What difference does it make? Age structure, gear selectivity, stochastic recruitment, and economic vs. MSY objectives in the Baltic cod fishery

Olli Tahvonen[a], Martin F. Quaas[b], Rüdiger Voss[b]
[a] Dept. of Economics, Dept. of Forest Sciences, University of Helsinki
[b] Dept. of Economics, University of Kiel

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Abstract

We quantify an age-structured optimization model for Baltic cod using data on population dynamics, fish market demand, and harvesting technology. Recruitment of Baltic cod is influenced by the irregular inflow of oxygen-rich water from the North Sea, and ecologists suggest maintaining older age classes that have higher egg survivability under adverse environmental conditions. We show that catch is maximized if harvest could be targeted solely to the oldest age class. However, given the existing gear, catch maximization leads to major economic losses and pulse fishing. The economic solution is a transition toward a steady state with smooth catch and high economic surplus. In sharp contrast to these large differences between the economic and various MSY equilibria revealed by the age-structured model, the classic biomass model for Baltic cod suggests that the difference is unimportant. The stochastic occurrence of favorable environmental conditions implies a threefold increase in recruitment, but the difference between stochastically optimized harvest and the deterministic feedback solution is negligible.

Keywords: age-structured models; optimal harvesting; MSY; stochastic fishery; stochastic programing

JEL classification: Q20, Q22

1 Introduction

Baltic cod is the most valuable fish species in the Baltic Sea, and the cod fishery has offered livelihood to a large proportion of fishermen in the region. In 1980s the cod stock reached its historical record, and 22% of global cod catches were obtained from the Baltic Sea. One consequence of this economic contribution is the availability of exceptionally abundant scientific knowledge on various ecological features of the Baltic cod population along with fishing technology. Baltic cod is characterized by strong variability in recruitment that is dependent on irregular inflow events of North Sea water. During adverse conditions egg survivability is highest among eggs of old females. This has led ecologists to conjecture that maintaining old age classes of the population is important especially for this particular fishery (e.g. Cardinale and Arrhenius 2011). We analyze the economics of Baltic cod and the ecologists' conjecture applying a stochastic age-structured optimization model. Our analysis will challenge established knowledge in resource economics with implications beyond this particular fishery.

The ecologists' conjecture is more or less based on aiming for Maximum Sustainable Yield (MSY) or similar models without economic features (Köster 2009). This is consistent with the fisheries policy of the European Union and the management of the Baltic cod fishery that have committed to the MSY policy (EU 2013)[1]. We analyze how MSY policy serves for maintaining the old age classes and the associated economic consequences. In addition to the important role in actual fisheries management worldwide, MSY is a central concept in economic and ecological studies on fisheries. In his survey Wilen (2000) concludes that while the dispute between MSY and economic optimum has long historical background, the practical difference between the resulting equilibria is often small and unimportant. A somewhat different view is included in a discussion of whether economic steady states represent a "win-win" outcome compared to MSY in producing

[1]European Union has accepted the United Nations Convention on the Law of the Sea, where coastal state fisheries are agreed to restore and maintain fish stocks producing MSY (UNCLOS, Article 61, 3)

both higher economic surplus and fish stocks. Grafton et al. (2007, 2010) present empirical examples where economically optimal populations exceed the MSY. These results are criticized by Clark et al. (2010a,b), who emphasize that economic optimum may well imply stock sizes below MSY and even extinction. This debate is based on biomass models (or a one-period delayed structure in Grafton et al. 2007). In analyzing these questions we contrast the biomass model vis-à-vis an empirically quantified stochastic age-structured framework.

Our model for Baltic cod optimizes total harvest and mesh size of trawl gear, and we estimate functions for nonlinear demand and stock-dependent harvesting costs. We quantify gear selectivity based on experimental data of the retention rates of Baltic cod in trawl nets. We show that three possibilities exist for defining the MSY outcome in this detailed age-structured setup, and in the case of Baltic cod they turn out to be either unattainable with existing gear, or without practical relevance, as they imply major economic losses: MSY is obtained with a very large mesh size – to target only the largest age class – combined with very large fishing effort. By contrast, applying the biomass model to this same fishery, the MSY versus economic outcome dispute appears to some extent similar as in the discussions of Grafton et al. (2007) and Clark et al. (2010a,b), but unimportant in quantitative terms – in line with Wilen (2000). Additionally, we find that with zero interest rate, and despite a stock-dependent harvesting cost, the economically optimal steady-state stock size of the age-structured population is smaller than the MSY stock size. The reason is that it is economically optimal to choose a somewhat smaller mesh size and less fishing effort, which reduces the population level, compared to MSY, where the attempt is to caught the oldest fish. This outcome cannot be understood in the biomass framework. The keys behind these results are the age-class structure and trawl mesh size as decision variables together with total harvest (or effort).

Environmental stochasticity is inherent in fisheries, but the understanding of its effects is more or less limited to models where details are reduced to the minimum. This has been a reasonable strategy for obtaining analytical results. In this vein, Reed (1979), Pindyck (1984), Sethi et al. (2005), McGough et al. (2009), Kapaun and Quaas (2013), and others analyze stochastic fisheries within the biomass models. By contrast, Getz and Haight (1989) discuss a stochastic fishery in the context of age-structured models. They emphasize that stochasticity is most strongly expressed among newborns. In biomass models environmental stochasticity causes variability of the entire biomass without possibilities for further fine-graining. In the case of Baltic cod the available ecological knowledge shows that stochasticity affects recruitment in a specific way that is not possible to analyze without including population internal structure.

There are very few stochastic studies with a detailed population structure. Costello et al. (1998) study the effects of El Niño events on a three age classes coho salmon fishery and the value of information of improved El Niño forecasts. The El Niño events are discretized to three phases (normal, weak, and strong) with the associated probabilities and development scenarios. Computation based on planning horizons of four and eight years and certainty equivalence principle approximates the stochastic solution. Holden and Conrad (2015) add stochasticity to a model with juvenile, immature, and adult stage classes. Stochasticity affects survivability at all stages. Harvest can be targeted to immatures or adults. Stochasticity is shown to increase or decrease the harvest, depending on the recruitment function. Grafton et al. (2007) use a stochastic one-period delayed-difference model, but do not report how stochasticity is specified, or its effects on harvesting.

Environmental variability affects Baltic cod egg survivability via ambient oxygen conditions determined by irregular inflow events of North Sea water (cf. El Niño in Costello et al. 1998). The magnitude of this effect depends on the age of the spawning females (Hinrichsen et al. 2016) and adverse effects are strongest among the eggs of young females. We include this effect by an age class-specific egg survivability that depends on environmental conditions. The nature of stochasticity and available data allow us to specify stochasticity as a two-stage Bernoulli process. Given this setup we apply stochastic programing that transforms the problem into a high dimensional nonlinear programing problem. Compared to dynamic programing the strength of this method is the avoidance of the “curse of dimensionality”. Its downside – the necessity of applying rather short planning horizons – turns out to be of minor importance for the problem at hand.

Given the actual 2013 population size as the initial state and for discount rates of 0–15%, the optimal 2013 harvest based on stochastic optimization is lower than harvest based on expected egg survivability, but the difference is only 2.2% or smaller. A similar result is obtained for other initial states as well. Computing stochastic solution over time shows that while a high egg survivability event triples recruitment, the variation in harvest is only 25%, and that the stochastic solution can be approximated for this model by the certainty equivalence solution with high accuracy.

