The Dynamics of an Open Access: The case of the Baltic Sea Cod Fishery

- A Strategic Approach -

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Abstract

The paper sets up a discrete-time, deterministic model of a single industry, in the light of the benchmark theory of Smith (1968). The model is used to describe the dynamics of recovery from a replenishable resource such as the case of the eastern Baltic Cod fishery. The model advances from Smith's (1968) theory since it includes a biological function dividing the change in the biomass into growth occurring during the year and recruits entering the spawning stock biomass and a dynamic entry/exit function applying a slightly more technical production function than the Schaefer production function. Theoretical possible types of steady state are discussed before the theory is applied to the eastern Baltic Sea cod fishery. The path the fishery has been following since 1982 is determined and it is discussed how it relates to the optimal path to steady state. The paper further throws light on questions as; Are we able to understand the dynamic behavior of fishermen in this fishery? Does a stable equilibrium exits and how is the path to this equilibrium described? When a fishery is regarded outside safe biological limits, could it be on the path to a positive steady state?

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1. Introduction

Since Warming (1911), Gordon (1954) and Scott (1955) there has been an increasing amount of literature describing fisheries economics. Warming (1911) and Gordon (1954) sought to explain why an open access fishery resulted in little or no profit. It was pointed out that entry of the mobile factors proceeds beyond the numbers sufficient for economic efficient use of the fish stock. Hence in the absence of property rights too much effort and too low biomass characterize the open access. Scott examined the difference in the intensity of fishing between a common property resource and a resource owned by a sole owner. These models characterize different equilibria without discussing the dynamics behind the equilibrium. Smith (1968) describes the dynamics of an open access resource use and is thereby a pioneer in applying phase diagrams in fishery economics. Smith (1968) characterizes the open access equilibrium including some hypothesis about the dynamics of a common property resource overexploitation. Although the stock equilibrium under open access might be positive the stock may be driven close to extinction along the path of adjustment due to overshooting. Wilen (1976) applied the dynamic theory of Smith to the pacific fur seal. Wilen (1976) showed that the sealing industry followed a pattern quite close to that predicted of Smith. The industry followed a convergent 'boom-and-bust' process characterized in the later periods by low and falling profits and industry exit. Bjørndal & Conrad (1987) also applied the theory of Smith (1968) with a special reference to the question of the stock extinction under open access. A non-linear deterministic model for the North Sea Herring Fishery showed that the industry overshoots, but the increase in the stock and hence the first loop of a convergent spiral is not completed since the fishery was closed in 1977. Therefore one could only guess that extinction might have occurred if the fishery was not closed.

This paper sets up a discrete-time, deterministic model of a single industry, which is used to describe the dynamics of recovery from a replenishable resource such as a fish stock. The applied case is the Eastern Baltic Cod Fishery. The model takes basis in Smith's (1968) theory of the dynamics of a resource recovery setting up a biological constraint and a technological constraint. The model does however differ from Smith's (1968) model since it applies more advanced biological and technological functional forms, which results in, that the type of steady state is not unique. The biological function is divided into a function describing the growth in the biomass not considering recruits and a function describing recruits entering the biomass. The technological function is a Cobb-Douglas production function, which is slightly more advanced than the Schaefer production function applied by Smith (1968). The theoretical model is applied to the eastern Baltic Sea cod fishery, which has been subject to a *de facto* open access since records are made in 1966. The resource is currently considered outside safe biological limits and the science recommends a closure of the fishery (Anon. (2000)). The applied model shows that the eastern Baltic Sea fishery most likely has a stable steady state and the optimal path to this steady state is a spiral why the path to steady state involves overshooting of effort and hence a (extreme) low level of biomass. The resource might be on its path to steady state.

Section 2 describes the dynamics of an open access and mention earlier studies in the area. It further develops a more advanced model, which is tested later in the paper. Section 3 describes the cod fishery in the Baltic Sea, while section 4 simulates the advanced model from section 2 applying the data on the Baltic Sea cod fishery. Section 5 analyses and concludes the paper.

2. The dynamics of an Open Access

Consider a renewable resource such as a fishery, which is exploited by an industry. The industry is characterized by an open access and hence faces a free entry-exit procedure. The dynamics of the system faces three behavioural restrictions namely the interactions of the resource, individual firms and the industry. These are the main ideas in the theory of Smith (1968).

The industry exploits the resource according to the following production function, where it is assumed that the production depends on the size of the resource stock.

$$Y_t = H(E_t, S_t) \tag{2.1}$$

Where Y_t is the production from the industry as a whole at time t, E_t is the effort employed in the industry at time t and S_t is the stock size at time t.

The industry as a whole faces an instantaneous profit function according to following equation.

$$\pi_t = p_t H(\cdot) - c_t E_t \tag{2.2}$$

Where p_t is the unit price the industry receives for its production at time t, c_t is the unit cost of employing effort the industry faces at time t. It is implicitly assumed that the industry is one of several sources to the market in question, otherwise the price would depend on yield and cost per effort unit. It is further assumed that the industry faces constant marginal cost.[1] To simplify further it is assumed that unit price and unit cost are constant through time.

The entry and exit process occurs depending on the profit level in the industry, a positive profit attracts effort to the industry, while a negative profit makes effort withdraw from the industry.[2] It is assumed there is an unlimited number of potential effort attracted to the industry if there is a positive profit. The entry/exit process therefore happens according to the following equation.

$$E_{t+1} - E_t = \mu \pi_t \tag{2.3}$$

Where $\mu>0$ is an adjustment parameter or a behavioural constant, the larger μ the faster reacts the industry to changes in profit.[3] This behavioural restriction contains both the industry and the single firm's behavioural restrictions.

The growth, the natural mortality and the recruits are for simplicity summarized in a single growth function. It is assumed there is no interaction between the

1 Often it is assumed that cost are stock dependent, which prevents total extinction of the resource. For the illustrative example marginal cost are assumed equal to average cost.
2 One could assume without loss of generality that a certain level of profit greater than zero is required in order to enter the industry and in order to stay in the industry.
3 A difference in the speed of reaction depending on whether considering entry of exit from the industry could be assumed.

growth function and the harvest function. The exploited yield curve is determined as follows.

$$S_{t+1} - S_t = F(S_t) - mH(E_t, S_t) \tag{2.4}$$

Where $F(S_t)$ is the growth function, it is assumed that the growth function has the following properties; $F(\underline{S}) = F(\bar{S}) = 0$, $F(S) < 0$ for $0 < S < \underline{S}$ and for $\bar{S} < S$, $F(S) > 0$ for $\underline{S} < S < \bar{S}$, $F'\left(S^{MSY}\right) = 0$ where $\underline{S}$ and $\bar{S}$ are respectively the minimum and the maximum self-sustaining populations. m is a mortality coefficient, depicting the precise effect of a unit of harvest in the stock, the mortality coefficient can be greater than one due to injury during harvest, discards etc.

With given initial values of the system it can be iterated forward in time and trajectories (S_t, E_t) can be plotted in a phase-space. The stationary point(s) are defined where the stock in period t+1 equals the stock in period t and the effort in period t+1 equals the effort in period t for all future t.

2.1. An example with simple functional forms

Applying specific functional forms as the one applied by Smith (1968) for the growth function and that harvest function allows a graphical representation of the theory. Assume the growth in the renewable resource follows a logistic growth function, which is a compensatory growth function.

$$F(S_t) = rS_t(1 - S_t/L) \tag{2.5}$$

Where r is the intrinsic growth rate and L is the carrying capacity. The industry is assumed to harvest according to a Schaefer production function, that is the harvest depends on the stock size, the effort employed and the catchability coefficient, q.

$$H(S_t, E_t) = qS_tE_t \tag{2.6}$$

Other possible production functions are the Cobb-Douglas production function $H(S_t, E_t) = qS_t^{\alpha} E_t^{\beta}$, with constant or decreasing returns to scale ($\alpha + \beta \leq 1$) or the exponential production function $H(S_t, E_t) = S_t\left(1 - e^{-qE_t}\right)$.

The theory presented here is in a discrete time setting, which differs from Smith (1968). The entry/exit process now happens according to the profit level in the industry. The process is defined as follows, where the average cost of a unit of effort employed is assumed to be constant, c, and the price of a harvested unit is assumed to be constant, p. μ reflects the response parameter.

$$E_{t+1} - E_t = \mu\left[pqS_tE_t - cE_t\right] \tag{2.7}$$

Assuming the harvest follows the Schaefer production function[4] implies the costs are inversely related to the stock and profit approaches minus infinity for a positive harvest when stock approaches zero. This is an economic protection against extinction of stock in the deterministic model.

The change in the stock over time is determined by the growth in the stock minus what is harvested in the stock.

$$S_{t+1} - S_t = rS_t\left(1 - S_t/L\right) - qS_tE_t \tag{2.8}$$

The nullclines or isoclines are defined where there is no movement in respectively the effort or the stock for any future t, hence $S_{t+1} = S_t = S$ and $E_{t+1} = E_t = E$. The long-term steady state occurs where the two isoclines intercept.

The effort nullcline is defined where there is no movement in effort, hence

$$S = \frac{c}{pq} \tag{2.9}$$

4 This is also the case with other production functions as for instance the Cobb-Douglas or the exponential production function.

The stock nullcline is defined where there is no movement in the stock, hence

$$E = \frac{r}{q} - \frac{r}{Lq} S \tag{2.10}$$

Steady state is thus defined as follows.

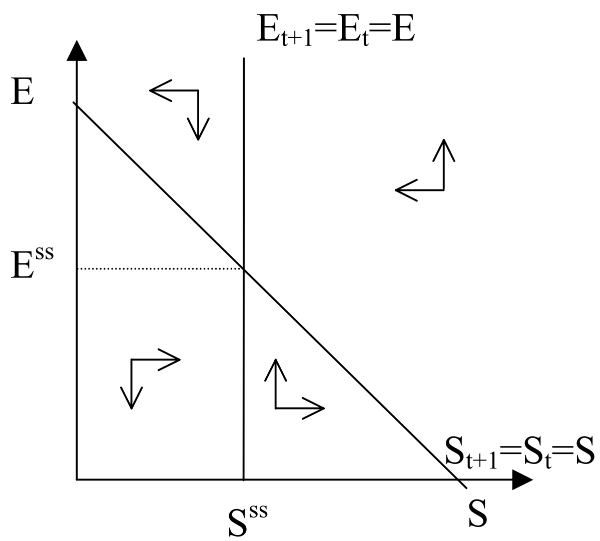
$$S^{ss} = \frac{c}{pq} \tag{2.11}$$

$$E^{ss} = \frac{r}{q} - \frac{r}{Lq} \frac{c}{pq} \tag{2.12}$$

Plotting the nullclines in a phase-space and determining the vector fields just of the nullclines gives an indication of the types of steady state, the Jacobian is however needed for final conclusion of the type of steady state.

