Management Strategy Evaluation framework for the Eastern Baltic cod fishery to test robustness of regulations against environmental variation and fleet response

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Abstract

A spatially-explicit Management Strategy Evaluation (MSE) framework was developed under FLR (Fishery Library in R) for evaluating performance and robustness of management measures. The framework applied to the international Baltic cod fishery tested the 2008 multi-annual management plan for the eastern cod recovery comprising various management measures, environmental regimes and fleet adaptation scenarios. The management measures included TAC control compared to direct and in-direct effort control, the latter being closed areas and seasons. The different environmental scenarios comprise favourable conditions for cod-recruitment induced by frequent inflows of saline and oxygen rich North Sea water into the Baltic Sea compared to stagnation periods without inflows. The fleet model included responses to management covering misreporting, improvement of catching power, capacity adaptation, and fishing effort re-allocation. The MSE framework was calibrated and implemented using international spatially and temporally-disaggregated landings and effort data. The main simulation result was that the adaptive-F approach (2008 EU management plan) will not rebuild the stock in the medium term, unless frequent favourable years for cod recruitment occur. Recovery was delayed under constant low recruitment where only a reduction of effort E to F = 0.3 will initiate recovery. Spatio-temporal closures increased the management plan performance by constraining effort-re-allocation to areas with lower catchability, while direct effort regulation was impaired by improvement of catching power, investments in capacity or spatio-temporal effort reallocation, which lowered the management procedure performance.

Keywords

Baltic cod (*Gadus Morhua*); Effort regulation; Fleet adaptation; FLR (Fishery Library in R); Management Strategy Evaluation (MSE); Multi-annual management plan; Spatio-temporal closures; TAC system.

1. Introduction

The eastern Baltic cod stock is outside safe biological limits (ICES, 2007). A long term management plan was in 2008 introduced to bring the stock back to precautionary levels. In recent years (including 2007) the Baltic cod management is based on a combination of TAC, gear and days-at-sea regulations complemented by closed areas and seasons (EU Commission, 2007). Previous management plans did not have significant effects on stock recovery, partly because these regulations led to unexpected responses of fishermen compensating for the intended reduction of fishing pressure (ICES, 2007). Among these responses are non-compliance with the TAC management, e.g. misreporting of landings, which introduces uncertainty in the stock assessments and, thus, reference points as well as impairing the robustness of the management in general.

A regime shift in the Baltic ecosystem in the early 1990´s (Alheit *et al.,* 2005) created adverse conditions for cod reproduction and exacerbated the poor performance of the current regulations in rebuilding the cod population. Since 2008, a multi-annual management plan has been introduced to recover the stock with an adaptive regulation system (‘adaptive F-approach’) setting effort (E) levels corresponding to a gradual reduction in fishing mortality, F, by 10 % per year until the stock is recovered to precautionary levels (EU Commission, 2007). Additionally, the implementation of the indirect control of E (periodical fishery closures) has been maintained as well as other technical management measures. Furthermore, the new regulation is associated with much higher fishing control efforts since 2007. The rationale behind this strategy was to guide stakeholders with concise decision rules that are consistent with the management objectives and that are applied each year and indexed on the most recent F estimate. The rules can then be converted into an annual percentage increase or decrease in Total Allowable Effort (TAE) or total allowable catches under the TAC system. As one of the first trials management system of an alternative to the widely applied TAC system under the European Community directives, the cod recovery plan is designed to implement both a direct and indirect control on E.

Because of the frequent changes in the management of the Baltic cod fisheries over the last 10-15 years with different types of regulations and management systems implemented consecutively and enforced in parallel, the effects of individual regulations and measures are difficult to evaluate in isolation. A spatially explicit and bio-economic model based on MSE was developed in order to reveal the effects of management on stocks and fisheries in both a biological and economic perspective, in which existing knowledge and new analyses of recent historical developments in both stock and fisheries are combined. The model framework allowed for testing management options in a multi-fleet and possible multi-stock context, including the evaluation of robustness towards changing fishing patterns resulting from adaptive behavior of fishermen. The model computes profit from area- and season-disaggregated revenue on an array of species minus costs of fishing, and in a further step (dependent on social considerations) defining several groups of fishermen responses either to regulations or changes in resource availability.

On this basis, the relative performance and the sensitivity of the F-adaptive approach for Baltic cod recovery to different scenarios of effort regulation compared to the current TAC system were investigated in relation to (i) different environmental conditions for cod recruitment success, (ii) misreporting levels on catches and effort, and (iii) fleet adaptation, in a single scenario-based MSE framework. Potential behavioral side effects of altered management regimes such as non-compliance, efficiency improvement and technological creeping, capacity adjustment, as well as redistribution of E in space (fishing areas) and time (fishing seasons) are particularly addressed in our study.

2. Materials and Methods

The simulation framework comprises three elements to test relative performance and robustness of management options against the possible biological and economic uncertainties in the fisheries system: the Operating Model (OM), the Observation-Error Model (OEM), and the Management Procedure (MP) (Rademeyer *et al.*, 2007): (i) The OM represents alternative plausible hypotheses about stock and fishery dynamics (the simulated ‘underlying true world’), allowing integration of higher level complexity and knowledge than generally used within stock assessments; (ii) The OEM describes how simulated fisheries data are sampled from the OM; and (iii) The MP or management strategy is the combination of the available simulated data, the stock assessment (‘perceived’ stock status) and the management model or Harvest Control Rule (HCR) that generates the management options, such as a target F rate, the TAC or the TAE. An important aspect of MSE is that the management options from the HCR are cycled back into the OM so that their impact is reflected in the simulated stock and fisheries as well as possible fleet adaptations. The OM is split into two sub-components (i) a multi-stock module considering population dynamics by area, and (ii) a multi-fleet module considering heterogenous fishing practices. The management module examines e.g. TAC management or closed areas and seasons. The simulation frame was developed in R (R 2007) and plugged into the FLR platform (‘Fisheries libraries in R’; www.flr-project.org; Kell *et al.*, (2007); www.efimas.org), a software toolbox for fisheries modelling.

2.1 The Operating Model

The relationship between the spatially-disaggregated fishing E and the resulting F is the core of the operating model. The stock-specific area-, season- and age- disaggregated Fs are computed from the partial Fs obtained for each fishing activity (i.e. a combination of a fleet and a gear). A linear relationship is assumed:

$$F_{co,vc,fl,ge,ar,se,sp,ag} = Q_{co,vc,fl,ge,ar,se,sp.ag} \times E_{co,vc,fl,ge,ar,se} \qquad \text{(equ. 1)}$$

The dimensions being ‘co’ for country, ‘vc’ for vessel category, ‘fl’ for fleet, ‘gr’ for gear, ‘ar’ for area, ‘se’ for season, ‘sp’ for species and ‘ag’ for fish age.

The catchability composite term, Q, quantifies factors other than fish availability (abundance) which can impact the catch rates:

$$Q_{co,vc,fl,gr,ar,se,sp,ag} = q_{sp} \times Sel_{gr,sp,ag} \times Sor_{co,vc,fl,sp,ag} \times Pow_{co,vc,fl,gr,sp} \times Mis_{sp} \quad \text{(equ. 2)}$$

‘q’ being a stock-specific calibration factor, ‘Sel’ the selectivity pattern specific to the gear used, ‘Sor’ the sorting ogive, ‘Pow’ the relative catching power of given fleet-segment, and ‘Mis’ the stock-specific mis-reporting factor. The effort allocation model splits the total E into the disaggregated E using effort shares as follows:

$$\begin{aligned} E_{co,vc,fl,gr,ar,se} = {} & Nbv \times COsh \times VCsh_{co} \times FLsh_{co,vc} \times AHFsh_{co,vc} \times \\ & SEsh_{co,vs,fl} \times GRsh_{co,vc,fl,se} \times ARsh_{co,vc,fl,gr,se} \times E_{co,vc,fl,gr,se,vessel} \end{aligned} \quad \text{(equ. 3)}$$

With ‘Nbv’ being the total number of vessels participating in the fishery, ‘COsh’ the country share, ‘VCsh’ the vessel category share (length categories), ‘FLsh’ the fleet share providing a degree of freedom for intermediate fleet typology from the model user choice (e.g. métier), ‘AHFsh’ a multiplicator factor of the initial fleet capacity in case of investement/disinvestment dynamics (Hoff and Frost 2007), ‘SEsh’ the “in activity” share introducing the time dimension, ‘GRsh’ the gear share splitting the E of the fleet into E per gear, ‘ARsh’ the area share introducing the spatial dimension. E in terms of number of vessels is converted into an E in terms of days at sea (in this particular case) using nominal effort per vessel.