Tahvonen (2009a,b) recognizes that in age-structured models MSY becomes dependent on harvesting technology, but our model with optimized mesh size and empirical detailed structure progresses from these theoretical findings by quantifying the effects for an empirically relevant case. While the importance of optimizing mesh size in age-structured models is emphasized in Diekert et al. (2010a,b) and Quaas et al. (2013), their models are deterministic and MSY is not analyzed. The stochasticity in our model has some similarities with the formulation in Costello et al. (1998), but we are able to compare the stochastically optimal solution with the solution based on certainty equivalence. Our model is not based on perfect selectivity, as the model by Holden and Conrad (2015), but rather on empirical estimates of actual gear selectivity, and it includes a very different, empirically grounded, specification of stochasticity. We additionally include estimated decreasing demand and stock-dependent harvesting cost while their model is linear in harvest and without cost. As such our model includes realism not typically present in stochastic fishery models, which are traditionally linear in harvest and have constant escapement as the optimal solution.

2 The stochastic age-structured problem

Let a stochastic variable denoting the state of environmental conditions in the sea (temperature, salinity, oxygen concentration) follow the difference equation

$$z_{t+1} = \hat{z} + \varepsilon_t,\ t = 0,...,T, \quad (1)$$

where $\hat{z}$ denotes average conditions and ε_t are i.i.d. random variables. We assume a Bernoulli process where ε_t can take a “high” or “low” value with probabilities p and $1-p$. The length of the time horizon is $T+1$, implying that the stochasticity can be described with a binomial tree that contains $2^{T+1} \equiv Q$ scenarios with the probabilities $\rho_i,\ i = 1,...,Q$.

The total harvest is denoted by H_{ti} at node it, that is, at period t given one particular scenario i. Assume that U is a single-period function for social utility from total harvest. Let the harvesting cost depend linearly on effort, implying that per period net surplus is given as $U(H_{ti}) - cE_{ti}$, where E_{ti} is effort for scenario i at period t and $c > 0$ is a constant. We assume that total per period harvest is given as

$$H_{ti} = B_{ti}{}^{\chi} E_{ti},\ t = 0,...,T+1,\ i = 1,...,Q,\ , \quad (2)$$

where $0 < \chi \le 1$ is a constant and $B_{ti},\ i = 1,...,Q,\ t = 1,2,...,T$ is “efficient biomass”. It is given as

$$B_{ti} = \sum_{s=1}^{n} w_s q_s(\sigma_{ti}) x_{sti},\ t = 0,...,T+1,\ i = 1,...,Q, \quad (3)$$

where w_s is the weight of fish in age class s, $q_s(\sigma_{ti})$ is catchability as a function of mesh size σ_{ti} and x_{sti} is the number of fish in age glass s. Note that when $\chi = 1$ in (2), the harvest per age class is given as a linear function of effort and age-specific biomass (Schaefer 1957). Denoting the discount factor by b we can write the expected net surplus from harvesting as

$$J = \sum_{i=1}^{Q} \rho_i \sum_{t=0}^{T} \left[U(H_{ti}) - cE_{ti}\right] b^t. \quad (4)$$

The numbers of fish in age class 1 depend on stochastically evolving environmental conditions and on the population age size and structure $\mathbf{x}_{ti} = [x_{1ti},...,x_{nti}],\ t = 1,...,T+1,\ i = 1,2,...,Q$, and are given as

$$x_{1,t+1,i} = \varphi(z_{ti}, \mathbf{x}_{ti}), t = 0,...,T,\ i = 1,2,...,Q, \quad (5)$$

where φ is a recruitment function. In (5) the environmental condition affecting node *ti* recruitment is observable from deterministic data at the same period *t* and uncertainty is present at future nodes.

We have specified the model by applying effort as the optimized variable. However, empirical data on total harvest are more reliable than data on effort. We thus eliminate effort and assume that the fraction of biomass harvested from each age class $\hat{h}_{sti}$ equals the fraction of age class-specific efficient biomass on the total efficient biomass and write

$$\frac{\hat{h}_{sti}}{H_{ti}} = \frac{w_s q_s(\sigma_{ti}) x_{sti}}{B_{ti}}, s = 1,...,n, t = 0,...,T,\ i = 1,2,...,Q. \tag{6}$$

This implies that the composition of the total catch in terms of the numbers of fish harvested from different age classes are given as

$$h_{sti} = \hat{h}_{sti} w_s^{-1} = q_s(\sigma_{ti}) x_{sti} H_{ti} B_{ti}^{-1},\ s = 1,...,n, t = 0,...,T, i = 1,...,Q.$$

The development of age classes $s = 2,...,n$ take the form

$$x_{s+1,t+1,i} = \alpha_s \left[x_{sti} - q_s(\sigma_{ti}) x_{sti} H_{ti} B_{ti}^{-1}\right], \tag{7}$$

$$x_{n,t+1,i} = \alpha_{n-1} \left[x_{n-1,ti} - q_{n-1}(\sigma_{ti}) x_{n-1ti} H_{ti} B_{ti}^{-1}\right] + \alpha_n \left[x_{nti} - q_n(\sigma_{ti}) x_{nti} H_{ti} B_{ti}^{-1}\right], \tag{8}$$

for $t = 0,...,T,\ i = 1,...,Q$ and where $\alpha_s,\ s = 2,...,n$ are age class-specific survivability coefficients. Finally, we include the initial state and nonnegativity conditions

$$x_{s01},\ s = 1,...,n,\ given, \tag{9}$$

$$x_{sti} \geq 0, \tag{10}$$

$$H_{ti} \geq 0, t = 0,...,T,\ i = 1,...,Q. \tag{11}$$

$$\underline{\sigma} \leq \sigma_{ti} \leq \bar{\sigma}, \tag{12}$$

for $s = 1,...,n, t = 0,...,T+1, i = 1,...,Q$ and where we include lower and upper bound constraints for the mesh size with $0 < \underline{\sigma}$. Note that in the age-structured framework the Schaefer (1957) harvest function or its extension in (2) requires interior solutions in the sense that the nonnegativity restrictions (10) for the number of fish in different age classes never become binding[2].

After eliminating effort from (4) using (2), the optimization problem is

$$\max_{\{H_{ti},\, s_{ti},\, t=0,\dots,T,\, i=1,\dots,Q\}} J = \sum_{i=1}^{Q} p_i \sum_{t=0}^{T} \left[U(H_{ti}) - cB_{ti}^{-c} H_{ti} \right] b^t \qquad (4')$$

subject to (5), (7), (8), and (10)–(12).

When comparing the economically optimal solutions and MSY we additionally compute solutions based on the perfect selectivity assumption. To obtain these solutions assume

$$H_{ti} = \sum_{s=1}^{n} w_s h_{sti},\ t = 0,\dots,T,\ \ i = 1,\dots,Q,$$

where the number of harvested fish from each age class h_{sti} are taken directly as decision variables. Instead of (4’) the aim is then to maximize

$$J' = \sum_{i=1}^{Q} p_i \sum_{t=0}^{T} U(H_{ti})\, b^t,$$

where U is a linear or strictly concave function.

Stochastic programing has its roots in stochastic linear programing (Dantzig 1955) and in the generalization to nonlinear models (Rockafellar and Wets 1975). The method is used e.g. in financial portfolio problems (Gülpınar et al 2004), dynamic games (Genc et al. 2007), land conversion problems (Messina and Bosetti 2006), and forestry (Tahvonen and Kallio 2006). The essence of the method is that the decision process is non-anticipative, that is, the decisions at any given period and state of the world become independent of the future realization of the random variable. Thus, the decision variables become functions of the system state including the stochastic variable as in stochastic dynamic programing. One strength of stochastic programing is that state variables can be kept continuous. In addition, while the problem of dynamic programing is the “curse of dimensionality”, the number of state variables in stochastic programing is not similarly

[2] This interior solution assumption can be overcome by a complementary slackness formulation (Tahvonen 2009a), but would hardly be tractable in a stochastic context.

limited. However, the limitation is that the problem becomes overwhelmingly large with long horizons. Yet, with discounting the effect of a finite horizon on the first period decision becomes smaller. To obtain a solution that approximates some stochastic realization over longer periods, we apply an iterative procedure where the system state after the first period decision is taken as a new state and the optimization is repeated over some desirable horizon.