The movement just of the nullcline determines the vector fields. Suppose we are on the E-nullcline, then a slight increase in the stock implies $E_{t+1}>E_t$ and hence the effort increases, which explains that the vector fields to the right of the E-nullcline point upwards and vice versa to the left of the E-nullcline. Now suppose we are on the S-nullcline, then a slight increase in E implies a location above the S-nullcline hence $S_{t+1}<S_t$ that is, the stock decreases over time and therefore the vector fields point to the left above the S-nullcline and to the right below the nullcline.

Figure 1. The nullclines for stock respectively effort. The interception of the nullclines determines the steady state. The arrows indicate the direction of the vector fields in the phase diagram



The vector fields indicate an oscillation around steady state. To confirm this hypothesis and to test whether it is a stable or an unstable equilibrium, the Jacobian matrix is determined and evaluated at steady state, which determines the behaviour of the system in a neighborhood of the steady state.

$$J = \begin{bmatrix} \dfrac{\partial\left(S_{t+1} - S_t\right)}{\partial S_t} & \dfrac{\partial\left(S_{t+1} - S_t\right)}{\partial E_t} \\ \dfrac{\partial\left(E_{t+1} - E_t\right)}{\partial S_t} & \dfrac{\partial\left(E_{t+1} - E_t\right)}{\partial E_t} \end{bmatrix} = \begin{bmatrix} -S^{ss}\, r/L & -qS^{ss} \\ \mu pqE^{ss} & 0 \end{bmatrix} \tag{2.13}$$

By evaluating the determinant and the trace of the Jacobian we are able to conclude whether the steady state is a stable or unstable fixed point.

$$|J| = \mu pq^2 S^{ss} E^{ss} > 0 \qquad Tr(J) = -S^{ss}\, r/L < 0 \tag{2.14}$$

Since the determinant is positive and the trace is negative it can be concluded that the fixed point is a stable steady state, but the eigenvalues are needed in order to determine the whether it is a globally asymptotically stable spiral, globally asymptotically stable star node or improper node or a globally asymptotically stable proper node. Therefore the eigenvalues, λ_i, of the Jacobian matrix are determined. It is however possible to conclude the fixed point is a globally steady state since the fixed point is unique.

$$\begin{vmatrix} -S^{ss}\, r/L - \lambda_i & -qS^{ss} \\ \mu pqE^{ss} & 0 - \lambda_i \end{vmatrix} = 0 \tag{2.15}$$

Solving this equation yields the eigenvalues.

$$\lambda_i = \frac{-rS^{ss}}{2L} \pm \sqrt{\frac{r^2\left(S^{ss}\right)^2}{4L^2} - \mu pq^2 S^{ss} E^{ss}} \tag{2.16}$$

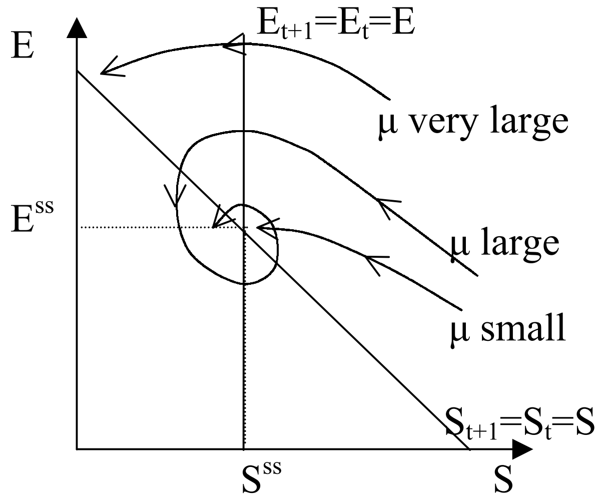
Since the square root is non-zero it can be concluded that the fixed point is either a globally asymptotically stable spiral or globally asymptotically stable proper node, which of the two depends on specific values of the parameters in the model. The steady state is a stable spiral when the eigenvalues are imaginary numbers that is following equation must be satisfied.

$$S^{ss} = \frac{c}{pq} < \frac{4L\mu pq}{\mu pq + r} \tag{2.17}$$

Hence among others the adjustment parameter, μ, affects the likelihood of which type of steady state. The larger the adjustment parameter is the more likely it is that the fixed point is a stable spiral. A higher adjustment parameter makes the industry react faster to changes in profit and hence overshooting is more likely and oscillation occurs. A smaller adjustment parameter implies the fixed point is more likely a stable proper node. Also the smaller the intrinsic growth rate is the more likely the equation is to be satisfied and the steady state is a stable spiral. If the intrinsic growth rate approaches zero the equation is satisfied since the steady state stock is smaller than the carrying capacity. A small intrinsic growth rate implies a slow growing stock, which makes overshooting of effort employed more likely. Also, the smaller the average cost of harvesting is or a relative large carrying capacity implies it is more likely the equation is satisfied and the steady state is a spiral.

The nullclines and possible trajectories are plotted in the phase diagram. Through every point in the phase diagram there is a trajectory. Trajectories intercept the E-nullcline horizontally and the S-nullcline vertically, trajectories cannot intercept each other.

Figure 2. Different possible trajectories plotted in a phase diagram, they indicate possible paths to follow to steady state dependent on the size of the response parameter, μ



Smith (1968) does not examine the effect of having an extreme large overshooting of effort and whether this overshooting can result in extinction of the resource or not. It is possible that the overshooting of effort is so large that the stock gets close to extinction along the optimal path to a positive steady state, but theoretically extinction will never occur as the slope of trajectories when the stock approaches zero is infinite. This is a specific case for the Schaefer production function and might chance with the choice of other production technologies. The slope of the trajectories is derived.

$$\frac{\Delta E_t / \Delta t}{\Delta S_t / \Delta t} = \frac{\Delta E_t}{\Delta S_t} = \frac{\mu\left[pqS_tE_t - cE_t\right]}{rS_t\left(1 - S_t / L\right) - qS_tE} \tag{2.18}$$

The limit is taken as the stock approaches zero.

$$\lim_{S\to 0}\frac{\Delta E}{\Delta S}=\lim_{S\to 0}\frac{\mu\left[pqSE-cE\right]}{S\left(r-r\,S/L-qE\right)}=\infty \tag{2.19}$$

To have extinction of the resource a finite slope is required, hence extinction in this model is not possible but as the adjustment parameter gets larger and larger the stock comes closer and closer to extinction and the overshooting becomes larger.

For empirical examples underlining this theory, see Wilen (1976) for the Pacific fur Seal who shows data follows a convergent spiral or Bjørndal and Conrad (1987) for the North Sea Herring stock who determined that the industry overshooted, but because of closure of the fishery the final 'bend' on a convergent spiral never occurred.

2.2. A more advanced example

This section distinguished from Smith (1968) as it allows for an area of different biological and technological functional forms. The biological dynamic is divided into a stock-recruitment function determining the recruits entering the stock and a growth function determining how the stock is growing based on natural growth and natural mortality. The functional forms are not specified. The function $F(S_t)$ determines the growth in the biomass, $G(S_{t-j})$ determines the recruits entering the biomass, where j is the age of the recruits when then enter the fished biomass and $H(S_t, E_t)$ is the harvest from the biomass, where S_t is the fished biomass at time t and E_t is the amount of effort employed in the industry at time t. It is assumed that the first derivative of the harvest with respect to stock respectively effort are positive; $H_S \geq 0$ and $H_E \geq 0$. The biological behavioural restriction is determined by the change in the biomass.

$$S_{t+1}-S_t=F(S_t)+G(S_{t-j})-H(S_t,E_t) \tag{2.20}$$

The profit in the industry is determined as the total revenue from selling the harvest minus cost of harvesting.

$$\pi = pH(S_t, E_t) - C(S_t, E_t) \tag{2.21}$$

When deciding whether an additional unit of effort is to be employed in the industry the amount of effort employed by the industry and the stock size is regarded outside control. Since we are assumed an open access, the behavioural restriction for the single fleet is determined by difference in the profit to zero.

The entry/exit process in the industry is determined by the returns in the industry, effort flows into the industry when there is a positive profit and extracts from the industry when there is a negative profit. For simplicity we are assuming constant average cost of production.[5]

$$E_{t+1} - E_t = \mu\left[pH(S_t, E_t) - C_t E_t\right] \tag{2.22}$$

Where μ is a behavioural constant, the larger μ the faster the industry reacts to changes in profit.[6] This equation determines the industry's behavioural equation.

The 'common property' character of the resource uniquely influences the cost structure of the recovery process. As a consequence there might by direct and significant diseconomies of production with divergence of private and social optima.

In steady state the stationary point(s) are defined where the stock in period t+1 equals the stock in period t and the effort in period t+1 equals the effort in period t for all future t. Assume therefore $S_{t+1} = S_t = S$ and $E_{t+1} = E_t = E$.

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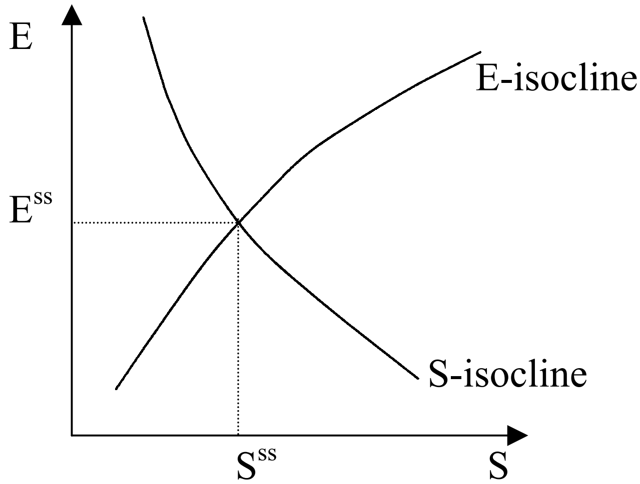
5 General cost hypothesis are that an increase in the catchability coefficient increases the cost; $\partial C/\partial q > 0$. An increase in the biomass increases the density and the species are easier to catch and thereby decreases the cost on the other hand if increases in the biomass do not change the density then it may be that cost are unchanged, hence $\partial C/\partial X \le 0$. If the inequality is strict, then recovery cost shows stock externalities. The efficiency of each unit of effort employed in the industry may be lowered by congestion, hence $\partial C/\partial E \ge 0$. If the inequality is strict, then recovery cost is said to suffer from crowding externalities.

