# Marginal damage cost of nutrient enrichment: the case of the Baltic Sea

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## Abstract

*The purpose of the article is to investigate the link between pollution and marine renewable resources. A bio-economic model of a fishery is developed to derive a marginal damage function for nutrient enrichment using the dynamic production function approach. This function can be compared with the marginal abatement cost and hence it provides the basis for polices that balance the use of nutrients in land-based industries (for example agriculture) with the external cost in the marine environment. The model is empirically applied to the case of the Baltic Sea, where Eastern Baltic cod fisheries are affected by nutrient enrichment. The results indicate that nitrogen loadings are too high and that they need to be reduced in order to get the optimal cod stock level.*

**Keywords:** Marginal damage function, marine environment, eutrophication, eastern Baltic cod, bio-economic modeling.

JEL classification: D24, H41, Q18, Q22, Q53

## 1. Introduction

Eutrophication is considered a serious environmental problem for the Baltic Sea (MacKenzie *et al.,*, 2002; Rockmann *et al.,*, 2007; HELCOM, 2009). Eutrophication is a change in the trophic status of the water. In case of eutrophication there is a high primary production caused by excessive input of nutrients; the water becomes turbid as a consequence of the dense phytoplankton population, and large aquatic plants are out-shaded and disappear along with their associated invertebrate populations. Moreover, decomposition of the large biomass of phytoplankton cells may lead to low oxygen concentrations (hypoxia and anoxia), which kill fish and invertebrates. In 1988, the Helsinki Commission (HELCOM)[1] decided to reduce 50% of nitrogen inputs to the Baltic Sea by the year 1995, but the target has not been achieved yet. The eutrophication remains a major environmental problem and the current annual nitrogen loads to the Baltic Sea needs to be reduced at least 20% in order to achieve a good ecological and environmental status by the year 2021 (HELCOM, 2007a; HELCOM, 2009).

Gren *et al* (2008) estimate the minimum annual cost for 20% nitrogen input reduction to vary between 210 million of DKK and 1.6 billion of DKK depending on specification. This is what in the environmental literature known as abatement cost. The counterpart to abatement costs is the reduced damage the abatement will entail. A number of empirical studies using contingent valuation method have been carried out to assess these benefits (Gren, Turner and Wulff, 2000; Söderqvist *et al.,*, 2010). These studies do, however, only deal with *stated* preference for the improved environment[2]. We will in this article develop a damage function based on revealed preference using the dynamic production function approach, also called valuing the environment as an input (Barbier, 2007). Our focus will be on production in the marine ecosystem which depends on the water quality, and we will use the Eastern Baltic cod as example. Hereby the indirect use-values of the provision of the ecosystem service water quality are valued. As the cod is only part of the production, and as we are not dealing with non-user values of eutrophication, this will not produce a complete damage function but will serves as example of the method and indication of the magnitude. Our main contributions are formally and explicitly to develop a marginal damage function of eutrophication on a fish stock based on the dynamic production

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[1] HELCOM is responsible for monitoring and implementing the 1988 Ministerial Declaration. The Commission originally includes six countries: Denmark, Sweden, Soviet Union, the Polish People's republic, the German Democratic Republic and the Federal Republic of Germany;

[2] See also Heal et.al. (2005) for a discussion of the different valuation methods and their different applicability to valuation of ecosystem goods and services.

function approach (see e.g. Kahn and Kemp, 1985; McConnell and Strand, 1989; Barbier and Strand, 1998; Barbier, 2003)[3], and empirical to apply the function to the Baltic Sea cod fishery.

There have been several studies of the relationship between nutrient loadings and fish stocks. Knowler (2001) empirically found the effects of phosphorus concentration on the recruits of the anchovy stocks in the Black Sea. Smith and Crowder (2005) found the effects of nitrogen loadings on the growth of the blue crab fishery in the Neuse River Estuary, while Simonit and Perrings (2005) found the effects of nutrient enrichment on the growth of fish stocks in Lake Victoria. Compared to these studies we propose a more general approach that includes both fisheries sector and pollution sector in our model and we do also formulate a more detailed bio-economic model using a two-stage biological growth function. Also by deriving the marginal damage function we allow for comparison with the marginal abatement cost, i.e. optimal pollution policy can easily be formulated.