We contrast the age-structured model with the solution for a biomass model that describes the same fish stock. The deterministic biomass model is specified as

$$\max_{\{h_t, t=0,\ldots\}} \sum_{t=0}^{\infty} \left[U(H_t) - H_t c(\tau x_t)^{-\chi} \right] \beta^t, \; s.t. \; x_{t+1} = x_t + F(x_t) - H_t, \; x_0 = given, \tag{14}$$

where x_t is total biomass, F is a biomass growth function, χ and τ are parameters, and τx_t approximates the efficient biomass used in the cost function of the age-structured model.

3 Data and parameter estimations

Ecological parameters

The survival rates and weights for the age classes are obtained from ICES 2013 (Appendix, Table 1). According to Hinrichsen et al. (2016), the age structure of the spawning stock plays an important role on egg survivability. Older and larger female cod produce more buoyant, larger eggs (Vallin and Nissling 2000). The larger eggs drift at a shallower depth in the water column and, under adverse environmental conditions, these will constitute the only fraction of egg production that may contribute to recruitment (Hinrichsen et al. 2016). Stochastic inflow events improve environmental conditions for a short time, and hence change the recruitment potential. This effect is mediated via the age structure. We incorporate this effect in a Ricker (1954) type stock-recruitment function:

$$x_{1,t+1,i} = \varphi_0 \left\{ \sum_{s=1}^{n} \left[(1-\xi_{it}) \beta_s^- + \xi_{it} \beta_s^+ \right] \gamma_s w_s x_{sti} \right\} \exp(-\varphi_1 x_{0ti}), \; t = 0,\ldots,T, \; i = 1,\ldots,Q,$$

where $\varphi_0 > 0$ and $\varphi_1 > 0$ are parameters and $\gamma_s,\ s = 1,...,n$ denote age-specific fecundity. The term $\left(1 - z_{it}\right)\beta_s^- + z_{it}\beta_s^+$ captures stochastic age-specific egg survivability that is low at a value β_s^- in the absence of an inflow event, $z_{ti} = 0$, or high at a value β_s^+ when an inflow event occurs, $z_{ti} = 1$.

We construct a time series (1951–2012) of stochastic egg survivability for each year and each female spawner age class in May (Hinrichsen et al. 2016). Survivability was ‘low' during 44 years and ‘high’ during 16 years. Thus, $p = 16/60 = 0.27$. The resulting age-specific egg survivability β_s^+ for good and β_s^- for bad oxygen conditions are reported in Appendix, Table 1.

Cod exhibits cannibalistic behavior. We capture this age- and density-dependent process based on the approach of Lewy and Vinther (2004). Let δ_s denote an indicator of instantaneous cannibalistic predation mortality that age class s exerts on juveniles. Density dependence of recruitment thus depends on 'cannibalistic' spawning stock biomass $x_{0t}^c = \sum_{s=1}^n \delta_s \gamma_s w_s x_{st}$. Using estimates of stock numbers, weight in the stock, and maturity from ICES (2013), and assuming log-normal auto-correlated errors (Cook et al. 1997), we estimate

$$\ln\left\{\frac{x_{1,t+1}}{\sum_{s=1}^n \left[\left(1 - z_{it}\right)\beta_s^- + z_{it}\beta_s^+\right]\gamma_s w_s x_{st}}\right\} = \ln(\varphi_0) - \varphi_1\left(\sum_{s=1}^n \delta_s \gamma_s w_s x_{st}\right) + \varepsilon_t \quad \text{with} \quad \varepsilon_t = \nu\varepsilon_{t-1} + \xi_{t-1},$$

where ξ_t is IIDN$(0,\sigma^2)$. We obtain $\ln(\varphi_0) = 1.744$ with a 95% confidence interval [1.277,2.211] and $\varphi_1 = 0.00157$ [1/1000 tons], with a 95% confidence interval [0.0001,0.0031]. For the computations, we use $\varphi_0 = \exp(1.744) = 5.720$.

For the biomass model we use the growth function from Froese and Proelss (2010):

$F = rx_t\left(1 - x_t / K\right)$, $r = 0.48$ and $K = 2283$ thousand tons.

Using the 2013 initial population the efficient biomass is 113 thousand tons, while the total stock biomass is 175 thousand tons. This yields $\tau = 0.6$ in (14). However, the 2013 population age structure is far from equilibrium solutions, where the value of τ is between $0.79 - 0.81$. As we concentrate on steady states in the model comparisons, we apply $t = 0.8$, but our main conclusions are not sensitive with respect to this parameter value.

Economic parameters

To estimate the parameter values for the utility and cost functions, we construct the time series of efficient biomasses B_t using estimated age class-specific stock numbers, weights, and fishing mortalities from ICES (2013). Further, we utilize the fact that the Baltic cod fishery has been de-facto open access in the past (Kronbak 2005, Quaas et al. 2012). Under open access, harvest is determined by the condition that the market price P_t is equal to the marginal harvesting cost, that is $P_t = cB_t^{-c}$. Using price data from Danish fishery accounts (http://statbank.dk/REGNFI01; years 1996–2013), and allowing for a time trend ($t = 2013 -$ year of observation) to capture effects of inflation on prices and exogenous technical progress in fishing technology, we estimate

$$\ln\left(P_t\right) = c_0 + c_t t - c \ln B_t + x_t,$$

where x_t is an IID error term. Applying OLS, we obtain the estimates $c_0 = 1.888$ with 95% confidence interval [1.041,2.734], $c_t = -0.0066$ with 95% confidence interval [-0.0213,0.0081], and $c = 0.426$ with 95% confidence interval [0.128,0.724], with $R^2 = 0.45$. The confidence interval for c includes the value $c = 0.644$ that Kronbak (2005) reports for this parameter.

We specify the marginal utility function as an iso-elastic inverse demand function $U'(H_t) = \bar{P} Y_t^{-h} H_t^{-n}$. Here, H_t is the overall catch quantities of Baltic cod (ICES 2013), Y_t is the catch of the largest North Atlantic cod stock, the Northeast Arctic cod, as a substitute for Baltic cod, and $\bar{P}$, h, and n are parameters to be estimated. Using this specification in the open-access condition $U'(H_t) = cB_t^{-c}$, we use data on catch quantities and efficient biomass to estimate

$$\ln(H_t) = a_1 + a_2 Y_t + a_3 t + a_4 \ln(B_t) + x_t,$$

where χ_t is an the IID error term, and again a time trend is included. Applying OLS, we obtain the estimates $a_1 = 3.557$ with 95% confidence interval [2.456,4.658], $a_2 = 0.199$ with 95% confidence interval [0.0048,0.350], $a_3 = 0.0098$ with 95% confidence interval [0.0031,0.0164], and $a_4 = 0.652$ with 95% confidence interval [0.541,0.763], with $R^2 = 0.93$. In the computations, we use $\eta = \varepsilon / a_4 = 0.426 / 0.652 = 0.653$, $\bar{P} / c = \exp(\eta a_1) = 10.212$. From the estimate of $\ln(c_0)$, we have $c = e^{1.888} = 6.604$, and thus $\bar{P} = 6.604 \times 10.212 = 67.442$. For the demand function, we use a reference value of Northeast Arctic cod supply of a million tons, and thus use

$$P_t = \bar{P}\, 1000^{0.199 \times 0.654} H_t^{-0.654} = 27.434 H_t^{-0.654}$$

euros per kg of fish. Appendix, Table 1 summarizes the values for the economic model parameters along with the parameters of the stock-recruitment function.