6 One might assumed a different response parameter to positive respective negative profit, see Smith (1968).

A possible plot of the isoclines is illustrated where the intersection determines the steady state.

Figure 3. A possible plot of the stock and effort isoclines, when production function and growth function becomes more advanced



To determine the type of steady state the Jacobian matrix is derived, evaluated at steady state and its properties are evaluated.

The determinant of the Jacobian is derived.

$$
\begin{aligned}
|J| &= \left(F_S\left(S^{SS}\right) + dG_S\left(S^{SS}\right) - H_S\left(S^{SS}, E^{EE}\right)\right) * \\
&\left(pH_E\left(S^{SS}, E^{SS}\right) - C\right) + pH_S\left(S^{SS}, E^{SS}\right) H_E\left(S^{SS}, E^{SS}\right)
\end{aligned}
\tag{2.23}
$$

The trace of the Jacobian is derived.

$$
\begin{aligned}
Tr(J) &= \left(F_S\left(S^{SS}\right) + dG_S\left(S^{SS}\right) - H_S\left(S^{SS}, E^{EE}\right)\right) \\
&+ \left(pH_E\left(S^{SS}, E^{SS}\right) - C\right)
\end{aligned}
\tag{2.24}
$$

If the trace is negative and the determinant is positive, then the steady state is a stable solution, if the trace is positive and the determinant is positive then the solution is unstable, if the determinant is negative, then the solution is a saddle point.

Assuming the effect of an increase in the stock increases harvest faster than the increase resulting from recruits and growth, this implies $F_S\left(S^{SS}\right)+dG_S\left(S^{SS}\right)-H_S\left(S^{SS},E^{EE}\right)<0$ and the first large bracket of the determinant and the trace are both negative.

Since the model is based on open access assumptions the average profit is zero in steady state, therefore the marginal profit must be less than zero in steady state, this implies $pH_E\left(S^{SS},E^{SS}\right)-C<0$.

Making these assumptions and knowing the first derivative of harvest with respect to stock respectively effort are positive allows us to conclude that the determinant is positive and the trace is negative, and hence the steady state is a stable solution.

To every point in the phase diagram there exist a path to the steady state, the initial point or the starting point hence determines exactly which of these paths to follow to steady state. The initial point does not affect the type of steady state.

3. The case of the Baltic Sea Cod Fishery

The Baltic Sea Fishery is a shared resource stock among members of the European Union (EU) (Denmark, Finland, Germany and Sweden) and Estonia, Latvia, Lithuania, Poland and the Russian Federation. The Baltic Sea consist of the central Baltic Sea, the Gulf of Bothnia, the Gulf of Finland, the Sound and the Danish straits. The Baltic Sea is a shallow sea with an average dept of app. 60 m, the only connection with the world sea is the Sound and the Danish Straits, and hence a total replacement of the water in the sea takes on average at least 35 years.

The Sea consists of a two-layered water mass with the brackish water characteristics to north and east (salinity of 0.5 pro mille) and the higher salinity to the south and vest (salinity of 18 pro mille). The area is characterized as the world largest brackish water area. The variable environmental conditions and the salinity tolerance are reflected in the species in the different areas. Thus, the number of marine species is highest in the areas near the Danish Straits and diminishes eastwards and northwards, while the number of fresh water species increases when the salinity decreases. The Baltic Sea fish fauna includes some 100 species but only the four main commercial species are regulated, these are cod, herring, salmon and sprat.

Due to diversity in salinity in the Baltic Sea two distinct types of cod are present (Anon. (2000), IBSFC, Christensen & Jørgensen (1989)); the eastern Baltic cod, often referred to as the Baltic cod (Gadus morhua callarias L.) and western Baltic cod, which is the Atlantic cod (Gadus morhua L.). The two types of cod differ in population genetics. The eastern cod occurs in the central and the northern part of the Baltic, the western cod inhabits the areas west of Bornholm Island and the Danish Straits. The species overlap in the area near Bornholm Island but mixing is assumed to be minimal (Christensen & Jørgensen (1989)). The eastern cod population is the largest accounting for app. 90 % of the cod stock in the Baltic Sea (IBSFC (2000)). The main difference between the cod in the Baltic Sea and the North Sea is the ability to spawn in less salinity levels, hereunder an increase in the egg diameter to make the eggs float the further northeast the cod spawn. This section considers the eastern Baltic Sea cod.

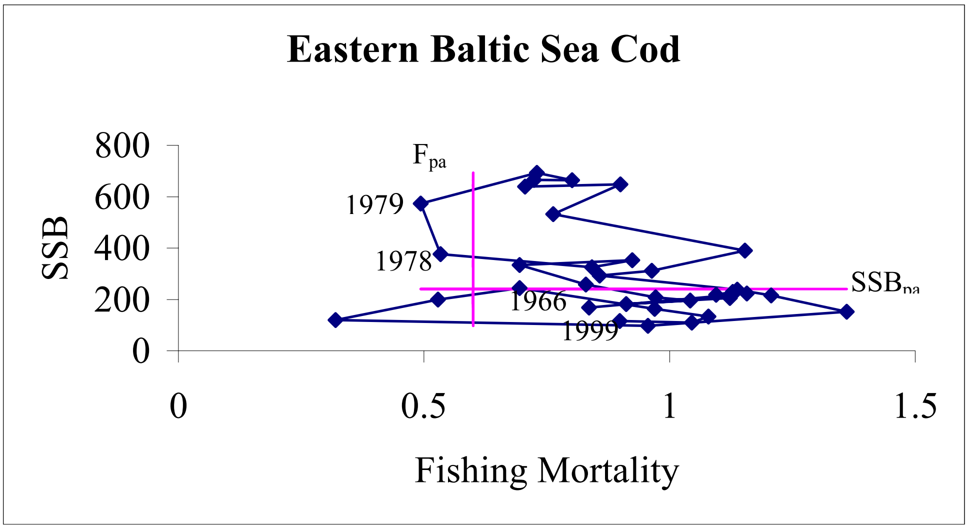
Cod is distributed over the entire Baltic Sea except the Bothnian Bay. In the Bothnian Sea and the Gulf of Finland the amount and the distribution of cod is rather limited except in periods with large stock.

The science regard the stock of the eastern Baltic cod without safe biological limits. The spawning stock has declined from historically low levels in 1980-1984 to the lowest level in record in 1992. The spawning stock has increased in most recent years, but is still below the long-term average.[7] In almost all years the landings have been far above the levels recommended by the science. The fleet capacity and fishing effort have not been reduced accordingly and the fish-

7 Due to favorable hydrographic conditions, unusually strong year classes in the late 1970's and early 1980's, which formed basis for additional exploitation in this period. It attracted vessels normally operating outside the Baltic Sea, and catch levels more than doubled, which probably can explain the historically low levels in 1984-1992. There were no TACs established by the IBSFC from 1982-1988.

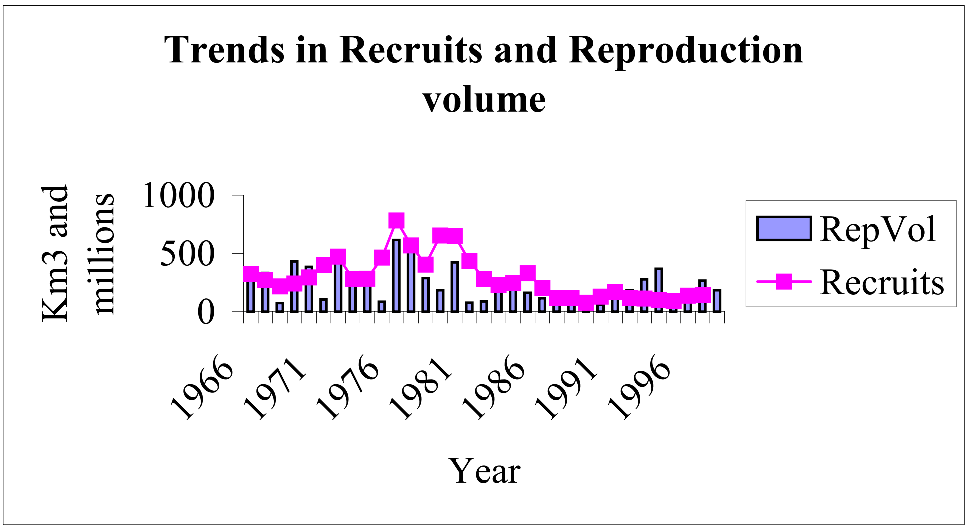
ing mortality has increased during the stock decline. The fishery is not sustainable under the current environmental conditions. Anon. (2000) estimates of the spawning stock biomass (SSB) indicate the second lowest level recorded since 1994 and is below the limit of the SSB (B_{lim}) estimated to 160000 tonnes. The fishing mortality is presently of 0.82, which is below the limit F_{lim} at 0.96 but above the precautionary approach estimated to 0.6. Because of the very low SSB the number of recruitments is considered dependent on the SSB, generally the recruitment has decreased over the last 3 decades. Considering the precautionary approaches for stock and fishing mortality set by ICES in 1999 it is seen that the stock only in 1978-1979 is within safe biological limits. For approximately half of the years in record the stock is exceeding the precautionary approach for the fishing mortality and is below the precautionary approach for the SSB, hence outside safe biological limits.

Figure 4. The SSB plotted against the fishing mortality for 1966-1999. Comparing with the precautionary approaches for biomass and fishing mortality in 1999 only two years in record (1978-1979) have been within safe biological limits



For successful spawning the cod eggs need minimum values for salinity (11 pro mille) and oxygen concentration (2 ml/l). These conditions only occur in the deepest areas as Bornholm Dee, Gdansk Deep and Gotland deep and are variable with inflows from the North Sea. Defining the size of the reproductive volume as the volume of water providing suitable conditions for successful cod spawning and plotting the reproduction volume against the recruits yields the following figure.