The partial fishing mortalities integrate possible differences in i) fishing power between fleets, ii) in fishermen sorting behaviour (discard), iii) in gear selectivity, and iv) in the area-season application of the effort (Nielsen *et al.* (in revision)). Each contribution from the different acting fleets is summed to obtain the area and seasonally disaggregated F:

$$F_{ar,se,sp.ag} = \sum_{co} \sum_{vc} \sum_{fl} \sum_{gr} F_{co,vc,fl,gr,ar,se,ag} \qquad \text{(equ. 4)}$$

The overall stock-specific F can be obtained removing the area and season dimension:

$$F_{se,se,ag} = -\log\left[\sum_{ar} N_{sp,ar,se} \times \exp\left(-F_{sp,ar,se} \Big/ \sum_{ar} N_{sp,ar,se}\right)\right] \qquad \text{(equ. 5)}$$

and then, $F_{sp,ag} = \sum_{se} F_{se,sp,ag}$ (equ. 6)

F is reflected in stock dynamics through the classic exponential decay equation with natural mortality M=0.2 for all fish ages, and age change each 1st of January. From the Baranov equation (Baranov, 1948) catches are computed from the area-disaggregated F. Total catches for the array of species are then distributed between fleets according to their contribution to the total Fs. The economic gross return ‘GR’ is computed from landings ‘L’ using stock-specific fish prices ‘P’ depending on the fish weight ‘W’:

$$GR_{co,vc,fl,gr,ar,se} = \sum_{sp}\left(L_{sp,ag} \times W_{sp.ag} \times P_{sp,gr}\right) \qquad \text{(equ. 7)}$$

The net revenue ‘ NR’, or profit, is computed from the gross return minus (spatial disaggregated) fishing costs. Costs cover variable and fixed costs where costs vary depending on vessel activity (e.g. fuel, ice, maintenance costs) while fixed costs (e.g. crew share, sales costs) are irrespective of activity. In the present context costs per vessel are assumed to be average costs within each fleet segment:

$$\begin{aligned} NR_{co,vc,fl,gr,ar,se} &= GR_{co,vc,fl,gr,ar,se} - \left(VCE_{fl,gr} \times E_{fl.gr}\right) - \left(VCR_{fl.gr} \times GR_{fl,gr}\right) \\ &- FC_{fl.gr} \times CP_{fl,gr,y} \times \left(CP_{fl,gr,y} \big/ CP_{fl,gr,y=0}\right) \end{aligned} \qquad \text{(equ. 8)}$$

where ‘VCE’ and ‘VCR’ are the variable cost functions in relation to E or revenue, respectively, i.e. costs per unit of effort or a percentage of the catch revenue. ‘FC’ is the fixed costs per vessel multiplied by the capacity ‘CP’. FC by year is scaled to the initial capacity (CP at y=0). Various aggregations of the net revenue can be computed accordingly, summing e.g. at the gear level or at the fleet level.

2.2 The Management Procedure (MP)

For the simulated time horizon, a one-year-lag of TAC is modeled following the multi-annual cod management plan. At the beginning of each year, y, a stock assessment is performed from the catch-at-age matrix assuming no observation error from sampling and tuned with population abundance estimates from the previous year's XSA (eXtended Survivors Analysis) assessing the yearly age-disaggregated F and abundance, N, at y-1. Then a Harvest Control Rule (HCR) is applied to decide on the age-disaggregated target F_{y+1} for the coming year, i.e., reduce F by 10 % compared to the year before until $F(4\text{-}7)_{target}$ is 0.3, applying $F_{mult}=0.9$ (ICES, 2007):

$$F_{y+1} = \begin{cases} F_{y-1} \times 0.9 \times 0.9 \quad if \quad F_{y-1} > F_{target} + \varepsilon \\ F_{y-1} \times 1.1 \times 1.1 \quad if \quad F_{y-1} < F_{target} - \varepsilon \\ F_{y-1} \quad if \quad F_{target} - \varepsilon < F_{y-1} < F_{target} + \varepsilon \end{cases} \qquad \text{(equ. 9)}$$

In the next step, a two-year short-term forecast (STF) is performed using the assessed age-disaggregated N(y-1) and two times applying the exploitation pattern of the previous years reduced by 10 % each time. The STF applies an average exploitation pattern S_a on the assessed F at y-1, i.e. $F_{av} = F(4\text{-}7)_{y-1} * S_a$ with S_a computed from the three previous years. In consistence with the HCR, F_{av} is then multiplied by f_{mult} each year. Recruitment is projected using the geometric mean of the 3 previous years recruitment (R_{y-3}; R_{y-4}; R_{y-5}) (ICES, 2007). The age-disaggregated TAC y+1 in number is computed using the TAC equation with the F_{y+1} obtained from the HCR and the N_{y+1} obtained from the STF. This TAC is converted to weight by multiplying with stock mean weigh-at-age and by summing over ages. Additionally, the TAC values are constrained by the HCR to remain within a given interval (+/-15 %) avoiding large annual fluctuations, except if F is larger than 0.6, in which case the TAC may be reduced by more than 15 %:

$$TAC_{y+1} = \sum_a \frac{s_a \overline{F}_{y+1}}{s_a \overline{F}_{y+1} + \overline{M}_a} N_{y+1,a} (1 - e^{-s_a \overline{F}_{y+2} - \overline{M}_a}) \times Wa \qquad \text{(equ. 10)}$$

N_{y+1} is the forecasted abundance by age a, W_a is the weight-at-age, and S_a is the annual selectivity pattern at age defined as:

$$s_a = \frac{\frac{1}{3} \sum_{y=Y-3}^{Y-1} F_{y,a}}{\frac{1}{9} \sum_{a=4}^{7} \sum_{y=Y-3}^{Y-1} F_{y,a}} \qquad \text{(equ. 11)}$$

Finally, the TAC in weight is divided by country to generate national quotas using the historical allocation key between the Baltic countries in agreement with the principle of relative stability (EU commission 2001). The final TAC is calculated removing the expected unofficial landings (ICES 2007) assuming the same level of misreporting across countries.

$$final\, TAC_{y+1} = TAC_{y+1} \times {}^{1}\!\big/_{MIS_{species}} \qquad \text{(equ. 12)}$$

The effort control management is modeled to decide on the Total Allowed fishing Effort (TAE) from one year to the next. The same procedures are used as for the TAC system explained above, however, when a HCR is applied to decide on the target F for y+1, then the TAE at y+1 is calculated using the linear link between E and F (using the assessed overall F_{y-1}):

$$E_{y+1} = \begin{cases} E_{y-1} \times 0.9 \quad if \quad F_{y-1} > F_{target} + \varepsilon \\ E_{y-1} \times 1.1 \quad if \quad F_{y-1} < F_{target} - \varepsilon \\ E_{y-1} \quad if \quad F_{target} - \varepsilon < F_{y-1} < F_{target} + \varepsilon \end{cases} \qquad \text{(equ. 13)}$$

In this HCR under the multi-annual management plan, F for y+1 is reduced by 10% from year y, as long as F>0.3. The F-reduction is translated directly into a reduction of E by 10% from year, y, assuming a constant catchability Q. No misreporting on E is assumed. No allocation key for distributing the TAE between fleets is assumed but rather a homogeneous reduction (or increase) of the partial fleet E across fleets in agreement with the principle of relative stability.

In the MP spatially- and temporally-explicit regulations are modeled specifying seasons, areas, years and fleets affected by the regulations. If a regulation is enforced for specific time period, the initial effort in that area in year y-1 is modified in a way that E is totally removed from closed areas and spatially re-allocated to the other possible fishing areas where the affected fleet fish (i.e. spatial E displacement). The re-allocation of E can be either equally distributed among open areas where the fleet traditionally fish or displaced proportionally to previous area specific CPUE in the traditional fleet fishing areas.

2.3 Fleet adaptation

Scenarios of fleet adaptation behaviour (i.e. structured implementation error) have been evaluated under the TAC regime. In the present single species application of the model, if the TAC is exhausted for a given country, fleets go on fishing and start misreport landings until quota raised by the misreporting factor is exhausted. Long-term TAC-induced E reallocation was tested by simulating investment/disinvestment dynamics (Annex 1).

Scenarios of TAE regulation induced E re-allocation were evaluated by simulation of short-term E displacement towards areas with higher CPUE. Because of a lack of international data the short term switching between demersal and pelagic gears targeting different species in the Baltic Sea could not be investigated. Monotonous improvements in catching power were investigated by increasing annually the power by 5 or 10 % across fleets (Marchal *et al.*, 2001). No distinction was made depending on fleet while smaller vessel size or gill-netters are less subject to invest in new materials than large trawlers (Marchal *et al.*, 2001).

Plausible scenarios of E re-allocation in time and space in response to spatio-temporal closures (indirect effort regulation measures; Nielsen *et al.*, 2006) were investigated at the short-term scale by: (i) a closure-induced uniform spatial re-distribution of E on all the remaining open areas in which the fleet is known to operate, and (ii) similar to (i) except that E is distributed proportionally to the relative area specific CPUE, (iii) equal re-distribution of the E between the remaining open months in given area. In all cases, impacted fleets were assumed to respond in the same way to a given regulation or a change in stock availability.

2.4 Conditioning of the model to the Eastern Baltic Cod stock and fisheries

Spatial and temporal dimensions of the model are flexible but need to be adjusted to the order of magnitude of the suggested spatio-temporal regulations and fleet behaviour feedback i.e. month and ICES square basis (default for which log-book data information is available). The fishery resource availability coefficients (Table 1) reflect the age dis-aggregated abundance pattern over time between the different areas and were obtained from analysing data of the revised ICES BITS survey (ICES WGBIFS 2007; Nielsen *et. al.*, 2001). The decline of Eastern Baltic cod can partly be explained by a change in the Baltic Sea abiotic conditions affecting cod reproductive success (Alheit *et al.*, 2005). Accordingly, ‘favourable’ and ‘adverse’ forcing environments for cod reproduction were identified depending of inflow events of North Sea water to the Baltic Sea. Consequently, two sets of SSB-R relationships depending inflow intensity were modelled as Beverton and Holt equations using data from ICES (2007): $R_y = a \times SSB_{y-1} / (1 + b \times SSB_{y-1})$

'R' being the number of recruits, with a = 1.15 and 2.35, and b = 0.00000519 and 0.00000608 for the adverse and good reproduction environment, respectively. For the default stochastic runs, the probability to get a good recruitment is set to 1 out of 5 years (p = 0.2).

The exploitation model was conditioned with catch at age and effort data from the international Baltic cod fishery (Denmark, Sweden, Latvia, Poland, Germany) extracted from aggregated logbook, sales slip and vessel register data. The missing data from other Baltic countries was completed by calibrating on basis of the ICES WGBFAS (2007) reported landings of the eastern cod stock covering all countries. The effort allocation model was initialised for 2003, i.e. the most recent year where international data were available. Hence, the E and gear (fleet) allocation used in the model is a snapshot used to test the effect of the fishing pattern change on the robustness of the MPs under a fluctuating spatial distribution of the population over the years and under different environmental conditions.