Eastern Baltic cod stock inhabits regions East of Bornholm (Denmark) in ICES (The International Council for the Exploitation of the Sea) sub-divisions 25-32 (Radtke, 2003) and has been managed under a recovery program since 2007 (EC, 2007). The main targets of the recovery program is to ensure the sustainable exploitation of the cod stocks by gradually reducing and maintaining the fishing mortality rates at certain levels (EC, 2007). The decline of the cod stock in early 1990s was considered a consequence of fishing pressure and environmental effects including temperature, salinity and oxygen (Köster *et al.*,, 2009). Many papers have studied the effects of temperature, salinity, oxygen and inflows from the North Sea (Westin and Nissling, 1991; Gronkjer and Wieland, 1997; Nissling, 2004; Koster *et al.*,, 2005; Mackenzie *et al.*,, 2007; Rockmann et al., 2007; Heikinheimo, 2008). However, there is still insufficient attention been paid to the effect of nutrient enrichment on the cod stock (Bagge and Thurow, 1994; HELCOM, 2009). In addition, changes in nutrient loadings are not included in the recovery program of the cod fisheries as a policy option.

In this paper, nitrogen concentration in spawning areas during spawning season will be chosen as an indicator of eutrophication. Then, the optimal cod stock will be defined by the means of a dynamic bio-economic model. Afterwards, a marginal damage function of eutrophication will be derived and compared with a marginal abatement cost function of nutrient loadings. The following specific questions will be discussed in our paper:

1. How is the optimal stock level of Eastern Baltic cod influenced by eutrophication?

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[3] There is several applications using habitat-fishery linkages (Barbier and Strand, 1998 and Barbier,2003), while other studies the impacts on fisheries of other coastal environmental changes (Kahn and Kemp,1985 and McConnell and Strand, 1989). However, none of these studies explicitly derive the marginal damage function.

2. What is the marginal damage to the cod fisheries from nutrient input to the Baltic Sea?
3. How large is the marginal damage compared with the marginal abatement cost?

The paper will be constructed as follows: the next part is the model description, which includes a general model of efficient pollution and a bio-economic to derive a marginal damage function of eutrophication. The following part is about the Baltic cod fisheries and data sources. Next, results from the model are presented. The paper finishes off with discussion and conclusions.

## 2. The Model

We consider two sectors in an economy: the agriculture sector (A) and the fishery sector (F). We model the nutrient emissions arising in the agricultural production as a stock pollution problem in the marine environment, in our case the fishery, with the following nutrient concentration-loading relationship:

$$N_{t+1} - N_t = \omega L_t - \varepsilon N_t \tag{1}$$

where $N_t$ and $L_t$ are nutrient concentration and nutrient loading at the beginning of period $t$, respectively; $N_{t+1}$ is nutrient concentration at the beginning of period $t+1$; $\omega$ is the nutrient absorption constant and $\varepsilon$ is the pollution stock decay constant; both $\omega$ and $\varepsilon$ are between zero and one. We assume that the nutrient concentration indirectly affect the output of the fishery sector. Without pollution, changes in biomass of an exploited fish population over time basically depend on the recruitment, growth, capture and natural death of individuals (Ricker, 1987; Beverton and Holt, 1993). The spawning stock is the mature part of the population that spawns and we assume without any loss in generality that the spawning stock is the part of the population exposed to the fishery. Recruitment occurs when the fish grow to maturity and enter the spawning stock. It takes some time to progress from spawning to recruitment; therefore, we apply a delayed discrete-time model (Clark, 1976; Bjorndal, 1988):

$$S_{t+1} = (S_t - H_t)G_t + R_t \tag{2}$$

where $S_t$ is the spawning biomass at the beginning of period $t$, and $H_t$ is the harvest quantity in period $t$. It is assumed that harvesting occurs at the beginning of period $t$ and that $S_t - H_t$ is the escapement[4]. There will be a net growth of the escapement in the period and it is described by the function $G_t = G(S_t)$[5]. As linear growth is unrealistic, it is assumed that natural growth is density-dependent. The recruitment is a function of the stock that needs $\gamma$ periods to grow into maturity $R_t = R(S_{t-\gamma})$. To model the effects of nutrient emissions, we include the nutrient concentration $N_t$ in both the growth and recruitment functions. It is assumed that nutrient concentrations in the period $t-\gamma$ and period $t$ affect the recruitment and the growth in period $t$, respectively

$$\begin{aligned} G_t &= G(S_t, N_t) \\ R_t &= R\left(S_{t-\gamma}, N_{t-\gamma}\right) \end{aligned} \tag{3}$$