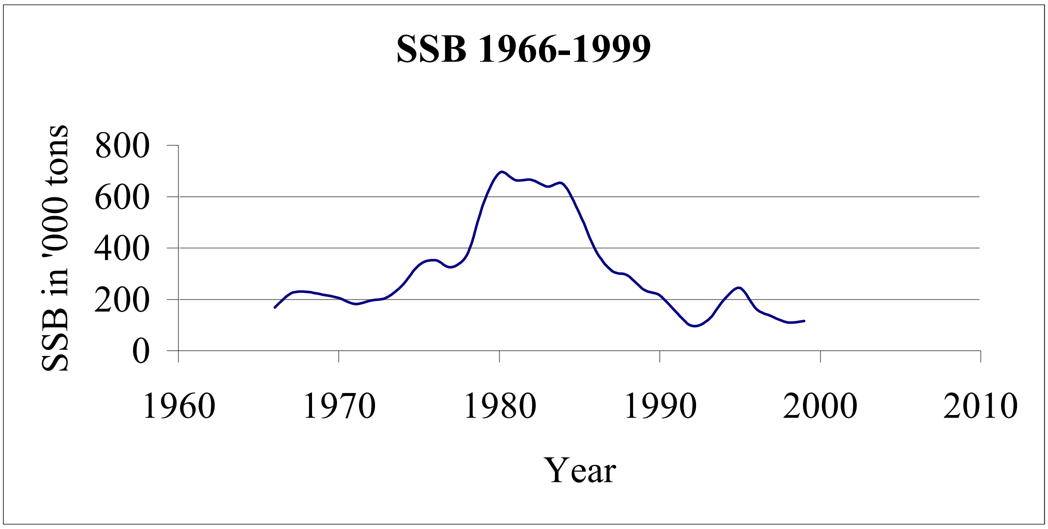
Figure 5. ***The reproduction volume in km^3 and the recruits in millions for cod in the eastern Baltic Sea for 1966-1999. Source: Aro (2000)***



The cod fishery in the eastern Baltic Sea has since 1966 been through an interesting development. Until 1981 the Baltic Sea experienced regularly inflows of saline water from the North Sea and hence yielded a relative high reproduction volume. During the same period the recruitment, measured at age 2 lagged 2 periods, is relatively high. Post 1981 the reproduction volume is lower and the recruitment are settled on a reduced level. The stock recruitment model in the most recent assessment (Anon. (2001)) is based on a Ricker curve based only on the years since 1982.

The high level of reproductive volume until 1982 combined with a TAC measure rebuilds the biomass to a high level. From 1982 to 1989 the biomass sustained on a higher, but decreasing, level, the fishery experienced an open access which resulted in huge effort since the numbers of trawls were increased and the gillnets were introduced. In addition the Baltic Sea experienced a lack of regularly inflows from the North Sea. This resulted in a undermining of the biomass until in 1989 where an extreme low level were reached and a new TAC introduced. Since 1989 the biomass has fluctuated on a critical low level.

Figure 6. The SSB in 1000 tons for cod in the eastern Baltic Sea for 1966-1999. Source: Anon. 2000



The cod fishery has thus experienced three phases

1. Build up of the biomass (1966-1982)
2. Undermining the biomass (1982-1989)
3. Effort to avoid an extinction of the cod in the Baltic Sea (1989-)

3.1. International Management of the Baltic Sea Cod

The International Baltic Sea Fisheries Committee (IBSFC) controls the fishing activity in the Baltic Sea, established on basis of the convention in 1973.

The main tool for management is total allowable catches (TACs), which IBSFC sets yearly, based on recommendations from the International Council for the Exploitation of the Sea (ICES), on the four main species (cod, herring, sprat and salmon) in the Baltic Sea. The first TAC for cod, herring and sprat were set in 1977 while the TAC for salmon was set in 1988. After IBSFC has allocated TAC's to the participating agents it is up to the authorities in the participating states to regulate and reinforce. The EU administers the TAC for the EU members. The TAC technical measures apply both to coastal zones and offshore because of need of consistency. In the Baltic Sea there is no generally accepted definition of a coastal zone. Several fisheries take place both in coastal zones and offshore.

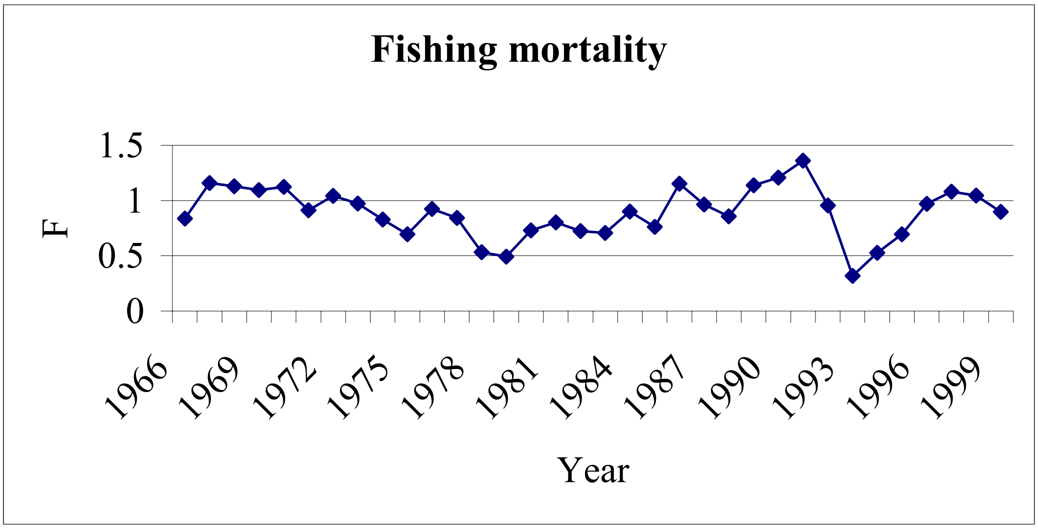
3.1.1. Total Allowable Catches

Until 1977 where IBSFC introduced the first TAC on cod in the Baltic Sea, the fishery was subject to an access based on bilateral agreement. In 1977 the exclusive economic zones was increased to 200 nautical miles dividing the territories according to the centre line, which gave some disputes around the islands Bornholm and Gotland. In particular the dispute between Sweden and Soviet around Gotland Island gave rise to an area frequently called the ‘white zone’ where there existed open access until 1987 where Sweden and Soviet came to an agreement. From 1977-1981 (both years included) TAC were set in other areas in the range from 174-235 thousand tons but in all of these years catch is exceeding the TAC. From 1982 to 1988 the fishery was not subject to any TAC and worked as an open access.[8] In 1989 a TAC at 220 thousand tons is re-introduced, and TAC measures are permanent for the future periods. The historically low level of the stock size in 1992 of both the eastern and the western stocks resulted in extremely low TAC-measures, in 1993 and 1994 the TAC are set at 40 and 60 thousand tons respectively, these are the only years in IBSFC management period, where the TAC are set below 100 thousand tones. Comparing the TAC with actual harvest indicates that the TAC often has been overruled. There have been no effective constraints on effort or activity of the existing fleet, therefore the fishery is considered to be a *de facto* open access.

The decline in the stock from 1983 to 1992 (where an extreme low level of spawning biomass was reported) might be explained by a lack of inflows, poor recruitment level and an increase in the fishing mortality. The fishing mortality is increased in the beginning of the eighties partly by the traditional fishery (bottom trawl fishery) and partly by the introduction of the gillnet fishery. The drop in the fishing mortality in the beginning of the nineties occurs shortly after the biomass is registered on a historical low level, the fishing mortality has however increased to be above one in the late nineties.

8 There might have been some technical measures regulating mesh size etc. and the EEZ existed but still the fishery was subject to a *de facto* open access.

Figure 7.   The fishing mortality for cod in the Eastern Baltic Sea 1966-1999. Source: Anon. 2000



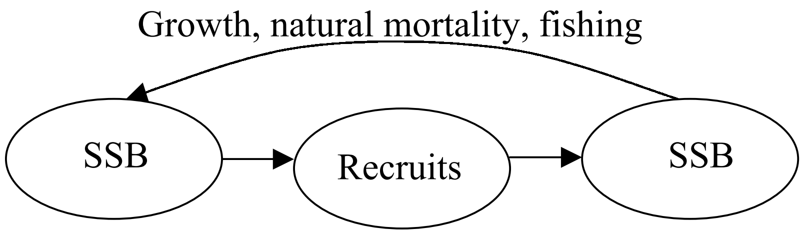
4.   The Model

This section applies a model based on the theory discussed in section 2.2. The model is divided into a model of the population dynamic and a model for the production function estimating specific functional forms. The functional forms applied are more advanced than the theory initially presented by Smith (1968) and applied to the Pacific fur seal by Wilen (1976) and applied to the North Sea herring by Bjørndal and Conrad (1987).

4.1.   Model for population dynamics

This section presents a simple description of the population dynamics. It is assumed that the increase in biomass results from natural growth and recruits, while the decrease in biomass is described by natural mortality and fishery.

Figure 8. The assumed relation between SSB and recruits for cod in the eastern Baltic Sea



Data in the eastern Baltic Sea cod fishery on harvest, biomass, recruits and other biological parameters are available from 1966-1999 (Source: Anon. (2000)). In the data set the recruits are measured at age 2 but are not assumed to enter the spawning stock biomass before age 3. The spawning stock biomass and the fished biomass are assumed to be equivalent, consisting of year class three and older.

The population dynamics are estimated as two separate functions; the stock-recruitment function and the growth function. The stock recruitment function describes the relationship between the spawning stock biomass and the recruits measured at age 2. The growth function determines the natural growth, and the natural mortality within the fished biomass, mortality from fishing is then subtracted. Hence the change in total resource stock is given by the growth to the stock plus the recruitment to the stock minus the harvest from the stock.

$$S_{t+1} - S_t = F(S_t) + G(S_{t-3}) - H(S_t, E_t) \tag{4.1}$$

Where S_t is the spawning stock biomass in year t, equivalent to the fished biomass, measured at the beginning of the year. F( ) is the growth function, G( ) is the stock recruitment function and H( ) is the harvest function in year t, measured at the end of the year.