To estimate catchabilities $q_s(\sigma_t)$, we focus on the trawling fleet, as trawlers are the most common type of gear in the Baltic cod fishery (Kronbak 2005). Thus, the variables σ_t can directly be interpreted as the mesh size of the trawl nets used. As the Baltic cod trawling fishery is among the best-studied fisheries worldwide with regard to the size selectivity of fishing gear (Madsen 2007), good data are available to estimate trawl net selectivity.

For a given mesh size, the fraction of fish retained in the trawl net increases with fish length. The common approach of fisheries scientists is to describe the 'selection curve' of the trawl net by a logistic function (Wileman et al. 1996). Based on extensive experimental data for Baltic cod, Madsen (2007, Table 3) provides estimates how the shape parameters depend on mesh size for the Bacoma escape window, which is the most common trawl net used for Eastern Baltic cod.

To convert the length-specific gear selectivity into age-specific catchabilities, we use empirical length-at-age distributions from the Baltic International Trawl Survey and estimate the shape parameters of a logistic function that gives age-specific catchabilities depending on mesh size

$$q_s(s_t) = \left\{1 + \exp\left[(s_t - e_{1s}) / e_{2s} \right] \right\}^{-1}$$

(Quaas et al. 2013). The parameters e_{1s} and e_{2s}, and all other age-specific parameters, are given in the Appendix, Table 1. Figure 1 shows the catchabilities when the mesh size is varied between 30 and 180 mm. The catchability is higher the smaller the mesh size and the older the age class.

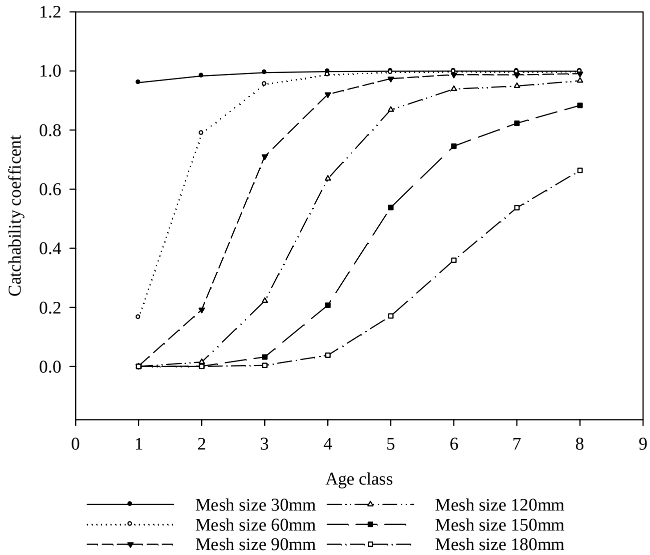


Figure 1. Bacoma mesh size and catchability

4. Results and discussion

First, we study how the MSY policy performs with respect to the economic objective within the deterministic setup by comparing the biomass and the age-structured models. Second, we study how high variability in egg survivability changes economically optimal solutions.

Deterministic solutions: contrasting economic optimum and MSY

According to the biomass model (Figure 2) the transitions to steady states are monotonic, and when interest rate varies between 0 and 15% the changes in optimal steady-state harvest levels are minor. Additionally the difference between economically optimal steady-state harvest and MSY harvest is small. This exactly reflects the argument in Wilen (2000). Given interest rates below 11%, the steady-state population level is higher than the MSY population level (cf. Grafton et al. 2007).