The recruitment and the growth functions are assumed to be continuous and differentiable. We denote the net benefit function of the agriculture sector, $\pi^A$, and the net benefit function of the fishery sector, $\pi^F$.[6] The social objective is to maximize the net present value of the joint net benefits of two sectors by choosing, $L_t$ and $H_t$:

$$\begin{aligned} &\max_{L_t,\ H_t} \sum_{t=0}^{t=\infty} \rho^t (\pi^A + \pi^F) \\ \text{Subject to} \quad &N_{t+1} - N_t = \omega L_t - \varepsilon N_t \\ &S_{t+1} = (S_t - H_t) G(S_t, N_t) + R(S_{t-\gamma}, N_{t-\gamma}) \end{aligned} \tag{4}$$

where $\rho$ is the discount factor, $\rho = \frac{1}{1+r}$ with discount rate $r$. The net benefit function for the agriculture sector can be interpreted as a restricted profit-function, where the sector is constrained in their use of nutrients (Fulginiti and Perrin, 1993; Squires, 1994). So, we will assume the profit function describes that the agriculture sector optimizes their production for a fixed level of nutrient loading. This means that the profit function in general is a function of output and input prices and the restricted and fixed nutrient loading ($L$):

$$\pi^A = \pi^A(p^A, w^A; L)$$

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[4] We have chosen this timing of harvest, growth and recruitment, because it fits with our empirical example. The basic results do not change with other timing assumptions.

[5] Since the growth function is multiplied by the escapement, the growth function is compounding forward the escapement at the rate of growth. The result is the spawning biomass at the end of the year after harvest and before addition of the recruitment.

[6] The index for time is left out of the net benefit functions to facilitate reading.

where $w^A$and $p^A$ are the prices of inputs and outputs in the agriculture sector, respectively. The fishery net benefit function is different, since it describes revenues minus cost for a given stock level:

$$\pi^F(p^F, w^F, H; S) = p^F H - C(w^F, H; S)$$

where $w^F$and $p^F$ are the prices of inputs and outputs in the fishery sector, respectively. $C(w^F, H; S)$ is a traditional cost function in fisheries depending on harvest and stock levels. One could optimize the fishery profit given a fixed level of nutrient concentration with the stock equation as a constraint. This would lead to a restricted profit function for the fishery. However, because our main focus is to derive a damage function of nutrient loading, we will continue with the formulation in (4), where the overall long run profit are maximized with respect to harvest and nutrient loading. The two profit functions are assumed to have the standard properties: non-decreasing in output prices and fixed inputs, non-increasing in input prices, linear homogeneous and convex in prices, concave in fixed quantities, continuous and twice differentiable. Problem (4) may be solved using the Method of Lagrange Multipliers. We formulate the (current) Lagrange expression as

$$\mathcal{L} = \sum_{t=0}^{\infty} \rho^t \left\{ \begin{array}{c} \pi^A + \pi^F + \rho\lambda_{t+1}\left[(S_t - H_t)G(S_t, N_t) + R\left(S_{t-\gamma}, N_{t-\gamma}\right) - S_{t+1}\right] \\ +\rho\varphi_{t+1}[\omega L_t + (1-\varepsilon)N_t - N_{t+1}] \end{array} \right\} \tag{5}$$

The first order necessary conditions for the problem (4) are:

$$\frac{\partial \mathcal{L}}{\partial H_t} = \rho^t(\pi_H{}^F - \rho\lambda_{t+1}G_t) = 0 \tag{6}$$

$$\frac{\partial \mathcal{L}}{\partial L_t} = \rho^t(\pi_L{}^A + \rho\omega\varphi_{t+1}) = 0 \tag{7}$$

$$\frac{\partial \mathcal{L}}{\partial S_t} = \rho^t\left\{\pi_S{}^F + \rho\lambda_{t+1}[G_t + (S_t - H_t)G_S] + \rho^{\gamma+1}\lambda_{t+\gamma+1}R_S\right\} - \rho^t\lambda_t = 0 \tag{8}$$

$$\frac{\partial \mathcal{L}}{\partial N_t} = \rho^t\left\{\rho\lambda_{t+1}[(S_t - H_t)G_N] + \rho^{\gamma+1}\lambda_{t+\gamma+1}R_N + \rho\varphi_{t+1}(1-\varepsilon)\right\} - \rho^t\varphi_t = 0 \tag{9}$$