The change in spawning stock is determined by three parts; the first part represent the natural change in stock caused by natural growth, natural mortality ignoring fishing mortality and the recruits. The second part determines the recruits that enter the biomass, since the spawning stock mainly consist of all year classes from three years and older, the recruitment to the stock depends on the size of the biomass lagged three periods. The lag three is chosen since the Baltic cod reach maturity around the age of 3 to 5 years. It is therefore assumed that at age three the recruits enter the SSB. It is tested whether the growth can be divided into natural growth and growth from recruits entering the stock. The Baltic Sea cod is assumed, much like other species in nature, to follow the logistic law of growth.

$$F(S_t) = aS_t - bS_t^2 \tag{4.2}$$

Where a is the intrinsic growth rate describing the growth in the stock when the biomass is small, b is the intrinsic growth rate divided by the carrying capacity for the growth function.

The recruits are assumed to enter the biomass at an age of three, since recruits measured from the stock are two years, only a fraction of these recruits survives and enters the SSB.

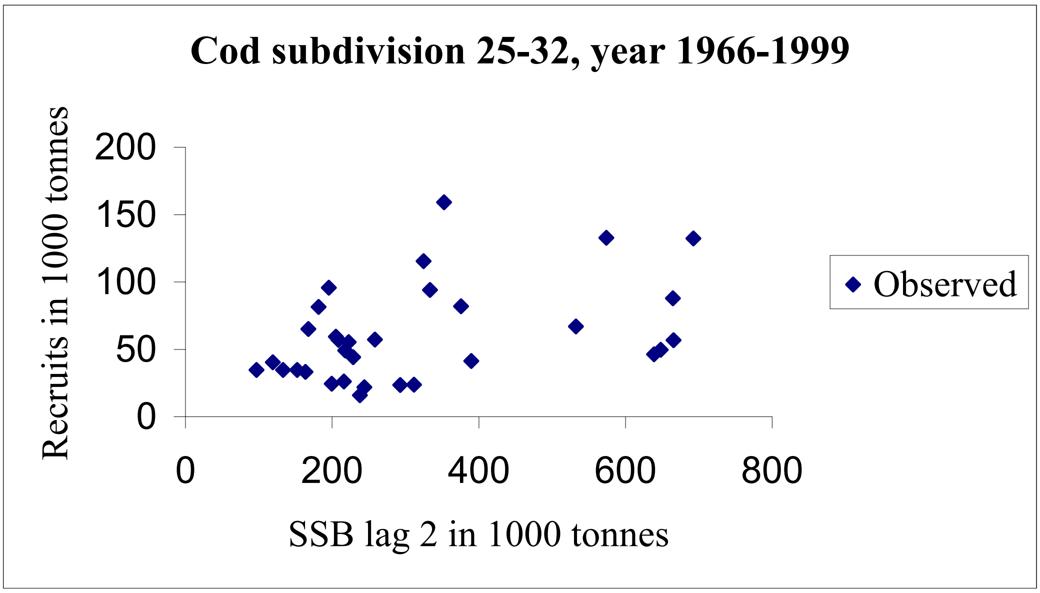
$$G(S_{t-3}) = dR_{t-1}(S_{t-3}) \tag{4.3}$$

Where d is the fraction of recruits surviving to year three when they enter the spawning stock biomass. The number of recruits is measured at age two.

4.2. Estimation of specific biological functional forms

The recruits at age 2 measured in thousand tonnes are plotted against the SSB in thousand tonnes lagged two periods.

Figure 9. ***The reproduction volume in km^3 and the recruits in millions for 1966-1999. Source: Aro***



Different recruitment functions are tested including different environmental variables to test, which one gives the best fit. The recruits are tested to follow a Ricker function, a Beverton-Holt function, a logistic growth function or a quadratic relationship with constant recruits for low level of biomass. Two environmental variables are included. Firstly it is tested whether a dummy for years with high salinity inflows is significant. This is however not the case in any of the functions when they are corrected for autocorrelation of first order. Secondly a variable measuring the reproduction volume is included. This variable turns out being significant in a Ricker recruitment function, but since there is no reliable way of predicting the size of the reproductive volume the approach applied in Anon. (2001) is also applied further in the paper. That is, according to the figure 5 the lack of regularly inflows reduces the reproduction volume since 1982 and the recruitment experience a shift reflecting a reduced level of recruitment since 1982.

The most significant recruitment function when corrected for heteroskedasticity is the Ricker recruitment function. The Ricker recruitment function is estimated as a conventional Ricker curve, a pre1981 and a post1981 Ricker curve.

The conventional Ricker curve corrected for autocorrelation is significant on a 9%-level.

$$Log\left(R_{t-1}/S_{t-3}\right) = -1.17 - 0.0018S_{t-3} \qquad \bar{R}^2 = 0.62 \tag{4.4a}$$
$$(-2.91) \quad (-1.79)$$

$$R_{t-1} = S_{t-3}e^{\left(-1.17-0.0018SSB_{t-3}\right)} \tag{b}$$

The Pre1981 Ricker curve includes data from 1966-1981 (both years included). The estimation is significant on a 12%-level but has an extremely low adjusted R-squared.

$$Log\left(R_{t-1}/S_{t-3}\right) = -0.98 - 0.000898S_{t-3} \qquad \bar{R}^2 = 0.12 \tag{4.5a}$$
$$(-5.51) \quad (-1.70)$$

$$R_{t-1} = S_{t-3}e^{\left(-0.98-0.000898SB_{t-3}\right)} \tag{b}$$

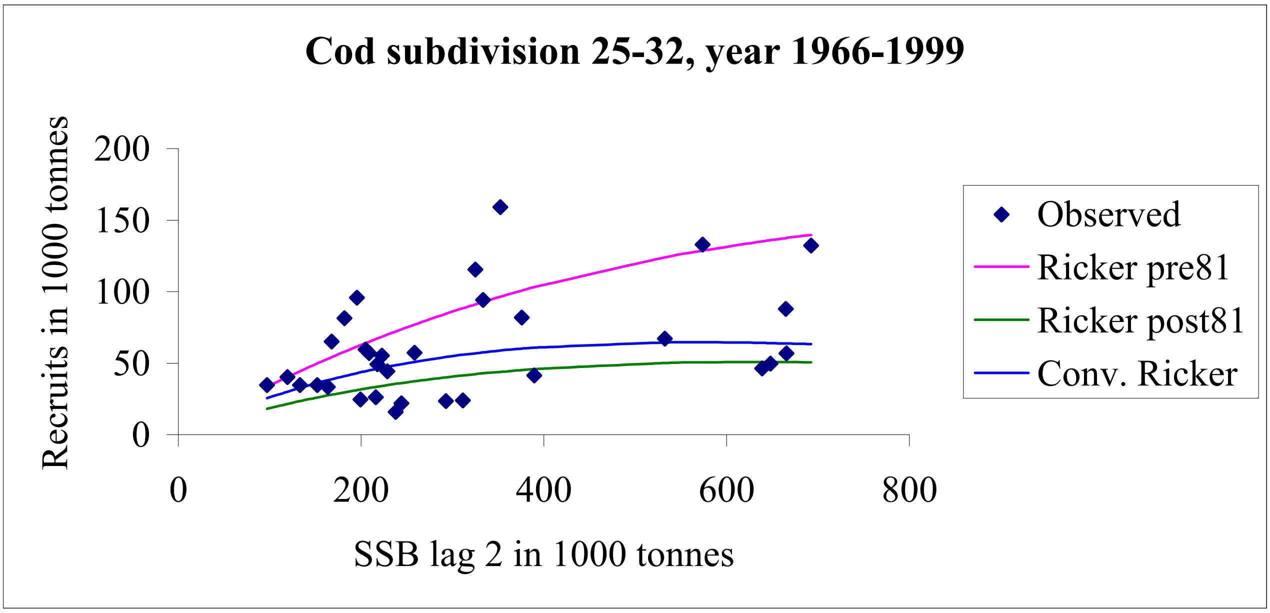
The post1981 Ricker curve is significant on a 5%-level

$$Log\left(R_{t-1}/S_{t-3}\right) = -1.53 - 0.0016S_{t-3} \qquad \bar{R}^2 = 0.31 \tag{4.6a}$$
$$(-7.17) \quad (-2.89)$$

$$R_{t-1} = S_{t-3}e^{\left(-1.53-0.0016SSB_{t-3}\right)} \tag{b}$$

Plotting these curves against the observed biomass and recruits yields the following figure.

Figure 10. The observed stock-recruitment relationship and 3 estimated Ricker recruitment functions. The Ricker pre81 for the period 1966-1981, the Ricker post81 for the period 1982-1999 and the conventional Ricker for the whole period 1966-1999. Source: Anon. 2000 and own calculations



Since other data applied later on in the model are newer data. Therefore the post 1981 Ricker curve is most relevant but might be considered as a pessimistic view of the recruits since it only reflects the period with low recruitment. A more optimistic view is the conventional Ricker curve, the recruitment curve is further assumed to be in the span between the two curves.

The growth, not considering recruits and harvest is estimated as a logistic function and is assumed not to experience any shift in level be identical over the whole record period. The subtraction of recruits and harvest allows estimating the growth resulting from natural growth and natural mortality. The estimated logistic growth curve looks as follows, where it is assumed that the growth occur before the stock is harvested.

$$(S-R)_{t+1} = \underset{(31.50)}{1.43S_t} - \underset{(-2.51)}{0.00021S_t^2} - H_t \qquad \bar{R}^2 = 0.96 \tag{4.7}$$

The fraction of cod surviving from year class 2 to year class 3, d, is estimated to be 0.76, with $\overline{R}^2 = 0.99$ and t-stat 158.97.