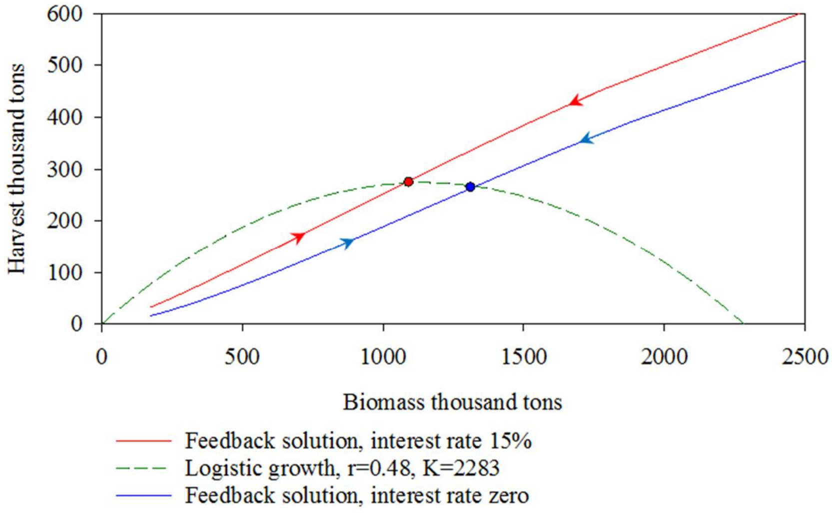


Figure 2. Optimal solution according to the biomass model

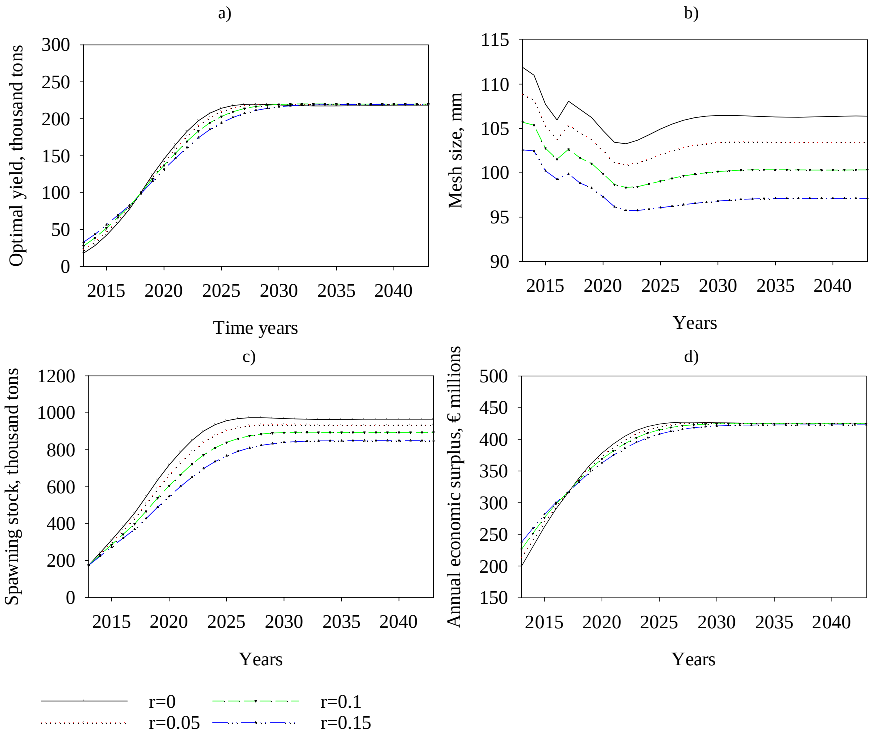
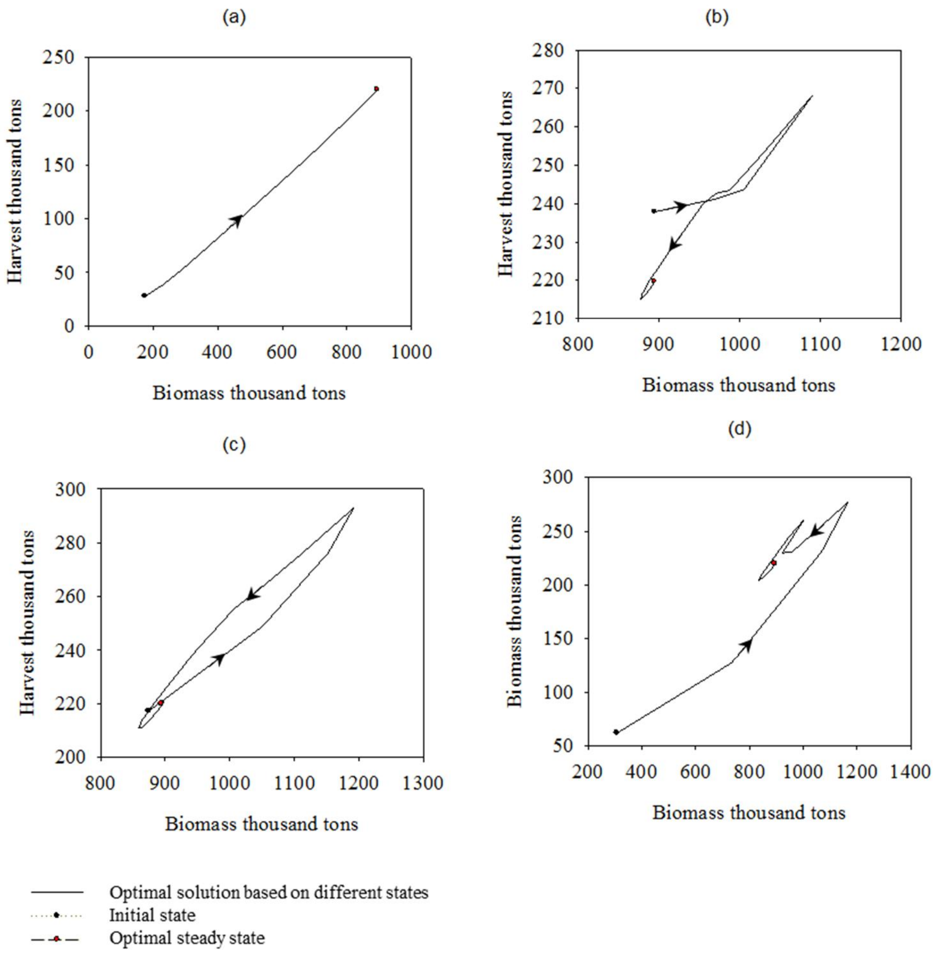


Figure 3a–d. Optimal harvesting and population development from the 2013 initial state

In a deterministic age-structured model egg survival is given an expected value, that is $p=0.27$ times the high survivability plus 0.73 times the low survivability. In Figures 3a–d the initial population state is as estimated for 2013 (Table 1), and interest rate is varied between 0 and 15%. Optimal harvesting is smooth over time and, given the nonlinear objective function, pulse fishing does not occur. Results additionally suggest that the 2013 initial spawning stock is far below the long-run optimal steady state of 850–860 thousand tons (Figure 3c). Along the transition toward the steady state the harvest level increases eightfold while the profit level only doubles, as market price decreases from €3.1 to €0.8 per kg of fish. The higher the interest rate, the lower are the steady-state population and profit levels. The mesh size additionally decreases with interest rate and the higher interest rate adjusts the population toward younger age classes. However, the effects of the interest rate on steady-state harvest are negligibly small.



Figures 4a–d. Different initial states and steady-state stability, interest rate 10%.

Note: a) 2013 initial state, b) 2013 initial state but $x_{10} = 1000 \times 10^6$

c) $5 \times$ 2013 initial state, d) abundant small age classes, no fish in old age class

Given an interest rate of 10% the steady-state biomass and harvest in the biomass model are 1158 and 274 thousand tons, while they are lower in the age-structured model, equaling 894 and 220 thousand tons. According to historical data, biomass has varied between 100 and 1100 thousand tons and harvest between 31 and 391 thousand tons (Eero et al 2007, ICES 2014). The mesh size has varied between 110mm and 120mm in the last 15 years. The optimal solutions for biomass and harvest are thus within observations, while the mesh size is slightly lower compared to present practice.

In Figure 4a–d the initial state is varied, leading to a great variability in optimal transition but without implications on the run steady state. This suggests that the equilibrium is globally stable.

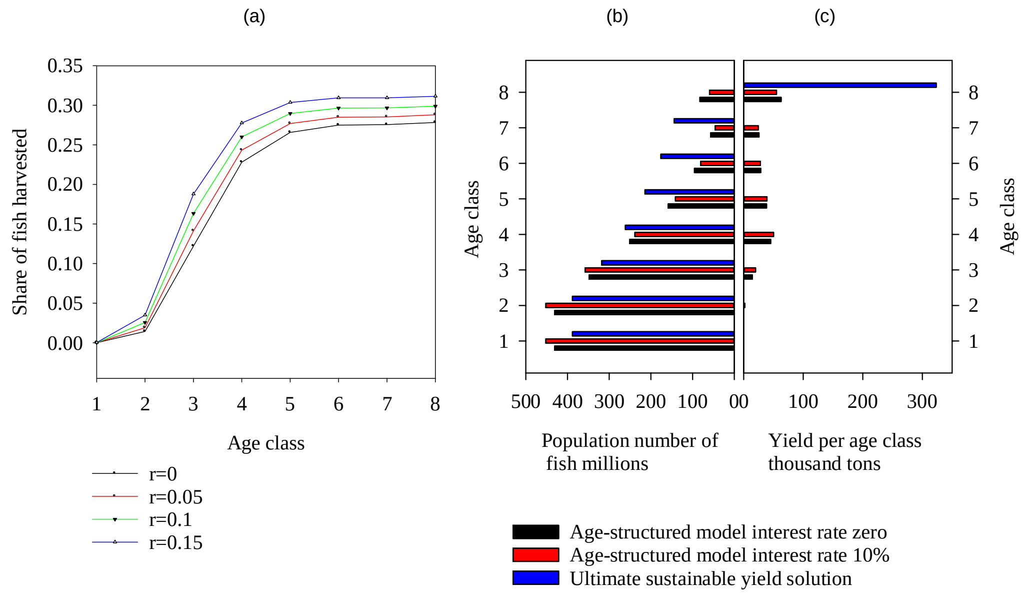
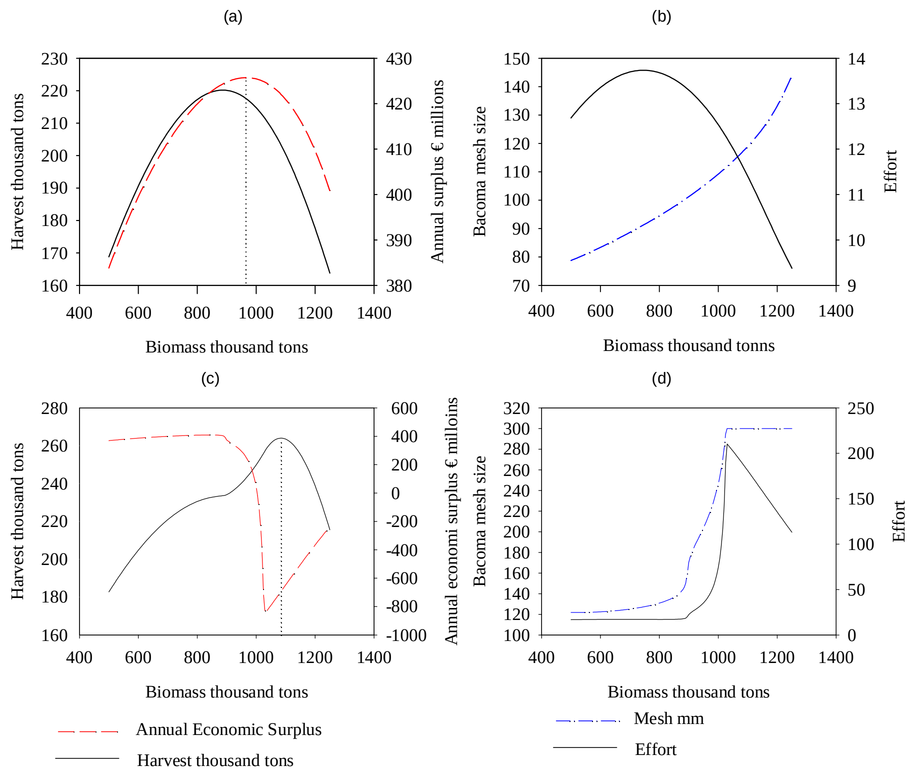