Catchability was decomposed applying Generalized Linear Models (Maunder and Punt, 2004) to model (i) the relative catching power per set of vessels (Table 2), (ii) the fish selectivity per gear (Table 3), and (iii) the sorting or discard behaviour per fishing activity (Table 3). Classes of vessels (fleet-segments) were defined to minimize the computation demand. These classes assume homogeneous features between vessels belonging to the same group. Classes were defined as a combination of country, vessel size and the gear. Country, vessel size, and gear are the maximum aggregation level for integrating the gear-specific selectivity, relative fishing power, and specific cost structure. Accordingly, the landing-effort data were aggregated by area, month, gear used, vessel category, and by country. Totally, 15 fleets belonging to 5 countries and 3 vessel size groups (>12 meter; 12-24 meters; >24 meters) were defined using 4 fishing gears (trawls, gillnets, pair trawls, and others) resulting in 30 fleet-segments. The fleet-specific fishing power was calculated relative to the fishing power of a Danish trawl fleet-segment of medium vessel size. After the calibration to q = 0.0002254 from the official landings, the catchability, Q, was further corrected using a raising factor to take into account misreported landings. This correction ‘Mis’ (in eq. 2) was calibrated to the ICES Working Group estimates of total landings in the 2003 calibration year (ICES, 2007). The stochastic runs draw each year a level of misreporting on catches from a normal probability distribution around the initially used value (mean = 1.76, standard deviation = 0.1).

Cost structure per set of vessels sharing a common activity was available from the Danish Institute of Food Economics (FOI; www.foi.life.ku.dk/English/Statistics/Fisheries). For the other countries, cost structure and dynamics data were not available. Consequently, virtual fleet sizes had to be assumed from the E per month for these countries and as a first approximation, the cost structure from Denmark by vessel size was used. The fish prices were fixed, expressed per gear and calculated from the Danish sales slip data dividing the landings in weight per gear by the values of landings. Revenue computed for each international fleet segment reflects the partial revenue as if the catches were simulated alone without consideration of revenue from catches of other species.

A spatio-temporal management regime for the Baltic cod fishery has been enforced by the EU Commission since 1995. Since January 2005, a MPA network with three fishing closures in the main Eastern Baltic cod spawning areas were enforced under the cod recovery plan (EU 2005; 2006; 2007). The closures were mimicked in the simulations as: (i) closure A, the EC closure proposal to protect spawning zones in the 40G5, 39G5, 38G5, 40G8, 39G9 and 38G9 ICES squares, and (ii) closure B, a realistically-sized seasonal closure of the ICES subdivisions 25, 26 and 27. Both designs apply from the 1st of June to the 31st of September for all fishing activities.

2.5 Simulation design

Simulation runs were split into two parts. (i) A 'historic part' (from 2003 to 2006 both years included) applying the stock dynamics, R, and F from the ICES (2007) assessment used to validate the biological Operating Model, and (ii) a 'projected part' from 2007 and onwards applying the different MPs to be tested as well as the partial area-, time-, and age-disaggregated stock Fs computed from the fleet-specific fishing activities. The simulation used a 15 year time horizon starting from 2003. The performance of the tested management options were evaluated against their relative capability to reach the pre-defined reference points for the Eastern cod stock (Blim = 160 kt, Fpa = 0.6 in ICES ACFM 1997; substainable F =0.3 in EU commission 2007). The robustness against uncertainties is evaluated relatively and qualitatively among scenarios.

3. Results

Under adverse environmental conditions, the TAC system failed to restore the SSB above the pre-defined SSB reference limits within the 15 years time horizon (Figure 1). The MP computed too optimistic short-term forecasts of biomass as a result of most recent high recruitment years leading to a higher TAC than needed to catch the amount corresponding to the targeted fishing mortality at F_{y+1}. As a cascading effect, the targeted F for the coming years is set higher by the HCR and F is trapped at high levels for some years. By contrast, the stock recovered relatively fast under the favourable environmental conditions and TAC system (Figure 1). The random high recruitment scenario performed at an intermediate level. Although based on the S-R relationship for adverse environmental conditions, applying the TAC procedure under this scenario, the upper quartiles of projections reached the reference limits for SSB (SSB ranged from 75 to 275 kt) and the F target of 0.3 (Figure 1). However, the TAC system performance was greatly impacted by a fluctuating level of misreporting on catches (Figure 2) as the simulated final range of the SSB was very large (from 25 to 225 kt).

Under the total (direct) effort regulation system and adverse conditions, the continuous decrease in E driven by the HCR is not sufficient to obtain the SSB reference limits even though the F target of 0.3 is reached (around 90 kt; Figure 3). However, random good recruitment increased the performance of the management system showing a positive recovery trend (between 90 and 190 kt). The lack of uncertainties on the F decrease reflects the continuous E-reduction under a constant catchability assumption over years, since the adaptive F approach in this case did not allow fluctuating E-levels in opposition to the TAC system. The effort system performed better than the TAC system as explained by lower landings, which enabled SSB to recover. Only the landings in the first year of application (i.e. 2007) were greater than the catch restriction set under the TAC system.

Applying a combination of the effort and TAC systems, the trend toward recovery was stronger (Figure 4) as the three upper quartiles of the stochastic runs were exceeding SSB reference limits within the time horizon of the simulations. This positive conjunction effect is partly explained by the lower level in allowable catches in 2007 than simulated under the effort system without catch restriction. Furthermore, the reduction in E over years by the HCR prevented fleet-specific catch quota exhaustion and balanced the effect of too optimistic allowable catches under the TAC system. The effect of uncertainties in misreporting rates on catches scaled the latter result further down as the effort reduction remained the main driver for catch reductions when associated with the TAC system.

The limited robustness of the TAC and the effort control system against fleet responses mitigated their respective performances (Table 4). Although the simulated change in number of active vessels from the investment/disinvestment dynamics led to a final surplus of + 50 % in SSB as some fleets dropped out of the fishery due to a lack of profits, the effort system is sensitive to changes in catching power over time. For example, already a 10 % regular increase in catchabilty over years led to a loss in SSB of around -30 % in the final year under the adverse environment scenario. Further, in our model fleets reduced their E first in areas where their CPUE values were historically low. This leads to a change in spatial fishing patterns when the total E is reduced and decreased the performance of the effort management system by -15 % in SSB in the final simulation year.

Both types of spatio-temporal closure designs tested were not sufficient alone (i.e. without TAC or direct effort control) to reach the predefined management targets. However, both closure designs tested led to positive surplus in SSB and landings in the medium term (Figure 5). The extended design of closing ICES subdivisions 25, 26 and 27 during 4 months each year led to a SSB surplus of about 30 kt and a gain in landings of 12 kt at the end of the simulation period. This gain was continuously increasing under constant favorable recruitment conditions, but starting to decline under the adverse environment scenario because the SSB was declining (Figure 5). The positive effect of the closure on SSB was due to a short-term loss in total landings (the first two years) in comparison to the absence of a closure. The losses in landings could not be compensated during the closure when E was equally re-allocated on the remaining accessible areas (results not shown). Gains in landings during open periods were observed, but this surplus in landings was not sufficient to balance out the losses during the closure periods. In case of directed effort reallocation proportionally to previous CPUE on the open areas, the surplus in SSB was slightly lower (about 33 kt against 35 kt). All in all, the resulting decrease in F from the first year of closure application was due to a changing spatial pattern in F (mainly displacement of E into the western Baltic Sea). When E was not displaced but instead redistributed to the open period within the eastern Baltic Sea, the positive SSB effect of the baseline scenario (i.e. spatial equal redistribution on open areas during the closure) was slightly down-scaled (Table 4) as fleets were able to compensate losses during other periods. Re-allocation of effort in time, however, was not able to completely compensate the positive SSB effect of the closure. The directed reallocation of E into areas of high catchability had only a minor impact on the robustness of the closure effect for both environmental scenarios (e.g. 33 kt in SSB against 35 kt under the adverse conditions; Table 4). This might be explained by the fact that reallocation mainly occurred outside the population area of eastern Baltic cod stock.

The combination of the TAC system with the spatio-temporal closure (design A) increased the robustness of the TAC system as the management objective was reached for both F and SSB (0.21 and 123 kt, respectively; Table 5). This might be explained by the absolute losses in landings because certain fleet-segments were not able to fully use their allocated quotas as an effect of the closures. Total catches were, thus, closer to the hypothetical catch restriction needed to get the targeted level of F at year y. In the mean time, the enhanced recruitment resulting from the SSB protection during the closures had positive effects on long term stock development. The combination of a TAC and direct effort control system plus closures provided the best results of all the scenarios tested, as the inter-quantile range of the stochastic runs (probability of inflow years = 0.2) at the end of the simulation period, is above the lower SSB reference limit while the targeted F was reached within 10 years (Table 5). The time for recovery under this latter combination of regulations is reduced with increased probability for future inflow years (Figure 7).

4. Discussion

The main aim of this study was to provide a spatially explicit and bio-economic simulation tool to disentangle and anticipate the relative effects of different management options for the Eastern Baltic cod and the fisheries. This stock has been managed in the past by a variety of frequently changed regulations. However, MSE tools capable of evaluating the bio-economic performance and robustness of shift in management regime were not developed yet. The present study is designed as a MSE aiming at identifying management strategies robust to various sources of uncertainties (Kell *et al.,* 2007; Rademeyer *et al.,* 2007; Hamon *et al.,* 2007). In agreement with the cod recovery plan (EU Commission 2007) different MPs included in the plan have been investigated, i.e. TAC HCR, Effort HCR and closures. It is the first MSE for this stock and the fisheries testing the robustness of MPs against two major uncertainties in the Baltic Sea system i.e. (i) the environmental effect on cod recruitment success (process error), and (ii) responses of fleets to regulations (implementation error), e.g., misreporting of catches and illegal landings which are emphasized as a critical factor by the EU Commission for the regulation success (EU Commission 2007). Results of the simulations are evaluated against the capability of the performance indicators, i.e., SSB and F, to reach reference limits previously defined in other studies (STECF 2006), i.e., > 160 kt in SSB and a sustainable F of 0.3.