Hence the biological growth function ignoring harvest can be determined.

$$S_{t+1} - S_t = aS_t + bS_t^2 + d\left(S_{t-3}e^{c_1 + c_2 S_{t-3}}\right) \tag{4.8}$$

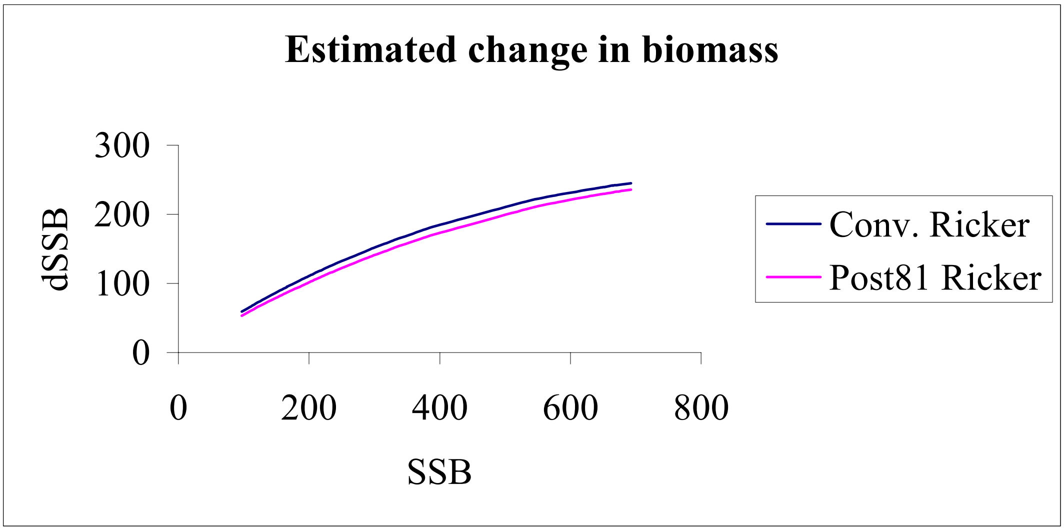
Where the parameter estimates are collected in the following table.

Table 1. The parameters estimated for an optimistic and a pessimistic Ricker recruitment function

	a	b	c_1	c_2	d
Pessimistic View	0,43	-0,00021	-1,529	-0,001568	0,76
Optimistic view	0,43	-0,00021	-1,167	-0,001771	0,76

The combined growth curves with the pessimistic (post81) and the optimistic (conv.) views are plotted in the following diagram.

Figure 11. The difference between the pessimistic (post81) stock-recruitment function and the optimistic (conventional) stock recruitment function



4.3. Model for the productivity dynamics

The data for the production dynamics are based on a sample period 1987-1999; data source Danish Research Institute of Food Economics. A single vessel is representative for the fleet.

4.3.1. The selected vessel

A typical vessel for the Danish cod fishery in the Eastern Baltic Sea is selected in order to describe the fishery. The selected vessel has a tonnage of 49,35 BRT which is a medium to large vessel in the Baltic Sea. The vessel is a trawl, which is the most common type of vessel catching cod in the Baltic Sea (Frost & Andersen (2001)). The vessel has been harvesting cod in the Baltic Sea during the whole sample period. In the beginning of the sample period the harvest consisted of almost 100% cod from the Baltic Sea. Later in the sample period the stock decreased and the composition of the harvest changes. The cod ratio from cod harvested in the Baltic Sea decreased to as little as to 2,6 %, this is a typical picture of the fleet in the Baltic Sea. In the end of the period the cod ratio increased to almost 50 %. Data for the selected vessel are shown in appendix V.

4.4. Measuring effort

Effort is measured in days at sea in sub-area 3D, which refers to the eastern Baltic Sea, which is the area of the Baltic Sea east of Bornholm Island. The data for the selected vessel in marked with a superscript i. Effort for the selected vessel, i, in the cod fishery, E_t^i, is measured as days in area 3D times the share of the value of the total catch, which is cod compared to other species harvested in the area.

$$E_t^i = days_t^i \frac{Value\ of\ cod\ \ in\ 3D^i}{Total\ value\ of\ catch^i} \tag{4.9}$$

The total effort employed in the Danish industry is determined. The Danish industry is marked with an superscript DK. Dividing the effort with the amount of cod caught by the selected vessel gives an inverse catch per unit of effort

(CPUE) measure, by multiplying with the total amount of cod caught in the Danish industry in the Baltic Sea the days at sea is measured for the respective year for the Danish industry.

$$E_t^{DK} = \frac{E_t^i}{Amount\ of\ cod^i} Amount\ of\ cod^{DK} \tag{4.10}$$

The effort employed in the rest of the industry is calculated by assuming it is proportional to the effort employed in Denmark, where the proportion is determined by the harvest ratio.

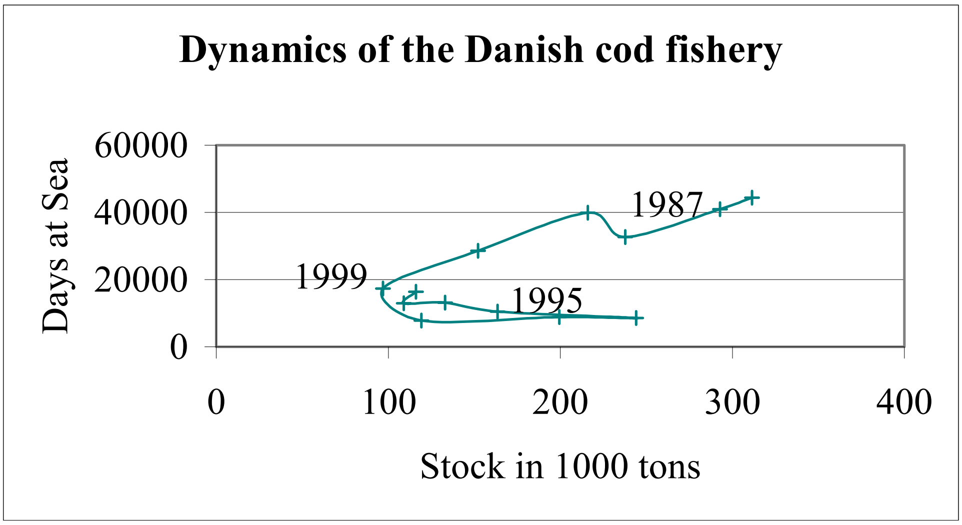
In the eastern Baltic Sea 77% of the value of the catch share of cod landed in Denmark in 1997 is caught by vessels belonging to Bornholm (Frost & Andersen (2001)), therefore the yearly cost per vessel applied in the data set are the yearly cost per vessel belonging to the region of Bornholm. The data on total yearly cost are found in the Account Statistics for Fishery 1995-1999, for calculation of the variable cost in the cod fishery see appendix III.

Table 2. Data for the eastern Baltic Sea cod fishery

Year	SSB 1000 tonnes	Danish harvest 1000 tonnes	Effort in Danish industry Days at sea	Yearly var. cost/trawl for cod in 3D, 1000 DKK	Price DKK/kg	Daily cost for cod in 3D 1000 DKK
1987	311,52	60,55	44346,46		7,08	
1988	292,91	56,50	40997,16		6,80	
1989	237,78	48,45	32630,67		6,96	
1990	216,01	41,96	39885,21		9,31	
1991	152,10	35,10	28558,82		10,19	
1992	96,96	14,92	17358,64		9,74	
1993	119,27	4,56	7843,20		7,08	
1994	199,45	12,23	8824,83		6,85	
1995	244,13	20,10	8559,17	175,91	6,48	5,80
1996	163,55	29,66	10451,19	259,92	5,99	8,40
1997	133,00	19,33	13144,53	277,41	7,44	5,37
1998	109,10	15,50	12942,09	653,70	10,05	6,28
1999	116,04	20,14	16333,54	686,33	10,41	6,61

Source: Danish Research Institute of Food Economics and own calculations.
A state-space diagram shows the combinations of the stock size and the days at sea for the period 1987-1999 for the Danish fleet, it helps illustrate the dynamics of the fishery.

Figure 12. A state-space diagram shows the combinations of the stock size and the days at sea for the period 1987-1999 for the Danish fleet. Source: Own calculations



4.5. Estimations of a specific form of the production function

Production functions are estimated in order to determine the steady state. Production functions are estimated based on the Danish industry. To find the best fit four different types of production function are estimated for the Danish trawl fleet harvesting cod in the Eastern Baltic Sea. These production functions are; A production function only dependent on the days at sea, a Cobb-Douglas production function, a Cobb-Douglas production function with the exponent of days equals one and an exponential production function, ensuring no more than the size of the stock is harvested. Estimation results for the different production functions can bee seen in appendix II.

The Cobb-Douglas function has the most significant estimates and is therefore applied in further analysis. The estimation is significant on a 7%-level and has a high adjusted R^2. The regression is OLS with t-statistics in brackets.

The Cobb-Douglas production function

$$Ln(H_t) = -7.472 + 0.748\, ln(days_t) + 0.644\, ln(S_t) \qquad \bar{R}^2 = 0.75 \qquad (4.11a)$$
$$(-4.358) \quad (3.969) \qquad (2.086)$$

$$H_t = 0.00057\, days_t^{0.748} S_t^{0.644} \qquad (b)$$

Hence assuming the total industry follows the estimated Cobb-Douglas production function[9] and assuming the vessel dynamic occurs according to the normalized profit per day at sea yields the following entry-exit procedure.

$$days_{t+1} - days_t = \delta \left(\frac{p \cdot c \cdot days_t^{\alpha} \cdot S_t^{\beta} - cost \cdot days_t}{p \cdot days} \right) \qquad (4.12)$$

Where δ is the response parameter determining how fast the number of days at sea are changed according to changes in profit. Estimates indicate that δ=4,07 is highly significant, with an adjusted $R^2 = 0.92$.

4.5.1. The total effort in the industry

The total effort in the industry is calculated by assuming that the total effort is proportional to the Danish effort employed, where the proportion is assumed to depend on the harvest ratio.

$$E_t = E_t^{DK} \frac{Amount\ of\ cod}{Amount\ of\ cod^{DK}} = \frac{E_t^i}{Amount\ of\ cod^i} Amount\ of\ cod \qquad (4.13)$$

The calculated effort for the industry is illustrated in the following table.

9 Since data for the whole industry not are available, the procedure assumed for estimating the production function follows the idea from Bjørndal and Conrad (1987) namely assuming the industry follows the production function estimated for a single highly representative country, in our case Denmark.