Figure 5a,b,c. Steady-state mortalities, population age structure, and yield per age class

We next compare the economic optimum and the MSY outcomes in different settings. We therefore first study the steady-state age compositions. By changing mesh size it is possible to adjust the yield between different age classes. Fishing mortality is highest for age classes 4–8 and increases with interest rate (Figure 5a). Accordingly, the number of fish decreases with age and a higher interest rate implies a younger population (Figure 5b). The main yield in biomass units is obtained from age classes 4 and 8 (Figure 5c). However, optimizing the mesh size leads to a population and harvest structure, which may still be rather far from the structure that would be optimal if a harvest from any age class could be freely chosen. Such a hypothetical possibility can be called "ultimate Maximum Sustainable Yield" (uMSY) (Getz 1980, Reed 1980). The yield-maximizing solution is to harvest fish only from age class 8, which is harvested completely at the end of each year (Figures 5b,c). This implies the beginning of period age structure in Figure 5b, where the number of fish is lower in small age classes but much higher in older classes (excluding age class 8).



Figures 6a–d. Comparison of economic equilibria and gear-constrained MSY
Note: a,b) Maximization of constant annual economic surplus
c,d) Maximization of gear-constrained MSY

The ultimate maximum sustainable yield produces an annual catch equal to 310 thousand tons, while the economically optimal annual catch with zero discounting is 210 thousand tons.

These results are in line with ecologists' arguments that it is especially important for Baltic cod to maintain a large stock of older and larger fish (Hinrichsen et al. 2016).

However, the maximum sustainable yield is actually constrained by available fishing gear and technology. To compute the maximum yield obtainable by the Bacoma trawl net we maximize the sum of annual catches over 100 years and optimize annual harvest and mesh size. This "gear-constrained Maximum Yield" (gcMY) leads to a solution with biannual pulse fishing (not shown), and an average annual catch equal to 270 thousand tons and average annual economic loss equal to - €667 millions. This is a major loss, as the maximum annual profit is positive and equals €425 millions. The loss occurs from the very high effort level and mesh size that are optimal to apply, as this yields an outcome closest to the uMSY solution with catch from age class 8 only.

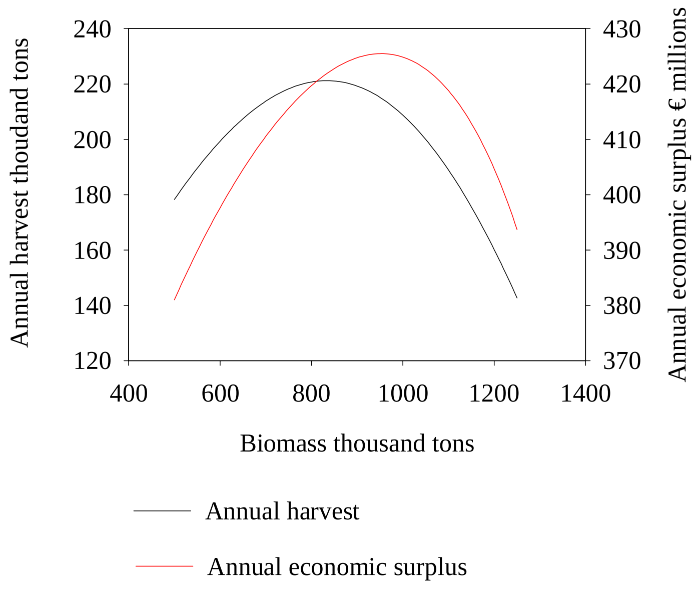


Figure 7. Comparing MSY and constant annual surplus with mesh size fixed at 100 mm.

In biomass models harvest is constant at MSY equilibrium. Similar equilibria can be computed for the age-structured model by removing time (and initial state restrictions) from equations (5), (7), and (8). According to Figure 6a,b, the constant annual economic surplus is maximized when biomass and catch equal 965 and 203 thousand tons, respectively. Given this equilibrium, the mesh size is 120 mm, and the index for effort obtains a value equal to 12. In Figures 6c,d the aim is to maximize constant annual catch, which is attained at the level 264 thousand tons when biomass is 1085 thousand tons. To reach this constant the annual catch requires a maximum mesh size (300 mm) and an effort level ten times higher than in the economic equilibrium. Note that the solutions for effort and economic surplus begin declining when mesh size reaches its maximum (biomass level □1030 thousand tons). Maximizing annual constant catch leads to an annual loss equal to - €692 millions. This is a consequence of very high effort level and large mesh size that are employed to direct catch to the oldest age class to the extent possible with actual gear.

According to an established result based on the biomass model the annual economic surplus is maximized with higher biomass compared to MSY. In Figures 6a and c this result is here violated: MSY is maximized when biomass equals 1085 compared to economically optimal 965 thousand tons. However, the familiar outcome is obtained if mesh size is fixed (Figure 7.)

These results put into question some very established results in resource economics. First, given the classic biomass model, zero interest, and stock-dependent harvesting cost the economically optimal population size is higher than the MSY population (Clark 1990, Wilen 2000, Grafton et al. 2007). When the biomass model is applied to the Baltic cod the same results hold (Figure 2). However, there is no guarantee that this result holds in the age-structured model (Figure 6 a,c). The striking result can be explained by optimized mesh size (Figure 7), and correspondingly different age composition of the population under economic equilibrium and gcMSY: total stock biomass is smaller, but efficient biomass is larger in economic equilibrium compared to gcMSY. This implies that the dispute between Grafton et al. (2007, 2009) and Clark et al. (2010a,b) may not be valid as such if viewed in the light of age-structured models. Second, in his review Wilen (2000) concludes that the difference between the economic equilibrium and MSY is typically minor and of minor importance. It is evident that this is not at all true in an age-structured model for Baltic cod fishery, albeit it looks to be true in the biomass framework.

An age-structured model clarifies the fact that it is restrictive to view MSY as a consequence of biological factors only. The three definitions for MSY reveal that they all include serious problems for Baltic cod: one is not admissible with existing gear and two others lead to major economic losses. This can be contrasted with the United Nations Convention on the Law of the Sea and the European Common Fisheries Policy that place MSY in a central place in fisheries management.