All derivatives marked with index are evaluated at time $t$. From (6), (7), (8), and (9) we have

$$\lambda_{t+1} = \frac{\pi_H{}^F}{\rho G_t} \tag{10}$$

$$\varphi_{t+1} = \frac{-\pi_L{}^A}{\rho\omega} \tag{11}$$

$$\lambda_t = \pi_S{}^F + \rho\lambda_{t+1}[G_t + (S_t - H_t)G_S] + \rho^{\gamma+1}\lambda_{t+\gamma+1}R_S \tag{12}$$

$$\varphi_t = \rho\lambda_{t+1}[(S_t - H_t)G_N] + \rho^{\gamma+1}\lambda_{t+\gamma+1}R_N + \rho\varphi_{t+1}(1-\varepsilon) \tag{13}$$

In equilibrium, all variables are stationary over time; therefore the *t* subscript can be dropped

$$\lambda = \frac{\pi_H{}^F}{\rho G} \tag{14}$$

$$\varphi = \frac{-\pi_L{}^A}{\rho\omega} \tag{15}$$

$$\lambda = \pi_S{}^F + \rho\lambda[G + (S - H)G_S] + \rho^{\gamma+1}\lambda\, R_S \tag{16}$$

$$\varphi = \rho\lambda[(S - H)G_N] + \rho^{\gamma+1}\lambda\, R_N + \rho\varphi(1-\varepsilon) \tag{17}$$

In equilibrium the growth function (2) and the nutrient equations (1) are as follows:

$$H = S - \frac{S - R}{G} \tag{18}$$

$$N = \frac{\omega L}{\varepsilon} \tag{19}$$

Substituting (14) and (18) into (16) yields

$$\frac{1}{\rho} = \left(\frac{\pi_S{}^F}{\pi_H{}^F} + 1\right)G + \frac{(S-R)}{G}G_S + \rho^{\gamma}\, R_S \tag{20}$$

If nutrient concentration is not included in the model, equation (20) is called the discrete-time analog of the golden rule for capital accumulation in natural resource economics (Clark and Munro, 1975). With nutrient included, equation (20) can be called the “pollution adjusted golden rule”. The term $\left(\frac{\pi_S{}^F}{\pi_H{}^F} + 1\right)$ on the right hand side is the marginal stock effect (MSE), which represents the stock density influence on harvesting costs (Clark and Munro, 1975; Bjorndal, 1988). The term $\frac{(S-R)}{G}G_S + \rho^{\gamma}\, R_S$ in (20) is the marginal productivity of the fish stock. It consists of two parts: the first part is related to the growth of the escapement, and the second part is related to the recruitment. The second part is discounted with $\gamma$ periods as a consequence of the delay in maturity. All three terms on the right hand side depends on nutrient concentration because the recruitment and the growth are functions of the nutrient concentration. Given a discount rate *r* and the other economic and biological parameters, equation (20) can be solved for the optimal stock level, *S**, as a function of nutrient concentration *N*. Furthermore, the optimal harvest level, *H**, can be derived from (18) as a function of N.

To find N* we substitute (14) and (15), (18) and (19) into (17) which yields

$$\frac{-\pi_L{}^A}{\omega}[\varepsilon + r] = \frac{\pi_H{}^F}{G}\left[\frac{S-R}{G}G_N + \rho^\gamma R_N\right] \tag{21}$$

Right hand side shows the value to the fishery of one less unit of nutrient concentration and the left hand side the same for the agriculture sector. Thus the equation gives the balance of the optimum equilibrium situation where the marginal abatement costs, left hand side, equals the marginal benefit, right hand side. Equation (21) show the balance with marginals with respect to nutrient concentration (reduction), if it is rearranged:

$$-\pi_L{}^A = \frac{\pi_H{}^F}{G}\left[\frac{S-R}{G}G_N + \rho^\gamma R_N\right]\frac{\omega}{\varepsilon + r} \tag{22}$$

the balance is expressed with marginals with respect to (reduction of) loadings: Marginal abatement cost with respect to loading:

$$MC^A(L) = -\pi_L{}^A \tag{23}$$

and marginal (abatement) benefit with respect to loading:

$$MB^F(L) = \frac{\pi_H{}^F}{G}\left[\frac{S-R}{G}G_N + \rho^\gamma R_N\right]\frac{\omega}{\varepsilon + r} \tag{24}$$