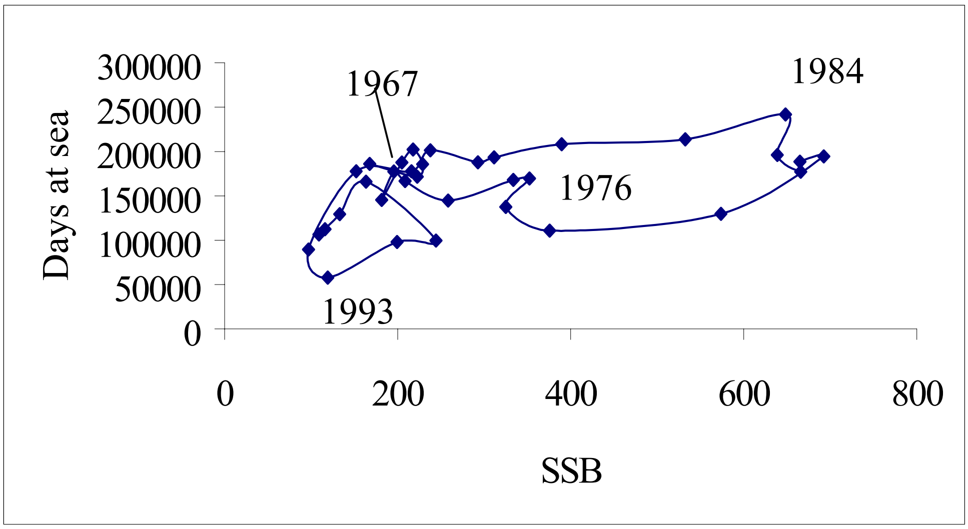
Table 3. Data for the eastern Baltic Sea cod fishery and the calculated effort for the whole industry

Year	Stock 1000 tons	Danish Harvest 1000 tons	Total Harvest 1000 tons	Total effort Days at sea
1987	311,515	60,55	207,081	151659,5
1988	292,91	56,50	194,787	141339,5
1989	237,777	48,45	179,178	120680
1990	216,007	41,96	153,546	145969,2
1991	152,103	35,10	122,517	99671,9
1992	96,963	14,92	54,882	63854,71
1993	119,265	4,56	45,183	77758,12
1994	199,454	12,23	93,354	67372,51
1995	244,13	20,10	107,718	45877,96
1996	163,546	29,66	121,889	42946,12
1997	133,003	19,33	88,6	60260,36
1998	109,1	15,50	67,429	56312,29
1999	116,037	20,14	72,989	59197,44

Since no estimates of effort earlier than 1987 are available, the effort is assumed to depend on the stock size and the fishing mortality. It is tested whether the effort is linear in fishing mortality, linear in the product of the fishing mortality and the biomass and whether it is log-linear in the fishing mortality and the biomass level. The most significant estimation indicates that the effort is linear in the product of the biomass and the fishing mortality.[10] Assuming the effort follows this relation allows for estimates of effort level from 1966-1999. The estimates of effort level for the total industry from 1966-1999 are included in appendix IV. A state-space diagram shows the combinations of the stock size and the days at sea for the period 1987-1999 for the total industry.

10 The estimation is significant on a 1%-level with an adjusted R^2=0,60.

Figure 13. A state-space diagram shows the combinations of the stock size and the days at sea for the period 1966-1999 for the total fleet harvesting cod in the eastern Baltic Sea. Source: Own calculations



5. Analysis and conclusion

Assuming the dynamics follows the estimated for stock-recruitment, growth and harvest, then the system of equations looks like follows.

$$days_{t+1} - days_t = \delta\left(\frac{p \cdot c \cdot days_t^{\alpha} \cdot S_t^{\beta} - cost \cdot days_t}{p \cdot days}\right) \quad (5.1)$$

$$S_{t+1} - S_t = aS_t - bS_t^2 + d\left(c_1 + c_2 S_{t-3}^2\right) - c \cdot days_t^{\alpha} \cdot S_t^{\beta} \quad (5.2)$$

Where the parameter values are collected in the following table.

Table 4. Parameter values estimated for the set of equations describing the dynamic system

a	α	b	β	c	c_1	c_2	D	δ
0,43	0,748	-0,00021	0,644	0,00057	40,74	0,00012	0,76	4,07

5.1. *Solving for steady state numerically*

The steady state is solved numerically for different values of price and cost. This is done by an initial guess for the days at sea inserted in the first equation for steady state. It thereby provides a value for the stock, which is substituted into the second equation for the steady state. The difference between initial guess and calculated value of days at sea is evaluated to see whether it is within an arbitrary value ε, if not then readjust the guess to the mean of the former guess and the calculated value. The process will converge to the steady state either from above or below.

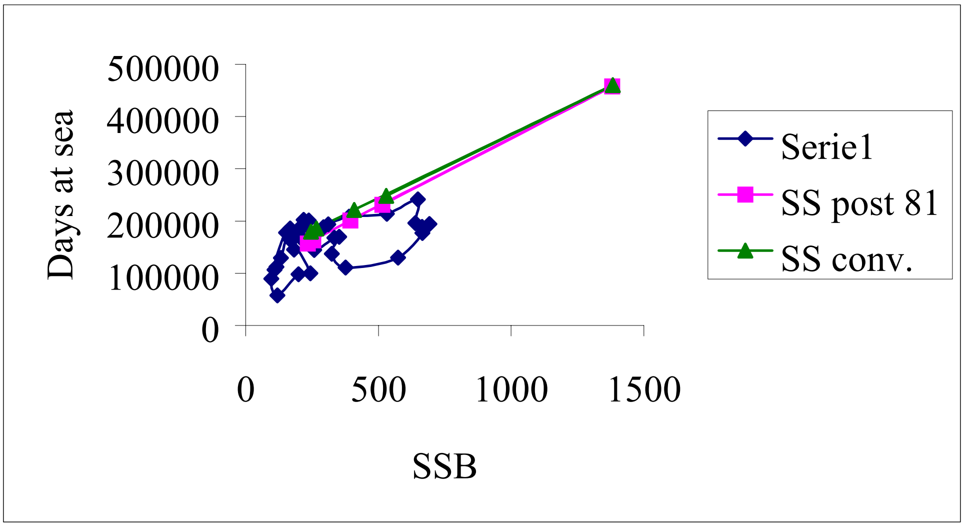
The following table illustrates the steady state for different cost and price values.

Table 5. Numerical simulations of the steady state values for the eastern Baltic Sea cod fishery

Year	Cost pr. day at sea DKK	Price DKK/kg	Price/cost ratio	Stock Conv. 1000 ton.	Days Conv.	Stock Post 81 1000 ton.	Days Post 81
1995	5795,59	6,56	0,001131	529,17	248154	514,57	231025
1996	8396,18	5,98	0,000712	1383,50	460160	1380,38	457514
1997	5371,55	6,97	0,001298	408,62	221060	393,84	201196
1998	6277,47	10,25	0,001633	267,0288	185361,4	253,9434	163025
1999	6605,13	11,26	0,001705	246,46	179432	233,85	156899

Plotting the state-space for the total effort and the steady state for the years 1995-1999 yields the following figure. It is noted that the steady state is very sensitive both in its biomass level and in its effort level to changes in the price-cost ratio. In 1996 where the price-cost ratio is extremely low the model suggest an unrealistic high level of biomass and effort.

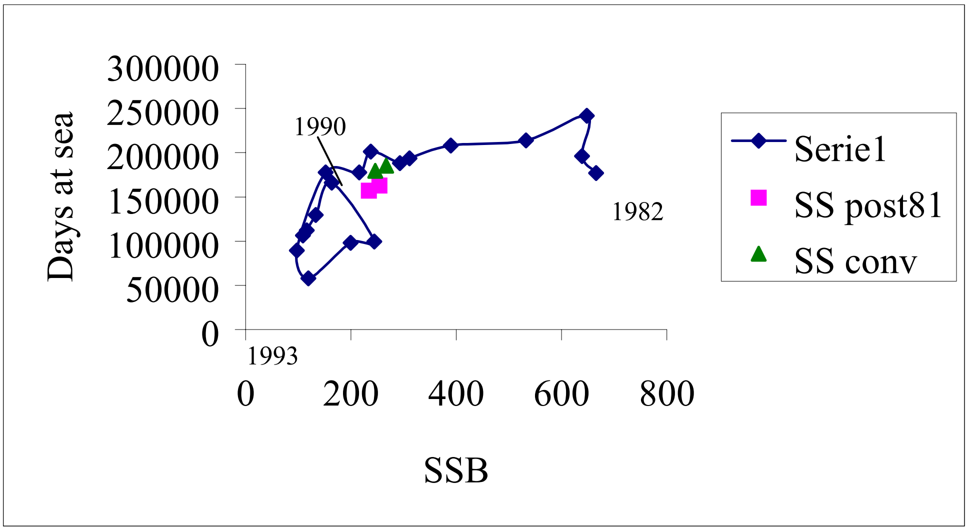
Figure 14. A state-space diagram shows the combinations of the stock size and the days at sea for the period 1966-1999 for the total fleet and the optimistic and the pessimistic steady states. Source: Own calculations



When the price-cost ratio is high as in 1998 and 1999 the biomass in steady state is low since it becomes more profitable to harvest down the stock. When the price-cost ratio is low as in 1996 the biomass in steady state is high and it is relatively more profitable to invest in the stock.

Assuming the 1998 and 1999 price and cost are fixed gives an area within the steady state is believed to be located. Plotting the steady state and the effort level in the industry from 1982-1999 yields a diagram indicating a movement to the steady state almost following a stable spiral where overshooting occurs in late 70'ties or early 90'ties. Hence the cod fishery in the Baltic Sea seeming follows the same pattern as the North Pacific fur seal fishery Wilen (1976) and the North Sea Herring fishery Bjørndal and Conrad (1987).

Figure 15. ***A state-space diagram shows the combinations of the stock size and the days at sea for the period 1982-1999 for the total fleet, fixing price-cost at the 1998-1999 level allows us to derive an area of steady states, indicating an overshooting of effort in the 90'ties. Source: Own calculations***



5.2. Conclusion

The results presented are not the first in the area but are more advanced then the first presentations of Wilen (1976) and Bjørndal & Conrad (1987) who tested the basic dynamic model presented by Smith (1968). The applied model shows with the more advanced biological function separating recruits and growth in the biomass and the Cobb-Douglas production function the eastern Baltic Sea fishery most likely has a stable steady state. The steady state does however assumed fixed price-cost ratio. The optimal path to the steady state is a spiral why the path to steady state involves overshooting of effort and hence a (extreme) low level of biomass as is also the case in the earlier applications of the theory. The model suggests that the resource might be on its path to steady state.