The results this far are based on recruitment that is endogenous but deterministic. However, the variation in recruitment is large and if the interest rate is 5%, the optimal steady-state harvest varies between 166 and 360 thousand tons depending on whether low or high survivability is assumed. It can be conjectured that stochasticity may further emphasize saving the old age classes as the adverse conditions disproportionately decrease egg survivability of young females.

Stochastic solutions

Stochastic programing expands the number of optimized variables and requires the application of short planning horizons. A 15-year horizon leads to a nonlinear programing problem with 589 804 variables. Solving such problems requires a lot of computer time and we apply a horizon of 11 and 12 years, as these are enough to closely approximate the first-year optimal harvest. In a deterministic setting (Figures 8a,b) and a 10% interest rate, a horizon of 12 years produces a solution that deviates from the infinite horizon first-period solution by 0.08–5% depending on the initial state. Dynamic solutions are obtained by an iterative procedure, where the system state after the first period is taken as a new state and the optimization is repeated over some desirable horizon.

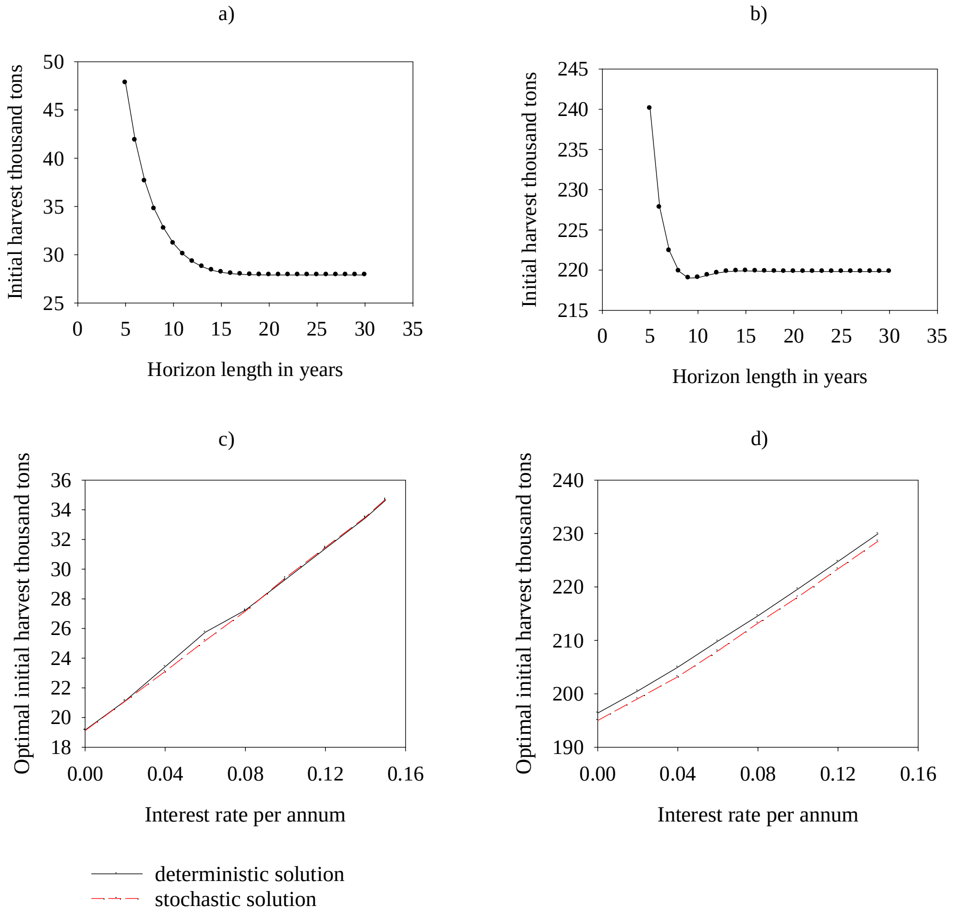


Figure 8a,b. Optimal initial harvest
a) Initial state: 2013 population, deterministic solution, interest rate 10%
b) Initial state: deterministic steady state, deterministic solution, interest rate 10%
c) Initial state: 2013 population, horizon length 12 years
d) Initial state: deterministic steady state, horizon length 12 years

Figure 8c shows the optimal initial deterministic and stochastic harvests with different interest rates when the 2013 population is the initial state. The stochastic solution is more conservative compared to the deterministic solution, albeit the difference between the solutions is small and hardly visible in the graph. Given an interest rate of 6% the difference is largest and reaches 2.2%. Figure 8d shows similar results when the initial state is the optimal deterministic steady state. With a larger initial population the absolute difference is larger and the stochastic solution is still more conservative for all the interest rates between 0 and 14% (p.a), but still the optimal stochastic harvest is only 0.8% lower than the optimal deterministic harvest. If the differences between low and high egg survivabilities are expanded to the maximum (that is no survivability with probability

0.27 and full survivability with probability 0.73), the qualitative difference is still the same and stochastically optimized harvests are 3–6% lower.

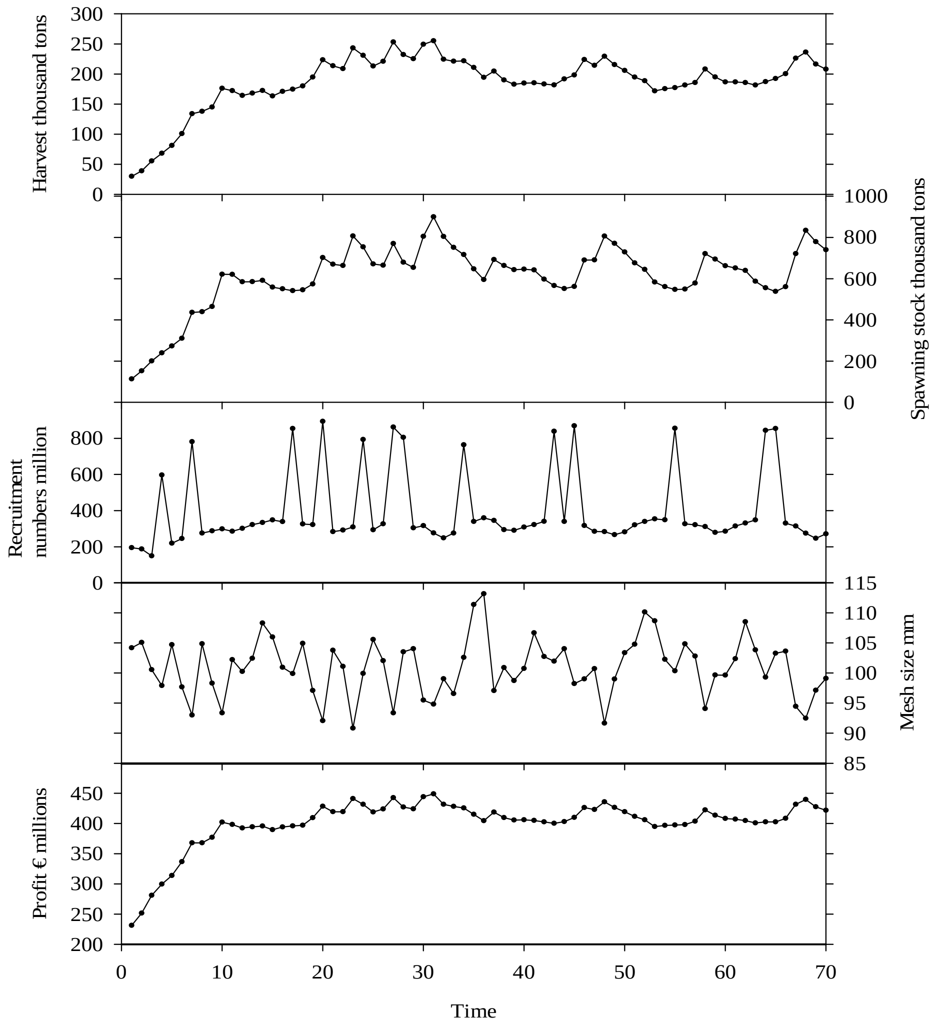


Figure 9. A stochastic solution example
Note: Initial state: 2013 population, interest rate 10%