The marginal abatement cost has been well documented (see e.g. Gren, 2008). In this study, we will focus on the marginal benefit function (24) to compute the marginal benefit function from nutrient input reduction for the fishery. The marginal benefit function will be applied for the case of the Eastern Baltic cod fisheries. In this case, $MB^F$ $(L)$ is measured in million DKK per year and *L* is measured in ton per year

## 3. The Eastern Baltic cod fisheries

Eastern Baltic cod is one of the most important species in the Baltic Sea. In Denmark, it accounts for over 33% of the total cod landed and contributed about 14% to the total landing value of Danish fisheries in 2009 (Anon, 2009). In Sweden, it accounted for 4% of the total catch, but it contributed about 19% to the total landing value of Swedish fisheries in 2004 (Osterblom, 2008). Nine countries currently harvest Eastern Baltic Cod: Germany, Finland, Russia, Estonia, Latvia, Lithuania, Poland, Sweden and Denmark. Poland, Sweden and Denmark had the largest catch shares, which accounted for 22%, 21% and 17% of the total cod landing from the Eastern Baltic Sea in 2009, respectively (ICES, 2010a). The harvesting of Eastern cod mainly occurs at the beginning of the year. For example in Denmark, landing from January to June accounted for about 73.2 % of the total Eastern Baltic cod landing in 2009 (Anon, 2009). There were about 13,900 fishing vessels with a total 246345 Gross Tonnages (GT) in the Baltic countries (without Russia) in 2005 (Horbowy and Kuzebski, 2006). Trawls and gillnets are the main fishing gears for Eastern Baltic cod fisheries, which contributed around 70% and 30% of the total landing in 2009, respectively (ICES, 2010b). In 2009, the total landing of Eastern Baltic cod was 48,439 tons, which was approximately equal to 12.4 % of the highest landing of 391,952 tons in 1984 (ICES, 2010a). The TACs is annually allocated to the member states with the same percentages, which is known as the relative stability (Nielsen and Christensen, 2006). The TAC of the Eastern Baltic cod has been separated from the Western Baltic cod since 2004, and it was set of 56,800 tons in 2010 (ICES, 2009).

The spawning season of Eastern Baltic cod starts in March and ends in September-October. During that period, the peak spawning time occurs from about April to the end of July (Bagge and Thurow, 1994; Wieland, Jarre-Teichmann and Horbowa, 2000). The Eastern Baltic cod first matures at about 2 to 4 year, and the spawning areas are mainly in waters of no less than 20 meters in ICES 25, ICES 26 and ICES 28 (Gronkjer and Wieland, 1997; Voss, Hinrichsen and John, 1999; Huwer, 2009). The spawning of the Eastern Baltic cod is strongly influenced by environmental factors. Successful spawning of the cod often occurs in the areas with salinity and oxygen equal or higher than 11 psu and 2 ml/l, respectively (Westin and Nissling, 1991; Vallin and Nissling, 2000). These environmental conditions occur in the Bornholm, Gotland Basins, and the Gdansk Deep within ICES 25-28 (Voss, Hinrichsen and John, 1999). In these spawning areas, salinity content is believed to connect to inflows from the North Sea, while oxygen content is linked with both inflows and nutrient loadings to the Baltic Sea (Hansson and Rudstam, 1990; Schinke and Matthaus, 1998; Vallin, Nissling and Westin, 1999; Bergstrom *et al.,*, 2010). The proper nutrient concentration, salinity and oxygen regimes in the spawning areas are considered main factors in producing the rich year classes of Eastern Baltic cod in the late 1970s and early 1980s (Bagge and Thurow, 1994). In contrast, the significant decline of the cod stock in early 1990s occurs in part because of the excess nutrients in the spawning areas that caused oxygen depletion (Gren, Turner and Wulff, 2000). The highest spawning stock and recruitment was 696,743 tons (1980) and 829,398 million (1978), respectively (ICES, 2009). In 2009, the spawning stock was 186,327 tons, and the recruitment was 198,143 million (ICES, 2011a). These levels were about 27% and 24% of the highest levels, respectively.

## 4. Data and estimations

It this section, the functions included in the marginal benefit function (24) is estimated. The functions are the recruitment, growth and profit functions. First, the data is described.