In relation to point (i), the environmental conditions prove to be a dominant factor, as both TAE and TAC regulations failed to drive the biomass to the target reference points (B_{pa}) under continuous adverse environmental conditions. The regulations failed to rapidly rebuild the stock even if F is below the Fpa of 0.6 which underlines the actual insufficient consistency of this reference point for a short-term recovery. The F target of 0.3, however, was reached under the TAE system within 10 years. Although the assumption of constant adverse environmental conditions within the given time horizon may be overly pessimistic, the environmental regime shift in the Baltic Sea associated with low recruitments in recent years, however, implies that long stagnation periods with adverse conditions for cod reproductions may not be exceptional also for the future (MacKenzie *et al.*, 2007). Accordingly, it is necessary to develop reliable environmental indicators for fisheries management and investigate how these can be incorporated most efficiently for the advisory process. Our model study showed that variance of the results would be considerably decreased, if environmental factors are included in the simulations and advice.

In relation to (ii), the TAC is highly sensitive to misreported catches as the stochastic lack of compliance to the TAC we simulated did introduce increasing uncertainty over years leading to very different simulated pathways towards the final stock biomass level. Misreporting on catches is demonstrated to be a strong noise factor (via the uncertainties of landings in the assessment) making the success of the TAC system almost unpredictable with the recent observed high level of non-compliance in this fishery (ICES, 2007). In our base case, the adaptive-F approach was based on a perfect stock assessment using indices directly drawn from the simulated ‘true’ population, assuming no sample error in landings other than misreporting and a constant fishing pattern. However, under real conditions with input being more variable or even biased the TAC system could have performed considerably worse.

A higher performance (probability of reaching the required stock level is high / probability of being in an unacceptable state is low) was demonstrated for the agreed management plan based on a direct effort control system supplemented by a TAC system. The effort HCR (i) is simpler, avoiding the need for short term accurate and a regular stock assessments as the assessed F in the previous year is only used as a signal to decide on the next level of E; (ii) does not need guesses on near future population abundance level; (iii) is also strongly coercive i.e. by no way allowing an increase of (nominal) E unless sustainable F is reached; and finally (iv) assumes no misreporting on E as an effect of an efficient control and enforcement system in practice, e.g. more at sea control effort and/or using satellite surveillance data. Furthermore, as fishermen are allowed to land and sell all legal-sized fish caught in an effort system the incentive to misreport is low. By contrast, the TAC system is much more sensitive to mis-reported landings than the TAE system.

The robustness of the direct effort reduction system is, however, also strongly dependent on the constant fishing pattern assumption. The constant catchability is likely to be violated in a TAE system, particularly if effort is managed in days at sea (nominal E). If allowed days at sea would be most practicable for implementation and enforcement of an effort system in comparison to other effort indicators i.e. engine power, etc. (Shepherd, 2003), the MSE would consequently have to take into account possible changes in the fishing pattern as discussed above.

So far, EU fishery management has mainly been conducted as a stock-based approach, i.e., the total fishing pressure exerted on each stock is deduced from an overall F from the indivisible contribution of all the fishing actors (Wilen *et al.*, 2002). In some cases, the poor performance of the stock-based approach for sustainable stock management led to questioning the underlying assumptions about constant fishing patterns. Innovative approaches have been suggested that better integrate changes in the management systems (EU FP6 CEVIS 2008). For example, including the so-called technological creeping effect (‘race for fish’ with more engine power, etc.) into the simulations, the expected SSB was lowered and stock recovery delayed. The efficiency of the effort (nominal E) reduction is impaired as long as the fleets become more and more efficient and are able to catch a greater amount without a change in E. However, evaluation of changing fishing pattern in a realistic way requires designing a multi-fleet dynamic model with fleet-based scenarios and spatio-temporal effort re-allocation scenarios on fleet basis. Fleet-based management re-centres resource management on fishing fleets including the often neglected economic dimension of fisheries. In our model fishing activity is analyzed as a set of individual economic actors including heterogeneous economic expectations and priorities decomposing the total stock-specific F by set of vessels, fleets or firms i.e. entities with a bio-economic meaning having specific features e.g. geographical range of action, fishing power, effort allocation behavior, etc. As cod is a shared stock between a number of coastal states, a high level of complexity reflects the heterogeneity between the fishing actors and fleets. Further, as the control variable for managers is effort E and not the annual F, the decomposition of the catchability linking E to F is crucial. Usually, the implementation error of the management plan could be added in the MP, but the structure of this error is certainly not simple. Indeed, fleet partial Fs fluctuate over time (and space) when fishing actors opportunistically change fishing activities targeting other species e.g. for economic considerations, and sometimes may even choose to leave the fishery. For this latter aspect, based on their past profits, some simulated fleet-segments chose to disinvest resulting in capacity reduction. The exit of vessels from the fishery is likely to occur under both, the TAC and effort control system as the allowed E per vessel is continuously reduced and, thus, the individual profitability as well. Although it is a pure management decision if the E from leaving vessels should be redistributed to other actors or simply removed, it might from a socio-economic point of view be preferable to establish an effort trade market compensating the economic losses for leaving vessels, but keeping the same level of total E in the system. Nevertheless, the particular case of the Baltic cod recovery plan makes a homogeneous reduction of nominal E across countries and fleets unavoidable as it has been assumed in the present simulations. Further, the risk of re-capitalization in the fishery from possible new entrants due to leaving vessels or stock recovery, should be avoided if a closed licensing system for fishing rights on Baltic cod is maintained.

In addition to overall TAC’s or TAE’s our model could further handle spatio-temporal closures, which explicitly aim at modifying the spatial fishing pattern to prevent parts of the stock from fishing. As such, the displacement of E to areas with lower catchability aims to indirectly reduce the overall standardized E exerted on the stock. The present model is designed to decompose the overall F into fleet/economic components. Area- and time-explicit partial Fs are linked to resource areas to weigh the specific contribution of fleets to the total catches along the spatially- and temporally-structured life cycle of stocks. When assuming a complete compliance of fishermen to the closure, the simulated spatio-temporal closure confirmed that spawning fish were protected during periods and areas, i.e. not caught later. Recruitment was consequently enhanced. The two designs tested, including the currently enforced closures, changed the magnitude of the closure effects, where the extended closure showed a higher positive effect by displacing a larger amount of E. This positive SSB-effect was, however, strongly dependent on the assumption that recruitment solely depends on SSB, while recent studies tend to reject this hypothesis for the Baltic cod (Köster *et al.*, 2005). The recruitment might be rather related to the magnitude and quality of the reproductive volume i.e. the volume of water that allows for successful egg survival and larval development (Nissling *et al.*, 1994; Köster *et al.*, 2005). Species interactions could also be a driver for variations in recruitment (Van Leeuwen *et al.* 2008). In this way, the modular structure of our model allows extending the biological OM with updated data, in particular using a food web model instead of the present single species approach. Further, scenarios testing the effect of possible changes in spatial (spawning) stock abundance pattern, e.g. depending on the forcing environment and/or fish behavior, remain to be investigated.

An investigation of the spatial dimension of the fishery could be of particular importance when harvested populations are overlapping. In this context, the effort control system is often criticized because the effort restriction is only based on catches of one stock or species (ICES, 2008). As a result of by-catch or a change in targeted species according to fishing areas or seasons other stocks could be overexploited in a mixed fishery. Effort re-allocation towards e.g. the western Baltic cod will have major impact on this stock. The simulated closure designs were robust against the tested fleet adaptation scenarios as effort re-allocation (in space or in time) could not entirely balance the closure effects. In our particular case closures partly resulted in effort being reallocated into the western Baltic

Sea, i.e. targeting a different stock. In a similar way, effort uncontrolled reallocation between stocks is likely to occur under a pure direct effort system e.g. if no area restriction for exerting the effort is defined. In the latter case, the agreed plan maintaining catch restriction per stock per area should prevent fleets to fish closer to their designated harbor. These implications should be further investigated in the multi-stock implementation of the model.

Effort reallocation scenarios have been tested dependent on the CPUE in fleet specific areas. The profit that fleets expect from open areas could likely drive more the E reallocation rather than catchability criteria alone (Hilborn 2007). In that case, sophisticated decision choice models such as Random Utility Models (Holland and Sutinen 1999; Salas and Gaertner 2004) may be methods of choice to re-distribute the E based e.g. on the knowledge of fleet specific cost structures (e.g. fuel costs, etc.). Different responses to the same regulation could further co-exist and fishermen response groups might be identified based on economic or social behaviour features (Castillo and Saysel 2005; Christensen and Raakjær 2006). Cost structure data and dynamics per fleet are by nature difficult to obtain due to their confidentially and could not be obtained for other countries than Denmark in the present study. Testing heterogeneous response would also require socio-economic data which were similarly not available for this study. Consequently, all fleets were assumed to act in the same way in response to a given regulation or a change in stock availability. Hence, one should keep in mind that the here demonstrated bio-economic positive effect of the spatio-temporal closure might be balanced out if fleets chose to increase their E in order to meet increased fishing costs. This latter scenario would particularly be possible under a TAC regulated fishery. The effort control would not be so affected by this side-effect as no increase of E is allowed by the HCR. Hence, the combination of the spatio-temporal closure with the direct effort control instead of the TAC system decided in the management plan could eventually preserve the closure effect in the overall MP.