These results of the Baltic Sea cod fishery show that even though the biomass has been critically low in 1992 the decrease in the pressure on the fishery made the stock increase avoiding extinction and starting an oscillation. The overshooting of effort only occurs in the first loop of the spiral, the biomass does not increase enough for overshooting of effort occurring again. That the biomass does not increase enough to end the convergent spiral path might be explained by the resource being outside safe biological limits. In more that half of the years in record the biomass is lower than the precautionary approach and the fishing mortality is exceeding the precautionary approach. The only years in record where the stock is within safe biological limits are the years 1978-1979, which are the years the stock is declining from in the data applied for this approach. The Baltic Sea cod fishery is thus shown to follow a convergent spiral to steady state, where overshooting occurs in 1991 resulting to a historical low level of biomass in 1992. The steady state level is however very sensitive to changes in price and cost levels. This is a critical limitation of the simulation model since the price-cost ratio is assumed to be fixed after determining the steady state.

Further limitations are that the data for the effort level are only based on a single typical Danish vessel; the author did not have other country specific data available it could however be interesting to examine the effect of other production functions estimated on the basis of data for the whole area. Also it is not taken into consideration the changes in the steady state level as price and cost ratio changes, price and cost are again based solely on the Danish data, here further research would be to examine the effect of changing price-cost ratio and hence the effect of a moving steady state.

Even this model has become slightly more advanced than earlier work in the area more research are still needed, among other things are to be examined the limitation of having constant average cost in the fishery and the effect of replacing the response parameter with a response function for instance including profits in other alternative fisheries.

6. References

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7. Appendix I

Table 7.1. TACs for cod in the Baltic Sea set by IBSFC

Year	TAC	Catch			*	Advice ICES		Catch - advice		TAC -
		West	East	Total	q - TAC	West	East	West	East	advice
1974		46,6	147,8	194,4						
1975		44,4	194,6	239,0						
1976		49,4	203,3	252,7						
1977	185	46,3	164,8	211,1	26,1					
1978	174	40,6	154,0	194,6	20,6					
1979	175	45,0	227,7	272,7	97,7					
1980	235	42,0	347,6	389,6	154,6					
1981	227	53,6	330,7	384,4	157,4					
1982		47,5	316,1	363,6						
1983		48,6	332,1	380,8						
1984		49,5	392,0	441,4						
1985		40,2	315,1	355,2						
1986		26,7	252,6	279,3						
1987		28,6	207,1	235,6		9	245	19,6	-37,9	
1988		29,2	194,8	223,9		16	150	13,2	44,8	
1989	220	18,5	179,2	197,7	-22,3	14	179	4,5	0,2	-27
1990	211	17,8	153,5	171,3	-39,7	8	129	9,8	24,5	-74
1991	171	16,7	122,5	139,2	-31,8	11	122	5,7	0,5	-38
1992	100	18,0	54,9	72,9	-27,1					
1993	40	21,2	45,2	66,4	26,4		0		45,2	-40
1994	60	30,7	93,4	124,0	64,0	22	25	8,7	68,4	-13
1995	120	33,9	107,7	141,6	21,6					
1996	165	50,8	121,9	172,7	7,7					
1997	180	43,6	88,6	132,2	-47,8		130	43,6	-41,4	-50
1998	145	34,2	67,3	101,5	-43,5	35	60	-0,8	7,3	-50
1999	126					38	88			0
2000	105					44,6	60			0

Note: The years 1992-1995 suffers from incomplete reporting.
* describes the deviation in total catch from the advise.
Source: ACFM (2000) and own calculations.

8. Appendix II - Estimation results

8.1. Production function estimations

All regressions are OLS with t-statistics in brackets.
A production function only dependent on the days at sea

$$\underset{}{Ln(H_t) = \underset{(-3.378)}{-6.129} + \underset{(5.131)}{0.949}\, ln(days_t)} \qquad \bar{R}^2 = 0.68 \tag{8.1a}$$

$$H_t = 0.00218 days_t^{0.949} \tag{b}$$

A Cobb-Douglas production function

$$Ln(H_t) = \underset{(-4.358)}{-7.472} + \underset{(3.969)}{0.748}\, ln(days_t) + \underset{(2.086)}{0.644}\, ln(S_t) \qquad \bar{R}^2 = 0.75 \tag{8.2a}$$

$$H_t = 0.00057 days_t^{0.748} S_t^{0.644} \tag{b}$$

An exponential production functio n, ensuring no more than the size of the stock is harvested.

$$Ln(S_t - H_t) = \underset{(-1.905)}{-0.399} + \underset{(24.333)}{1.065}\, ln(S_t) - \underset{(-3.822)}{0.00000481} days_t \qquad \bar{R}^2 = 0.99 \tag{8.3a}$$

$$H_t = S_t\left(1 - e^{-0.00000481 days_t}\right) \tag{b}$$

The Wald coefficient test shows that the null-hypothesis where the constant equals zero and the coefficient in front of ln(S) equals one cannot be rejected. Therefore the parameters are set to be respectively zero and one in the associated production function.
The exponents on $days_t$ in the first two estimations indicates a yield/days at sea elasticity smaller than one, this might be explained by no economies of scale as in a schooling fishery.

A Cobb-Douglas production function with the exponent of days equals one

$$Ln(H_t / days_t) = -8.856 + 0.432\, ln(S_t) \qquad \bar{R}^2 = 0.11 \quad (8.4a)$$
$$(-6.252) \quad (1.575)$$

$$H_t = 0.00014 S_t^{0.432} days_t \qquad (b)$$

9. Appendix III

Calculation of the variable cost of the Danish cod fishery in the Baltic Sea

	1995	1996	1997	1998	1999
A) Gross output for cod in 3D, 1000kr/firm	429,35	524,87	495,67	1065,50	1302,40
B) Gross output in total, 1000kr/firm	1888,40	2045,68	2500,37	2260,83	2623,07
C) Share of cod (A/B)	0,23	0,26	0,20	0,47	0,50
D) Total cost, 1000kr/firm	737,20	869,90	1278,40	1187,60	1291,00
E) Total cost of hired labor, 1000kr/firm	208,80	240,20	405,80	421,90	456,00
F) Depreciation, 1000kr/firm	162,20	171,80	200,60	177,30	182,00
G) Labor input of crew, Days at sea/firm	153,00	148,50	235,10	242,10	265,27
H) Labor input of fisherman, Days at sea/firm	145,60	194,70	186,30	216,20	158,97
I) Wage per day (E/G)	1,36	1,62	1,73	1,74	1,72
J) Labor cost of fisherman, 1000kr/firm (I*H)	198,70	314,93	321,57	376,76	273,28
K) Variable cost, 1000kr/firm (J+D-F)	773,70	1013,03	1399,37	1387,06	1382,28
L) Variable cost of cod, 1000kr/firm (K*C)	175,91	259,92	277,41	653,70	686,33
M) Vessel profit, 1000kr/firm (A-L)	253,44	264,95	218,26	411,79	616,07
N) Days at sea harvesting cod in 3D pr. firm	30,35	30,96	51,64	104,13	103,91
O) Variable cost per day, kr. (L/N*1000)	5795,59	8396,18	5371,55	6277,48	6605,13

Source: Fiskeriregnskabsstatistik 1995-1999.

10. Appendix IV

Calculated effort level in the total industry for cod fishery in the eastern Baltic Sea 1966-1999.

Year	SSB	Fishing Mortality Age 4-7	Estimate Days at sea
1966	167,655	0,8358	68782,59
1967	222,639	1,1574	126486,6
1968	228,855	1,1289	126816,4
1969	217,804	1,0948	117047
1970	205,063	1,1227	113008,4
1971	181,671	0,9119	81319,09
1972	195,548	1,0419	100009
1973	208,71	0,9716	99538,35
1974	258,466	0,8296	105252,4
1975	333,55	0,6943	113675,7
1976	352,515	0,9243	159937,5
1977	324,917	0,8418	134258,3
1978	375,705	0,5337	98424,64
1979	573,723	0,4932	138894,5
1980	692,578	0,73	248171,1
1981	664,691	0,8018	261604,7
1982	665,617	0,724	236549,8
1983	638,764	0,7054	221174,8
1984	648,115	0,9001	286353,5
1985	532,292	0,7628	199306
1986	389,569	1,1531	220501,2
1987	311,515	0,9635	147329,7
1988	292,91	0,8577	123318,8
1989	237,777	1,1376	132775,9
1990	216,007	1,2068	127956,6
1991	152,103	1,3608	101599,5
1992	96,963	0,956	45501,28
1993	119,265	0,3199	18727,81

1994	199,454	0,5284	51732,71
1995	244,13	0,6944	83212,88
1996	163,546	0,9696	77838,1
1997	133,003	1,0793	70463,35
1998	109,1	1,0452	55973,68
1999	116,037	0,8988	51194,02

11. Appendix V

Data for the selected Danish vessel harvesting cod in the Eastern Baltic Sea

Year	Harvest Cod in 3D	Harvest Cod in 3D	Days at sea in 3D	Total harvest 3D	Total harvest 3D	All waters	All waters Harvest	All waters Harvest	Cod/total harvest	Price DKK/kg
1987	240416	1869310	182	244497	1899983	182	244497	1899983	0,983856	7,775314
1988	267005	1855355	205	274520	1909428	205	274520	1909428	0,971681	6,948765
1989	217022	1588785	151	219803	1620533	174	230840	1825886	0,870145	7,320848
1990	152593	1478185	151	156516	1500114	187	168786	1869255	0,790788	9,687109
1991	128649	1330311	114	137056	1360140	197	173036	2153485	0,617748	10,34062
1992	89677	951756	118	98805	976935	227	168037	2243821	0,424168	10,61316
1993	14810	107858	27	15347	110261	134	85078	1170929	0,092113	7,282782
1994	5360	39029	4	5507	39281	130	122170	1515100	0,02576	7,28153
1995	65481	429349	32	71265	452656	154	160695	1888399	0,227361	6,556849
1996	87817	524865	31	87860	525604	167	175875	2045677	0,256573	5,976804
1997	71096	495672	54	75932	518281	204	174013	2500365	0,19824	6,971869
1998	103945	1065495	111	124692	1135741	199	167260	2260830	0,471285	10,25057
1999	115621	1302396	108	128116	1353686	211	161537	2623068	0,496516	11,26436

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