaction. *ICES J. Mar. Sci.*, **62**: 1408–1425. doi:10.1016/j.icesjms.2005.05.004

LABLAIKA, I. N., and M. N. LISHEV. 1961. Possibilities of forecasting the distribution of stock and efficiency of fishing for Baltic cod during pre-spawning and spawning periods. ICES CM 1961/Baltic/Belt Sea Committee No. 90.

LEWY, P., and M. VINTHER. 2004. A stochastic age-length-structured multi-species model applied to North Sea stocks. ICES CM 2004/FF:20.

MACKENZIE, B.R., and T. KIØRBOE. 2000. Larval fish feeding and turbulence: a case for the downside. *Limnology and Oceanography*, **45**: 1–10.

MACKENZIE, B.R., H.-H. HINRICHSEN, M. PLIKSHS, K. WIELAND, and A. S. ZEZERA. 2000. Quantifying environmental heterogeneity: habitat size necessary for successful development of cod *Gadus morhua* eggs in the Baltic Sea. *Mar. Ecol. Progr. Ser.*, **193**: 143–156. doi:10.3354/meps193143

MACKENZIE, B. R., H. GISLASON, C. MÖLLMANN, and F. W. KÖSTER. 2007. Impact of 21st century climate change on the Baltic Sea fish community and fisheries. *Global Change Biology*, **13**: 1348–1367. doi:10.1111/j.1365-2486.2007.01369.x

MARSHALL, C. T., L. O'BRIEN, J. TOMKIEWICZ, F. W. KÖSTER, G. KRAUS, G. MARTEINSDOTTIR, M. J. MORGAN, F. SABORIDO-REY, J. L. BLANCHARD, D. SECOR, P. J. WRIGHT, N. V. MUKHINA, and H. BJÖRNSSON. 2003. Developing alternatives indices of reproductive potential for use in fisheries management: case studies for stocks spanning an information gradient. *J. Northw. Atl. Fish. Sci.*, **33**: 161–190. doi:10.2960/J.v33.a8

MATTHÄUS, W., and H. SCHINKE. 1994. Mean atmospheric circulation patterns associated with major Baltic Inflow. *Deutsche Hydrographische Zeitung*, **46**: 321–338. doi:10.1007/BF02226309

MATTHÄUS, W., and G. NAUSCH. 2003. Hydrographic-hydrochemical variability in the Baltic Sea during the 1990s in relation to changes during the 20th century. *ICES Mar. Sci.Symp.*, **219**: 132–143.

MEIER, H.E.M. 2006. Baltic Sea climate in the late 21st century: a dynamical downscaling approach using two global models and two emission scenarios. *Clim. Dyn.,* **27** (1992): 39–68. doi:10.1007/s00382-006-0124-x

MÖLLMANN, C., G. KORNILOVS, M. FETTER, and F. W. KÖSTER. 2004. Feeding ecology of Central Baltic Sea herring and sprat. *J. Fish Biol.*, **65**: 1563–1581. doi:10.1111/j.0022-1112.2004.00566.x

MÖLLMANN, C., B. MÜLLER-KARULIS, G. KORNILOVS, and M. A. ST. JOHN. 2008. Effects of climate and overfishing on zooplankton dynamics and ecosystem structure regime shifts, trophic cascade and feedback loops in a simple ecosystem. *ICES J. Mar. Sci.* (in press). doi:10.1093/icesjms/fsm197

MURAWSKI, S.A., P. J. RAGO, and E. A. TRIPPEL. 2001. Impacts of demographic variation in spawning characteristics on reference points for fishery management. *ICES J. Mar. Sci.,* **58**: 1002–1014. doi:10.1006/jmsc.2001.1097

MYERS, R. A., A. A. ROSENBERG, P. M. MACE, N. BARROWMAN, and V. R. RESTREPO. 1994. In search of thresholds for recruitment overfishing. *ICES J. Mar. Sci.*, **51**: 191–205. doi:10.1006/jmsc.1994.1020

PLIKSHS, M., M. KALEJS, and G. GRAUMAN. MS 1993. The influence of environmental conditions and spawning stock size on the year-class strength of the Eastern Baltic cod. ICES CM 1993/J:22.

PLIKSHS, M., H.-H. HINRICHSEN, F. W. KÖSTER, J. TOMKIEWICZ, and V. Berzins. 1999. Baltic cod reproduction in the Gotland Basin: annual variability and possible causes. ICES CM 1999/Y:31.

SPARHOLT, H. 1994. Fish species interactions in the Baltic Sea. *Dana*, **10**: 131–162.

1996. Causal correlation between recruitment and spawning stock size of central Baltic cod? *ICES J. Mar. Sci.*, **53**: 771–779. doi:10.1006/jmsc.1996.0098

TOMKIEWICZ, J., and F. W. KÖSTER. 1999. Maturation processes and spawning time of cod in the Bornholm Basin of the Baltic Sea: preliminary results. ICES CM 1999/Y:25.

UZARS, D., and M. PLIKSHS. 2000. Cod (*Gadus morhua callarias* L.) cannibalism in the Central Baltic: Interannual variability and influence of recruitment, abundance and distribution. *ICES J. Mar. Sci.*, **57**: 324–329. doi:10.1006/jmsc.1999.0527

VALLIN, L., A. NISSLING, and L. WESTIN. 1999: Potential factors influencing reproductive success of Baltic cod, G*adus morhua*: a review. *Ambio*, **28**: 92–99.

VINTHER M. 2001. Ad hoc multispecies VPA tuning applied for the Baltic and North Sea fish stocks. *ICES J. Mar. Sci.,* **58**: 311–320. doi:10.1006/jmsc.2000.1012