Bio-economic data has been used and simulated forward in time in the present study to evaluate the short-term as well as the long-term effort re-allocation (side-) effect on stock development in response to regulations depending on spatially-explicit and heterogeneous fleet-specific economic features. Furthermore, the model can comprehend economic determined fleet capacity change via investment/disinvestment dynamics (see also Annex A). Given the limitations and un-certainty in available economic input data the results can not be used for predictions in the present context. However, in a socio-economic perspective, the ambition of such a simulation tool is to fully evaluate the economic efficiency of scenarios. The established model can support such bio-economic analysis of management regimes based on fleet economic indicators when further data is made available, i.e., to evaluate the capacity of regulations to drive the multi-fleet fishing activity and capacity toward individual and/or global socio-economic targets.

Annex A

The AHF-model (Hoff and Frost, 2007) suggests a function to model capacity change via investment/disinvestment dynamics which is reused in the present model in a simplified way. Following, at a yearly time scale, at the beginning of the year, the capacity of a fleet is adjusted according to an investment decision function. The capacity change in the current year, taking LAG years before the current year, is a function of the projected average profit PR through LGT+1 year, which is given by:

$$\overline{PR}_{fl,y} = \left(\frac{1}{LGT_{fl}+1} \sum_{i=0}^{LGT} NR_{(y-1)-LAG-i} \right) \times \frac{\left(1-(1+r)^{-LT}\right)}{r}$$

with the right second term being the discounting of the average future revenues, with NR the net revenue, r being the interest rate, LT being the expected lifetime of a vessel and the subscripts y for year and fl for fleet. Then, the investment decision function to model the capacity C change is given by:

$$C_{fl,y} = \begin{cases} \dfrac{I^{+} \times \overline{PR}_{fl,y}}{V_{IN}} \\ \dfrac{I^{-} \times \overline{PR}_{fl,y}}{V_{OUT}} \end{cases}$$

With I^+ and I^- constituting parts of the profit dedicated to the investment or disinvestment, respectively, and with V_{IN} and V_{OUT} being the price of entry (i.e. price for a new vessel) and exit, respectively.

Acknowledgements

This work has been made through cooperation between the EU-FP6-502516-EFIMAS Project, the EU-FP6-022686-CEVIS projects, and the Danish National DFFE-Sustainability Package-Project (Effort Regulation in the Baltic Sea), Danish Ministry of Food, Agriculture and Fishery. The work does not necessarily reflect their views and in no way anticipates the EU Commission's and the Ministry’s future policy in this area. We would like to thank Per J. Sparre and Keith Brander DTU-Aqua, Hans Lassen, ICES Secretariat, and Ayoe Hoff and Hans Frost, FOI, University of Copenhagen for commenting on the study.

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Figures Captions

Figure 1. Under the TAC management, simulated recruitment R, Spawning Stock Biomass (SSB), landings (L), and average fishing mortality, F, from age 4 to 7 (F4-7) with stochastic environmental pre-conditions (Box and Whiskey plot; N=30; 1 favourable year out of 5 years), or constant adverse conditions (dotted line), or constant favourable conditions (solid line). The SSB sustainability reference levels Bpa and Blim (ICES WGBFAS, 2007) are indicated in the second window as well. The inner histograms enable visual inspection of the shape of the distributions of the N simulations (y-axis) for respectively the R, SSB, L and F (x-axis) in the final year (i.e. in 2016).

Figure 2. The same as figure 1 but with stochastic misreporting on landings from a normal probability density function (mean =1.76; sd=0.1).

Figure 3. The same as figure 1 but under the direct effort control management (TAE) instead of TAC.

Figure 4. Same as figure 2 but under the TAE and the TAC management combined.

Figure 5. Simulated R, and L, and SSB (in weight) under the spatio-temporal closure MP with the following combinations from the top left to the bottom right: A-ADV-ABS and A-ADV-REL; B-ADV-ABS and B-ADV-REL, A-FAV-ABS and A-FAV-REL, A-FAV-ABS-TAC and A-FAV-REL-TAC, with ‘A’ and ‘B’ being the closure design, ‘ADV’ and ‘FAV’ being under the adverse and favorable conditions, respectively, and ‘ABS’ and

‘REL’ being absolute or relative to the baseline scenario. The term ‘TAC’ is when the TAC management is active. In this latter case, the baseline scenario is the F status quo for the simulation without ‘TAC’

Figure 6. Under the reallocation scenario on the higher catchability areas the spatio-temporal closure effect (closure design A) on fleet total effort distribution in gain/loss term relative to the no management scenario is mapped in the closure period June to September in the final year (black circle: gain; grey circle: loss in days at sea).

Figure 7. Probability that simulated SSB is above the Blim threshold (Blim = 160kt) for the agreed management plan (i.e. a combination of TAE and TAC regulations, and closure A) assuming equal effort redistribution, and under different environmental scenarios (i.e. probability of inflow years of 0.2, 0.4 and 0.6 respectively; N=30).

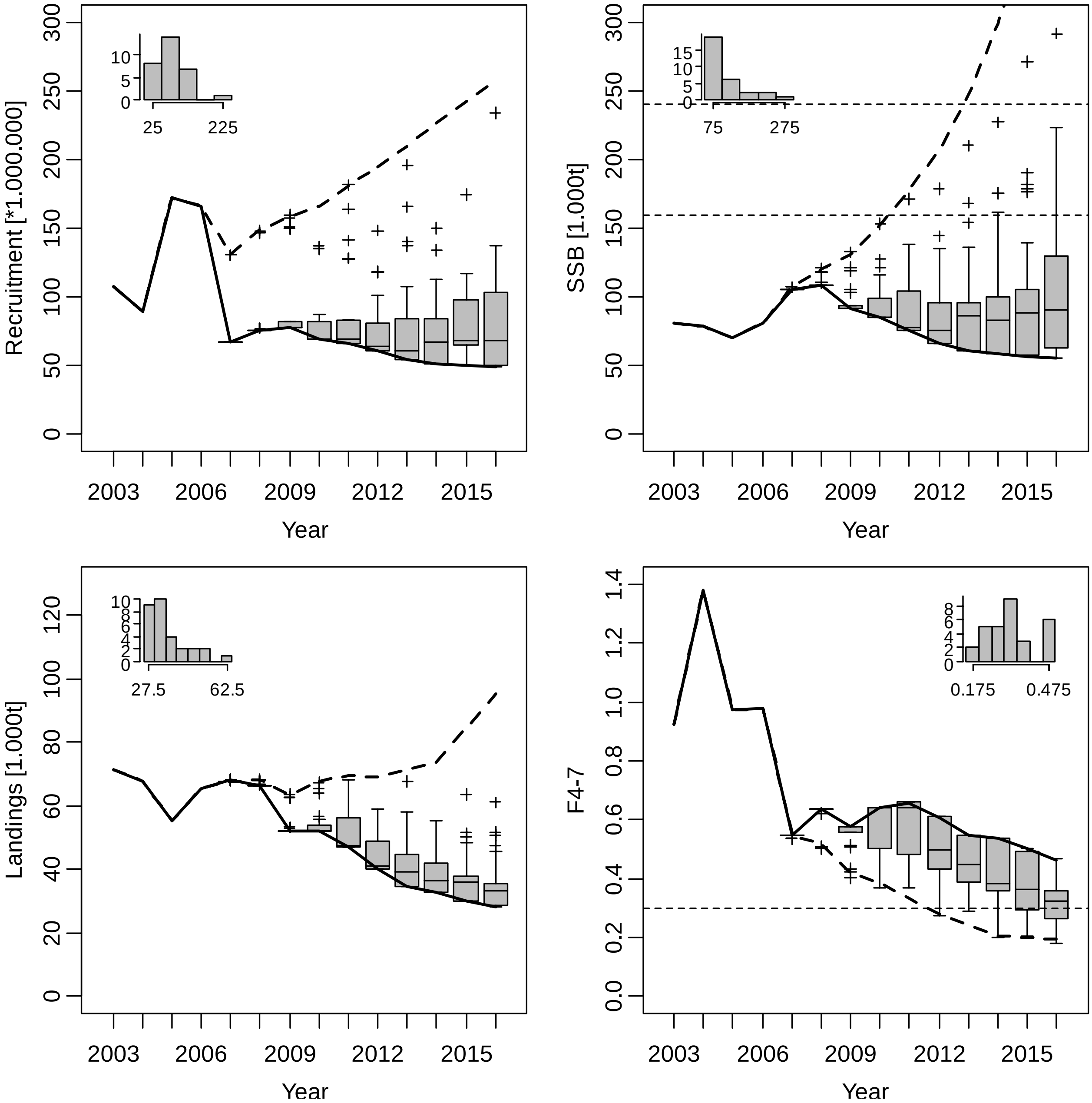

Recruitment [*1.000.000]
0
50
100
150
200
250
300
10
5
0
25
225
2003
2006
2009
2012
2015
Year
SSB [1.000t]
0
50
100
150
200
250
300
15
10
5
0
75
275
2003
2006
2009
2012
2015
Year
Landings [1.000t]
0
20
40
60
80
100
120
10
8
6
4
2
0
27.5
62.5
2003
2006
2009
2012
2015
Year
F4-7
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
8
6
4
2
0
0.175
0.475
2003
2006
2009
2012
2015
Year

Figure. 1.