Figure 9 shows a possible realization of the stochastic fishery over time. The computation is performed by taking into account the probability of 0.27 for high egg survivability, albeit in the given scenario it happens to occur only 13 times within the 70-year interval. Observe that while high egg survivability approximately triples recruitment compared to low survivability, the corresponding increase in annual harvest is only approximately 25%. The increase in spawning stock and harvest is realized four years after the occurrence of high egg survivability. This is the delay until the large cohort enters age classes 4–8, which form the main fraction of yield. Because of the age class structure the stochastic effects of high egg survivability on yield and profit can be anticipated beforehand. Since the problem is nonlinear in harvest, it is optimal to spread the increase in harvest over several years. Observe that it is optimal to slightly increase the mesh size two years after high eggs survivability to prevent from harvesting the large cohort before it has reached age classes 4–8. Compared to the deterministic solution in Figure 2c, stochasticity increases the average mesh size, but only by 3–5mm.

Since in our case stochastic optimization yields a minor effect on harvest compared to a deterministic solution, it may be expected that the deterministic feedback solution could be used to approximate the stochastic solution. This is tested in Figures 10a,b, which compare these two solutions over a 70-year time period. Indeed, the difference in the outcomes is only minor, and hardly visible in the graphs. This suggests that in the specified setup the true stochastic solution can be rather accurately approximated by the deterministic feedback solution.

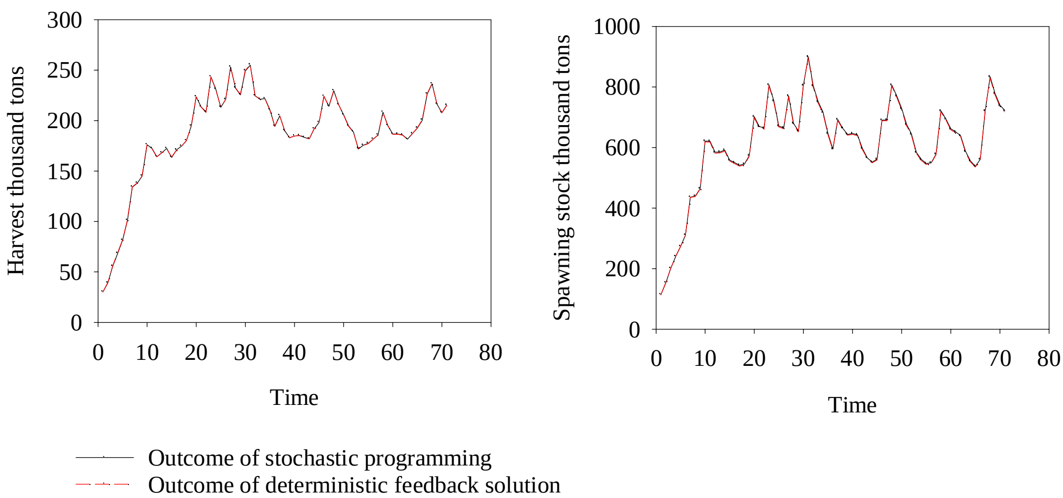


Figure 10. a,b. Comparison of the stochastic programing and deterministic feedback solution
Note: Interest rate 10%, horizon length 11 years

Comparing our stochastic results with Grafton et al. (2008) is not possible, as they do not report how stochasticity is specified in the model and how it changes the solution. Holden and

Conrad (2015) assume selectivity in the sense that fishing can either target immatures or adults, and if only adults are harvested the optimal escapement is the same as in the deterministic model. When harvesting only immatures stochastic harvesting can be more or less conservative compared to deterministic harvesting. Their empirical analysis does not reveal the magnitude of the difference between the stochastic and deterministic solutions. In addition to different selectivity specifications our model differs from Holden and Conrad (2015), as our objective function is nonlinear and harvesting cost depends on population abundance. Comparing the results is difficult because of this and the differences in how environmental variation is specified.

5 Conclusions

Ecologists conjecture that in the case of the Baltic cod fishery it is especially important to maintain a large stock of older and larger fish, as their eggs have higher survivability during adverse environmental conditions. This conjecture can be studied by an age-structured model when using mesh size as an optimized variable in addition to total harvest. Our analysis shows how these biological factors transmit to economically optimal harvesting along with solutions that aim to maximize physical yield.

We show that it is possible to define at least three different notions of MSY in the age-structured setting. They all differ substantially from economic equilibrium, and face serious problems with respect to practicability. These phenomena are consequences of the attempts to target harvest to the oldest age class by applying very high mesh size and fishing effort. Contrastingly, the classic biomass model, if applied to Baltic cod fishery, produces a result where the difference between MSY and economic equilibrium is rather unimportant. Our results are consequences of the age-structured model and of optimizing the trawl net mesh size. We conjecture that similar outcomes follow if it is possible to catch the MSY age class by applying costly gear (e.g., fish traps), but some other gear type is preferable when taking cost into account (e.g., trawling gear).

Environmental variability is especially high for Baltic cod, suggesting that a stochastically optimized harvest and mesh size may strongly deviate from deterministic solutions. We show that this holds in the sense that seasonal variation in recruitment and population levels are high and optimal mesh size is somewhat increased. However, despite the high variability in population development, the variability in optimal harvest is much lower and the optimal stochastic solution can be accurately approximated by the deterministic feedback solution. This is not *a priori* evident as our model does not satisfy the preconditions for certainty equivalence, i.e. quadratic objective function, linear dynamics, and random walk stochasticity.

Appendix.

Table 1: Age class-specific parameter values for Eastern Baltic cod fishery.

		age class							
Parameter		1	2	3	4	5	6	7	8
natural survival	a_s	1.00	0.82	0.82	0.82	0.82	0.82	0.82	0.82
high egg survival	b_s^+	0.00	0.607	0.760	0.730	0.710	0.732	0.763	0.861
low egg survival	b_s^-	0.00	0.017	0.084	0.156	0.232	0.301	0.359	0.473
Maturities	g_s	0.00	0.13	0.36	0.83	0.94	0.96	0.96	0.98
Cannibalism	d_s	0.00	0.04	0.60	1.04	1.35	1.30	1.25	1.38
Weights	w_s	0.00	0.177	0.347	0.794	0.912	1.100	1.662	2.740
catchability	e_{1s}	49.92	74.36	102.52	128.80	152.65	169.52	183.24	195.12
parameters	e_{2s}	6.24	10.90	13.92	15.82	17.03	18.14	21.61	22.26
individuals 2013	x_{s0}	194.853	173.859	105.768	63.768	28.198	14.333	5.447	2.298

Table 2: Parameter values for an Eastern Baltic cod fishery.

parameter	j_0	j_1	p	C	c	n	$\bar{P}$
unit	year^{-1}	1000^{-1} tons			10^6 €		€kg^{-1}
value	5.720	0.00157	0.267	0.426	6.604	0.654	27.434

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