Data on annual cod landings, spawning stock biomass (SSB), and recruitments are available directly from ICES database (ICES, 2010a; ICES, 2011a). The total nitrogen indicator (NTOT) is derived from HELCOM database (HELCOM, 2010) Following Thanh (2011), we use environmental data collected in ICES Sub-divisions 25, 26 and 28 with bottom depths greater than or equal to 20 meters. We use data collected during the spawning season of the cod stock, which is from March to September. The nitrogen concentration in the spawning areas during the spawning season is calculated as follows:

$$N_t = \frac{\sum_{i=1}^{n} NTOT_i}{n} \tag{25}$$

where $N_t$= the nitrogen indicator in year t, n = number of observations,

$NTOT_i$ = the nitrogen concentration $\begin{cases} in \quad ICES\ 25, 26\ and\ 28 \\ from\ March\ to\ September\ of\ year\ t \\ in\ stations\ with\ bottom\ depth \geq 20\ m \end{cases}$

The nitrogen indicator and biological data of the Eastern Baltic cod fisheries from 1966 to 2009 are in table 1.

**(Table 1 is about here)**

Account statistic data from the Ministry of Food, Agriculture and Fisheries Denmark are used to estimate the variable cost function. In particularly, a time series set of annual cost and annual catch of fishing firms from 1995-2009 in Bornholm (Rønne) are used for the estimation. Variable costs are the total variable costs of a fishing firm multiplied by the share of cod in total harvest and deflated with the consumer price index (2000=1). The data for estimation is described in the following Table 2.

**(Table 2 is about here)**

The stock-recruitment relationship of the Eastern Baltic cod is assumed to follow a quadratic function, and the nitrogen concentration is included as follows (Simonit and Perrings, 2005):

$$R_{nt} = aS_{t-\gamma}N_{t-\gamma} - b{S_{t-\gamma}}^2 - c{N_{t-\gamma}}^2S_{t-\gamma} \tag{26}$$

or the alternative form used for estimation

$$\frac{R_{nt}}{S_{t-\gamma}} = aN_{t-\gamma} - bS_{t-\gamma} - c{N_{t-\gamma}}^2 \tag{27}$$

Juvenile cod is assumed to join in spawning stock at age 3, so the delay period is $\gamma$=2. The estimation of the recruitment functions for the Eastern Baltic cod are described in table 3.

**(Table 3 is about here)**

The model explains 53% the variance of the dependent variable, and all the parameters are significant at the 5% level or better. Additionally, the models indicate the autocorrelation in the residuals, which is often noted in time series data derived from VPA. In equation (27), $R_{nt}$ is measured in millions, $S_t$ is measured in thousand tones, and $N_t$ is measured in millimole/m3. Given the average weight of cod at age 2 from 1966 to 2009, w=0.209 kg (ICES, 2010b), the final stock-recruitment function is determined:

$$\begin{aligned} R_t = wR_{nt} = 0.042131\, S_{t-2}N_{t-2} - 0.00034\, {S_{t-2}}^2 \\ - 0.001222\, S_{t-2}{N_{t-2}}^2 \end{aligned} \tag{28}$$

Following Ricker (1987), the growth function is assumed as follows:

$$G_t = e^{\delta_t} \tag{29}$$

where $\delta_t$ is called the net natural growth rate, which equals the instantaneous growth rate minus the instantaneous natural mortality rate.We assume that nitrogen enrichment has minimal effects on the growth of the cod stock and therefore it is ignored in the growth function[7]. The relationship between the net natural growth rate ($\delta$) and the spawning stock biomass ($S$) is assumed to be density-dependent and to follow a linear form[8]:

$$\delta_t = \delta\ (S_t) = o + qS_t \tag{30}$$

The net natural growth rate (δ) may also be calculated according to the following formula:

$$(S_{t+1} - R_t) = (S_t - H_t)e^{\delta_t} \ \Rightarrow\ \delta_t = \ln\left(\frac{S_{t+1} - R_t}{S_t - H_t}\right) \tag{31}$$

**(Table 4 is about here)**

Table 4 shows the estimation of equation (30) using data for 1966-2009. The model has significant parameters at the 1% level and explains 33% of the variance of the dependent variable. In addition, δ'(S) < 0 for all stock levels, which implies that the net natural growth rate reduces when the stock increases.