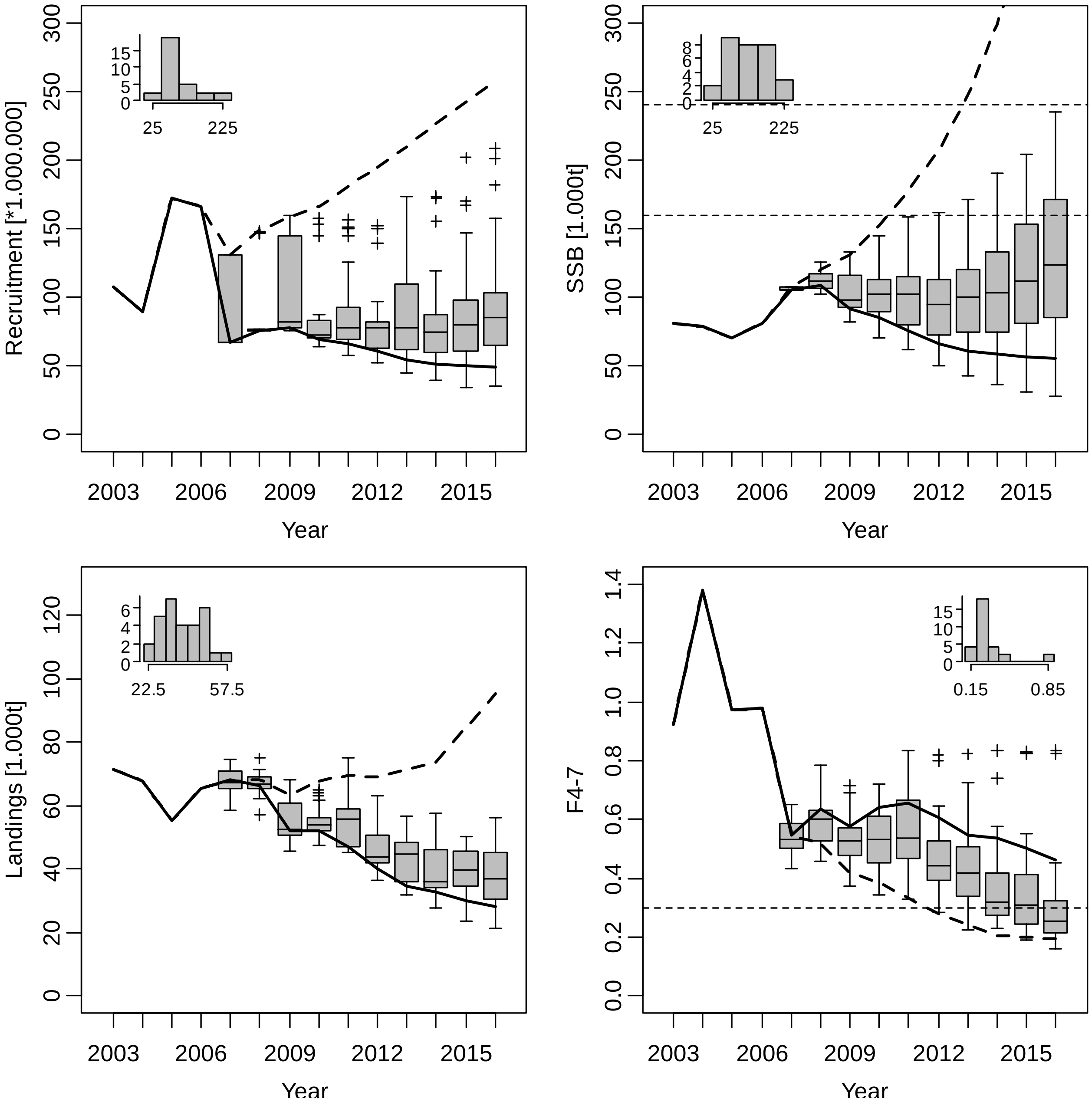
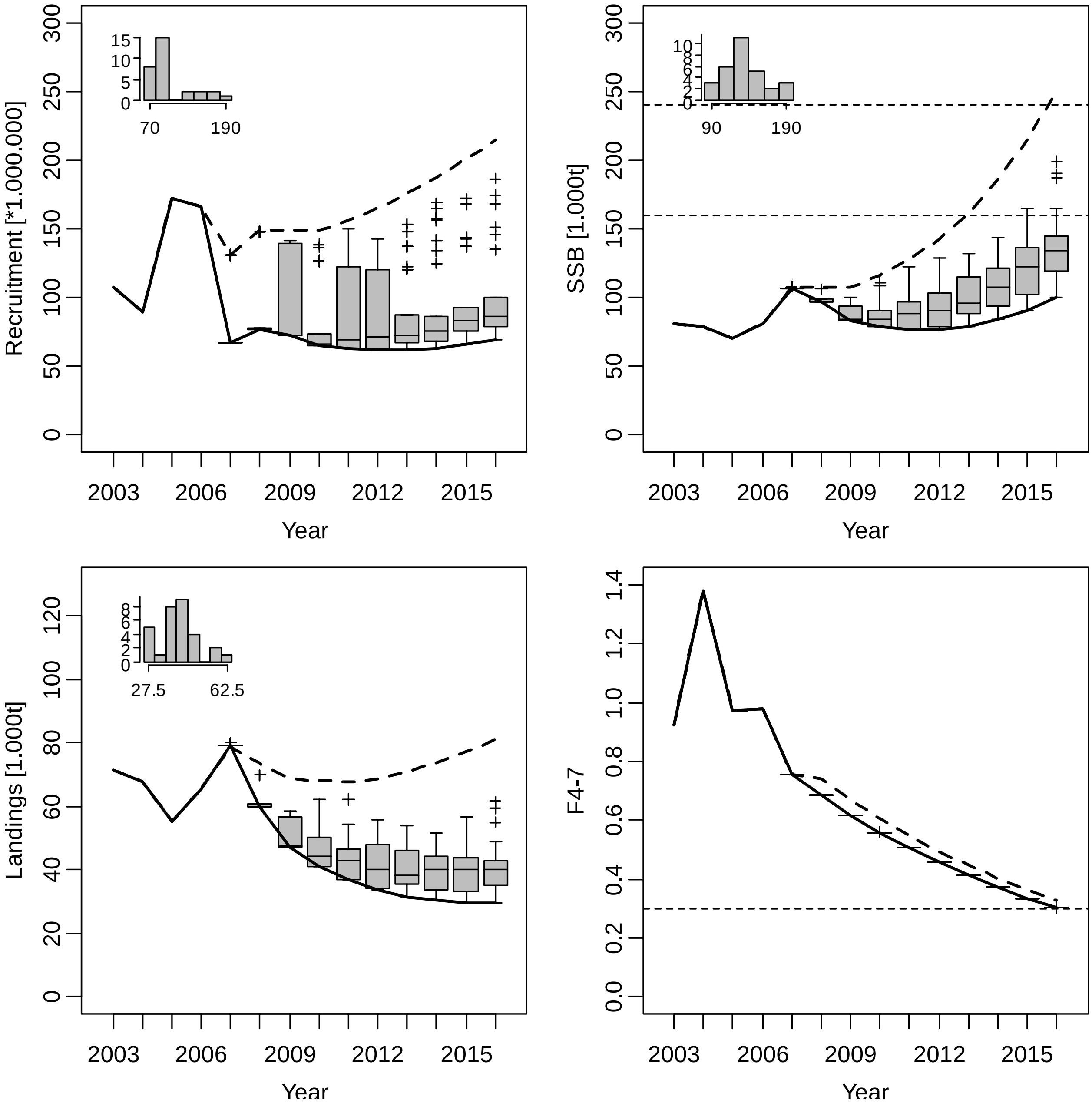

Recruitment [*1.000.000]
0
50
100
150
200
250
300
15
10
5
0
25
225
2003
2006
2009
2012
2015
Year
SSB [1.000t]
0
50
100
150
200
250
300
8
6
4
2
0
25
225
2003
2006
2009
2012
2015
Year
Landings [1.000t]
0
20
40
60
80
100
120
6
4
2
0
22.5
57.5
2003
2006
2009
2012
2015
Year
F4-7
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
15
10
5
0
0.15
0.85
2003
2006
2009
2012
2015
Year

Figure 2.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SSB [1.000t]
Landings [1.000t]
F4-7
Year
2003
2006
2009
2012
2015
0
50
100
150
200
250
300
15
10
5
0
70
190
10
8
6
4
2
0
90
190
20
40
60
80
100
120
8
6
4
2
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0.4
0.6
0.8
1.0
1.2
1.4

Figure 3.