From (28) and (30), we have the model of the cod population dynamics under the influence of nitrogen:

$$\begin{aligned} S_{t+1} = (S_t - H_t)e^{1.140578 - 0.0012049 S_t} &+ 0.042131\, S_{t-2}N_{t-2} \\ &- 0.00034\, {S_{t-2}}^2 - 0.001222\, S_{t-2}{N_{t-2}}^2 \end{aligned} \tag{32}$$

It is assumed that the total variable cost of the fisheries is a function of the total harvest (*H*) and the spawning stock biomass (*S*) (Clark, 1990; Sandberg, 2006; Rockmann *et al.*,, 2009). Since cod is an internationally traded commodity, it is further assumed that cod fisheries have a perfectly elastic demand curve. The net benefit function of the Eastern Baltic cod fisheries in period *t* can be defined as follows:

$$\pi(H_t, S_t) = pH_t - C_t(S_t, H_t) \tag{33}$$

where $p$ is a constant price and, $C_t$ is the total cost of the fishery in period $t$. The price of the Eastern Baltic cod is calculated as follows:

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[7] There might be indirect and long term effects through the food web. For example, nutrient enrichment may cause an increase of phytoplankton population that is eaten by zooplankton. Sprat, which is the prey for herring, eats zooplankton and cod eats herring.

[8] The quadratic function form was tested empirically using data from the eastern Baltic cod fishery, but the results were not successful. Estimated parameters showed an upward parabola.

$$p = \frac{\sum_{t=1}^{y} p_t}{y}$$

where $p_t$ is the cod price in period *t* taken from the account statistic database and deflated with the consumer price index (2000=1) and *y* is the number of periods that data is available. The total variable cost of the Eastern Baltic cod fisheries is calculated as follows:

$$C_t = \sum_{i=1}^{n} c_{ti} h_{ti} \tag{34}$$

where $C_t$ is the total cost of the fishery in period *t*, $c_{ti}$ is the unit cost of fleet *i* in period *t*, $h_{ti}$ is the harvest of fleet *i* in period *t*, and *n* is the number of fleets. The unit cost of fishing firms in the Bornholm region is assumed to be the unit cost of harvesting for the entire Eastern Baltic cod fisheries (Kronbak, 2002; Rockmann et al., 2009).

$$C_t = \overline{c_t} \sum_{i=1}^{n} h_{ti} = \overline{c_t} H_t = \frac{C_{bt}}{h_{bt}} H_t = \frac{C_{bt}}{m} \tag{35}$$

where $H_t$ is the total harvest of the fishery in period *t*, $\overline{c_t}$ is the unit cost of the Bornholm fleet in period t, $C_{bt}$ is the total cost of the Bornholm fleet in period *t*, $h_{bt}$ is the total harvest of Bornholm fleet in period *t* and $m = \frac{\sum_{i=1}^{n} h_{bt}}{\sum_{i=1}^{n} H_t}$ is the Bornholm average share of the Eastern Baltic cod landing. Following Clark 1990, Alaouze (1999) and Sandberg (2006) the total variable cost for Bornholm fleet is assumed to be the following in a power function

$$C_{bt} = \alpha_b {S_t}^{\beta_1} {h_{bt}}^{\beta_2} \tag{36}$$

where $\alpha_b$, $\beta_1$, $\beta_2$ are parameters to be estimated. Substituting (36) into (35) yields

$$C_t = \frac{\alpha_b {S_t}^{\beta_1} {h_{bt}}^{\beta_2}}{m} = \alpha_b m^{\beta_2 - 1} {S_t}^{\beta_1} {H_t}^{\beta_2} = \alpha\, {S_t}^{\beta_1} {H_t}^{\beta_2} \tag{37}$$

where $\alpha = \alpha_b m^{\beta_2 - 1}$. Using the data from the Bornholm cod fisheries, the estimation for the variable cost function (equation 36) is described in the table 5.