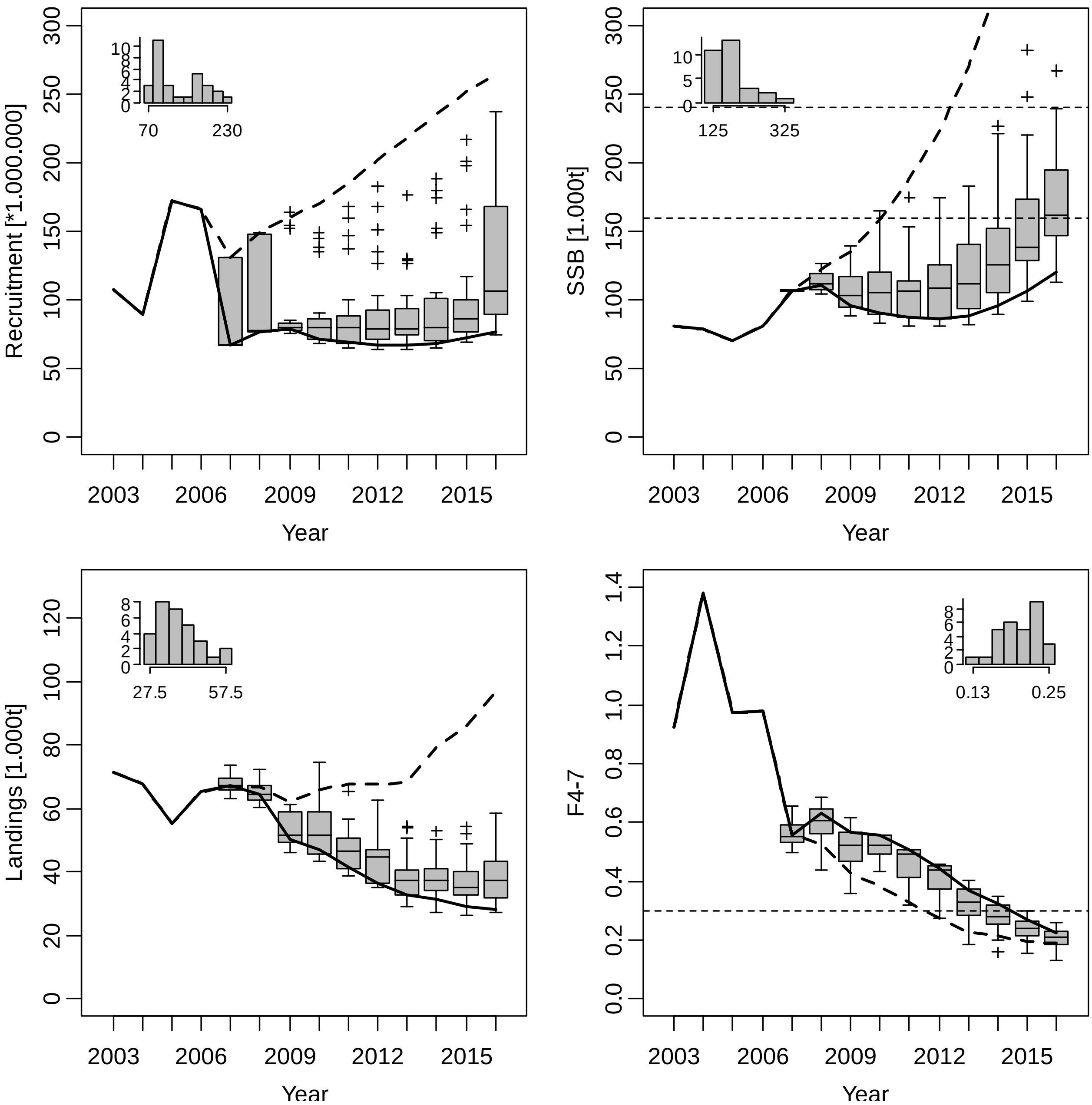
Recruitment [*1.000.000]
0
50
100
150
200
250
300
10
8
6
4
2
0
70
230
2003
2006
2009
2012
2015
Year
SSB [1.000t]
0
50
100
150
200
250
300
10
5
0
125
325
2003
2006
2009
2012
2015
Year
Landings [1.000t]
0
20
40
60
80
100
120
8
6
4
2
0
27.5
57.5
2003
2006
2009
2012
2015
Year
F4-7
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
8
6
4
2
0
0.13
0.25
2003
2006
2009
2012
2015
Year

Figure 4.

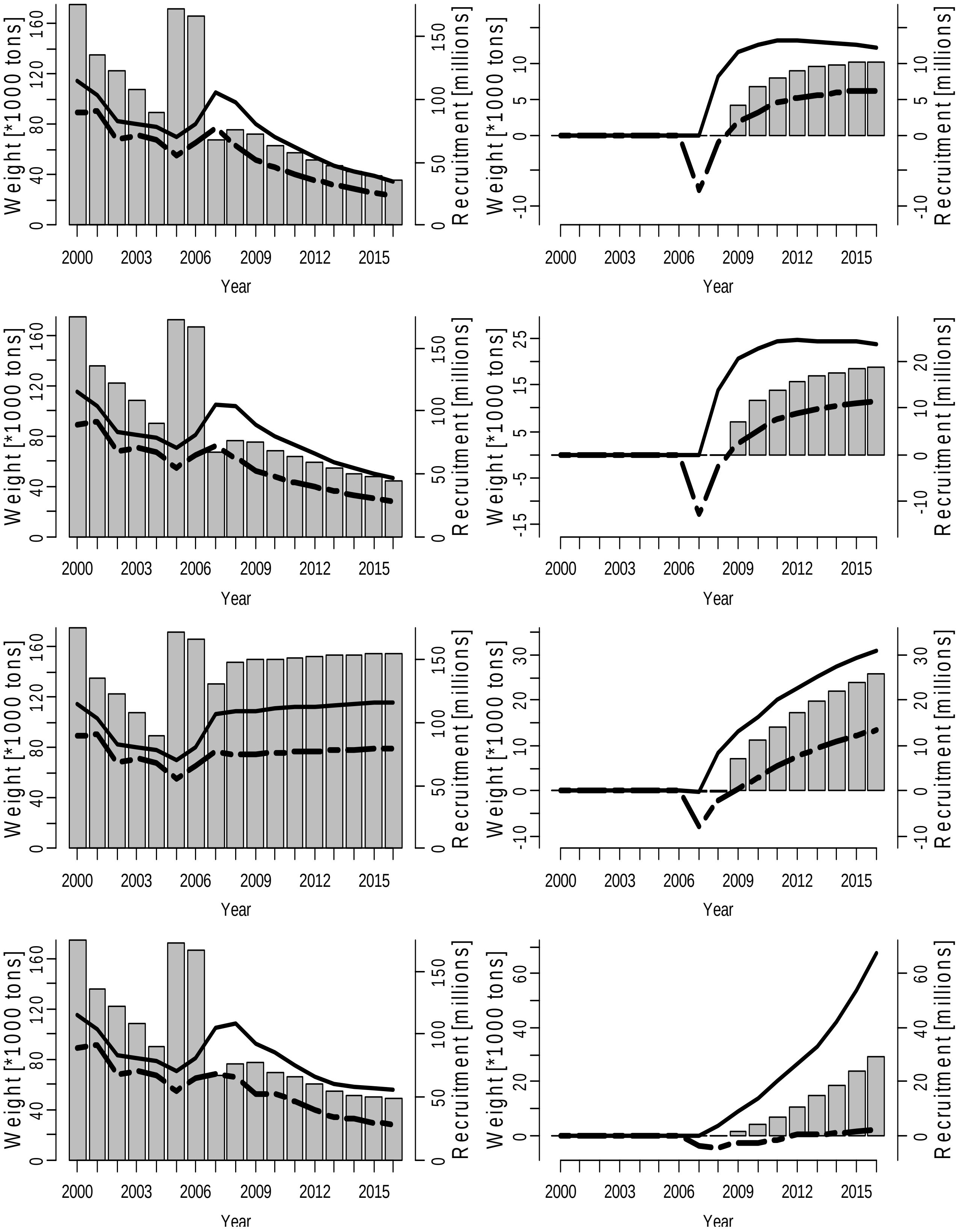
Weight [*1000 tons]
Recruitment [millions]
Year
2000
2003
2006
2009
2012
2015
0
40
80
120
160
50
100
150
-10
-5
5
10
15
20
25
30
60

Figure 5.

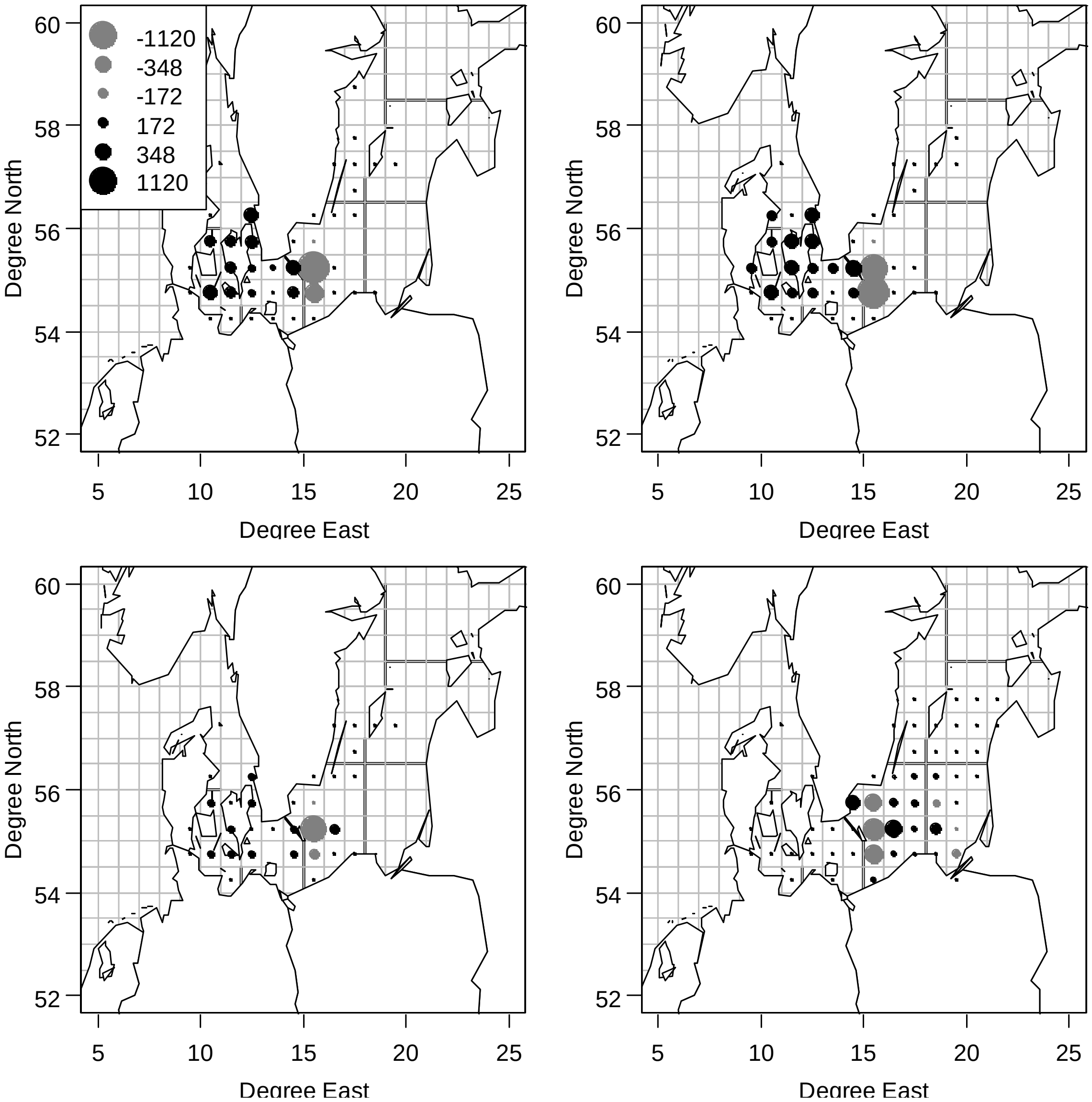
-1120
-348
-172
172
348
1120
60
58
56
54
52
Degree North
5
10
15
20
25
Degree East

Figure 6

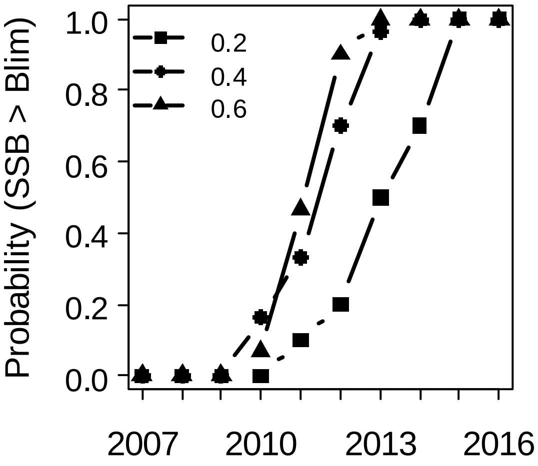
Probability (SSB > Blim)
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
2007
2010
2013
2016

Figure 7.

Table 1. Cod availability distribution in the Eastern Baltic Sea (ICES subdivisions 25-32) in terms of relative fraction (%) per subdivision SD, per quarter Q and per fish age (1 to 8 with age 8 the plus group), from Nielsen *et al.* (*in revision*).

	Age	2	3	4	5	6	7	8+
1st & 2nd Q	SD25	59.69	58.66	66.30	57.69	46.38	42.08	39.09
	SD26	37.60	28.61	24.88	30.08	34.48	45.97	49.38
	SD27	0.16	1.02	0.58	0.26	0.21	0.00	0.00
	SD28	2.55	11.71	8.24	11.96	18.94	11.95	11.52
	Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
3nd & 4th Q	SD25	76.65	41.78	80.97	81.68	91.58	77.91	79.36
	SD26	8.49	14.90	17.32	17.57	7.67	19.01	18.41
	SD27	0.00	0.00	0.02	0.00	0.00	0.00	0.00
	SD28	14.86	43.32	1.68	0.75	0.83	3.08	2.23
	Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 2. Generalized Linear Model (GLM) providing estimates of standardized fishing power per fleet (log-linear model weighted by the numbers of days at sea; log(CPUE) ~ fleet + Quarter : SD) applied on the 2003 logbook data. Fleets are combinations of a country, a vessel size (1: <12m; 2: 12-24m; 3:>24m) and a gear (T: trawl; D: pair trawl; G: gillnet).

Source	Group	Estimate	Std. Error	z value	Pr(>|z|)	Exp(Estimate)
(Intercept)		6.59	0.00	6065.28	0.00	
fleet	Denmark.1.D	-2.45	0.12	-20.19	0.00	0.09
	Denmark.1.G	-2.17	0.00	-1436.45	0.00	0.11
	Denmark.1.other	-0.51	0.00	-179.05	0.00	0.60
	Denmark.2.D	-0.87	0.00	-274.08	0.00	0.42
	Denmark.2.G	-2.06	0.00	-1183.67	0.00	0.13
	Denmark.2.other	0.29	0.00	113.75	0.00	1.33
	Germany.1.T	-1.56	0.03	-57.28	0.00	0.21
	Germany.2.D	0.65	0.03	25.17	0.00	1.91
	Germany.2.G	1.14	0.00	263.49	0.00	3.11
	Germany.2.T	0.55	0.00	432.34	0.00	1.73
	Germany.3.D	0.65	0.03	25.17	0.00	1.91
	Germany.3.T	0.74	0.00	513.48	0.00	2.09
	Latvia.1.G	-1.44	0.07	-19.79	0.00	0.24
	Latvia.2.G	-0.50	0.00	-612.70	0.00	0.61
	Latvia.2.other	-0.80	0.00	-181.76	0.00	0.45
	Latvia.2.T	-0.15	0.00	-110.56	0.00	0.86
	Poland.1.G	-0.99	0.00	-840.24	0.00	0.37
	Poland.1.other	-0.57	0.00	-483.29	0.00	0.56
	Poland.1.T	-0.86	0.02	-47.16	0.00	0.42
	Poland.2.D	-0.29	0.00	-88.73	0.00	0.75
	Poland.2.G	-0.14	0.00	-194.19	0.00	0.87
	Poland.2.other	-0.21	0.00	-197.78	0.00	0.81
	Poland.2.T	0.25	0.00	387.48	0.00	1.28
	Sweden.1.G	-0.94	0.00	-1126.60	0.00	0.39
	Sweden.1.other	-0.78	0.00	-585.29	0.00	0.46
	Sweden.1.T	-1.07	0.00	-321.97	0.00	0.34
	Sweden.2.G	-0.15	0.00	-146.33	0.00	0.86
	Sweden.2.other	-0.09	0.00	-48.27	0.00	0.92
	Sweden.2.T	0.02	0.00	26.06	0.00	1.02
	Denmark.2.T	0.00	0.00	0.00	0.00	1.00
Quarter : SD	Q1 : SD25	0.09	0.00	91.39	0.00	1.10
	Q2 : SD25	0.23	0.00	228.95	0.00	1.26
	Q3 : SD25	0.04	0.00	39.22	0.00	1.04
	Q4 : SD25	0.08	0.00	70.69	0.00	1.08
	Q1 : SD26	-0.17	0.00	-147.61	0.00	0.85
	Q2 : SD26	0.05	0.00	45.13	0.00	1.05
	Q3 : SD26	0.09	0.00	80.49	0.00	1.10
	Q4 : SD26	0.00	0.00	0.00	0.00	1.00

Table 3. Selectivity and discard per gear for the first five fish ages from Nielsen *et al. (In revision)*. The selection is calculated from S1=L50*ln(3)/(L75-L50); S2= S1/L50; Selection=1/1+exp(S1-S2*length)). The discard is calculated from L50 and L25 and discard=1-1/(1+exp(((L25*ln(3)) / (L50-L25))- (log(3)/(L50-L25))*length)). Average fish length corresponding to each age is deduced from the inversed Von Bertalanffy growth function using Linf=187.550, K=0.064 and t0=-1.086

		L25	*L50*	*S1*	*S2*		*selection (%)*				
						age (year)	*1.50*	*2.50*	*3.50*	*4.50*	*5.50*
						length (cm)	*28.60*	*38.46*	*47.70*	*56.37*	*64.50*
selectivity	Gillnet (G)			37.9937	0.9155		0.00	5.83	99.66	100.00	100.00
	Trawl (T)			14.8656	0.3433		0.64	15.95	81.92	98.89	99.93
	Pair trawl (D)			23.5652	0.5493		0.04	8.03	93.33	99.94	100.00
	others			38	0.9		0.00	3.28	99.29	100.00	100.00
discards	Gillnet (G)	39.099	38.853				0.00	5.48	100.00	100.00	100.00
	Trawl (T)	38.439	37.962				0.00	51.30	100.00	100.00	100.00
	Pair trawl (D)	38.439	37.962				0.00	51.30	100.00	100.00	100.00
	others	38.439	37.962				0.00	51.30	100.00	100.00	100.00

Table 4. Simulated indicator values for the final year (i.e. in 2016) for the SSB and F(4-7) for different combinations of management options (TAC, TAE, and Spatio-temporal closure design A), forcing environment context, and the tested fleet response to the regulation

simulation conditionning			indicators at the time horizon	
management option	environment context	fleet adaptation	SSB	F(4-7)
-	adverse	-	22 985	0.83
TAC	adverse	-	56 154	0.47
TAC	adverse	investment/disinvestment	84 245	0.23
TAE	adverse	-	99 923	0.30
TAE	adverse	5% regular increase in catching power	77 040	0.34
TAE	adverse	10% regular increase in catching power	69 215	0.36
TAE	adverse	remove first on lowest catchability areas	85 801	0.33
closure A	adverse	equal reallocation	35 251	0.72
closure A	adverse	reallocation on highest catchability areas	32 733	0.74
closure A	adverse	equal time reallocation of the effort cut	31 102	0.74
-	favourable	-	85 152	0.83
TAC	favourable	-	420 043	0.19
TAE	favourable	-	250 160	0.33
TAE	favourable	remove first on lowest catchability areas	250 161	0.33
closure A	favourable	equal reallocation	115 985	0.72
closure A	favourable	reallocation on highest catchability areas	109 927	0.74
closure A	favourable	equal time reallocation of the effort cut	105 635	0.74

Table 5. Simulated indicator values for the final year (i.e. in 2016) for the SSB and F(4-7) for different combinations of management options under the adverse environmental conditions. (*) is the inter-quantile range.

simulation conditionning			indicators at the time horizon	
management option	environment context	fleet adaptation	SSB	F(4-7)
-	adverse	-	22 985	0.83
TAC	adverse	-	56 153	0.46
TAE	adverse	-	99 923	0.30
closure A	adverse	equal reallocation	35 250	0.72
TAC + closure A	adverse	equal reallocation	123 638	0.21
TAE + closure A	adverse	equal reallocation	117 170	0.28
TAC + TAE + closure A	stochastic	equal reallocation	[216 644 ; 270 788]*	[0.15 ; 0.18]*