**(Table 5 is about here)**

The model explains 76% of the variance of the dependent variable. The spawning stock coefficient is significant at the 5% level, while the constant and the harvest coefficients are significant at the 1% level. The DW test is inconclusive about autocorrelation in the residuals. However, the Durbin's alternative test (durbinalt) for serial correlation and Breusch-Godfrey test for higher-order serial correlation shows that there is no autocorrelation in the residuals. The variable cost function for Bornholm fleet is written as follows (the *t* subscript is dropped)

$$C_b = 59.15 * S^{-0.4} * {h_b}^{1.04} \tag{38}$$

Given the average share of Bornholm cod landing from 1995 to 2008: m= 0.13, the variable cost for the Baltic Sea cod fisheries is written (the *t* subscript is dropped)

$$C = \frac{C_b}{m} = 54.51 * S^{-0.4} * H^{1.04} \tag{39}$$

Regardless of the very complex hydrologic in the Baltic, we will adapt the simple formula (1) and calibrate it to the Baltic. The model has two parameters $\varepsilon$ that is the decaying rate and $\omega$ that is the dilution of the loading. The decaying is estimated based on Wulff et al (2006). Wulff et al (2006) gives a total nitrogen budget with the Baltic separated into four compartments: two compartments cover the Baltic proper, one for the top layer, and one for the bottom layer. In total the pool of nitrogen in the Baltic Proper is $2.8868*10^{11}$mole. The net exchange out of the Baltic and to Bothnian Sea account for a loss of $8.7*10^{9}$ mole year$^{-1}$, while the nitrogen fixation and denitrificationprocesses together give a net loss of $4.68 \cdot 10^{10}$ mole year$^{-1}$: in total this gives a decaying rate $\varepsilon = 0.192$ year$^{-1}$.

The present loading to the Baltic Proper is approximately[9]$L_{2007} = 626{,}000$ ton year$^{-1}$. One way to account for the dilution would be to convert into mole and divide by the volume of the Baltic, however, this will not account for the high concentration found in the spanning areas. Instead we note that both the loading and nitrogen concentration level seems to be constant over the last years, we therefore assume that the present nitrogen concentration level of $N_{2010} = 22$ mole m$^{-3}$ is in equilibrium with present loading. We then have $0 = \omega L_{2007} - \varepsilon N_{2007}$ and can find $\omega = 6.748 \cdot 10^{-6}$ mole m$^{-3}$ ton$^{-1}$.

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[9] From REF helcom the total load is 744 900 ton year-1. According to Wulff el al (2006) 84% of the total load enters the Baltic Proper.

With the empirical parameters from the Baltic Proper, equation (19) can be written as follows

$$N = \frac{\omega L}{\varepsilon} = 0.000035L \tag{40}$$

Giving the relations between concentration and loading in equilibrium to be used in the marginal benefit function (24).

## 5. Results and discussion

The optimal harvest and optimal stock are calculated by solving equation (18) and (20) by numerical methodes (R Development Core Team, 2012). Figure 1 shows the optimal stock, optimal harvest, net benefit and net present value of the cod fisheries under the influence of nitrogen concentration (discount rate *r*=0.04). The optimal nitrogen concentration is about 17millimole per m$^3$, while the 2010 nitrogen level is about 22 millimole per m$^3$. It implies that nitrogen concentration in the spawning areas should be reduced about 22% to attain the level optimal for the fishery.

**(Figure 1 is about here)**

Table 6 shows the optimal stock, optimal harvest and net benefit of the cod fisheries under three nitrogen scenarios, given a discount rate *r*=0.04. The optimal nitrogen level would give an increased benefit of 82 million DKK per year compared to the 2009 nitrogen level, given the optimal harvest policy.

**(Table 6 is about here)**

The total and the marginal yearly benefits of different nitrogen reduction targets are calculated using equations (33) and (24) and shown in figure 2. The maximum net benefit of the cod fisheries from nitrogen input reduction is at the target of 22 % nitrogen input reduction.

**(Figure 2 is about here)**

In 1988, the Helsinki Commission (HELCOM) decided to reduce 50% of nitrogen inputs to the Baltic Sea by the year 1995, but the target has not been achieved yet. The eutrophication remains a major environmental problem and the current annual nitrogen loads to the Baltic Sea needs to be reduced at least 20% in order to achieve a good ecological and environmental status by the year

2021 (HELCOM, 2007a; HELCOM, 2009). We assume that the relationship between nitrogen loads and concentration in the cod spawning areas follows equation (40). It implies that 20% decrease of the nitrogen loads, the target recommended in the Baltic Sea Action Plan, eventual will result in decrease 20% of nitrogen concentration in the spawning areas. Gren *et al*(2008) estimate the minimum annual cost for 20% nitrogen input reduction (total abatement cost) vary between 210 millions of DKK (295 millions of SEK) and 1.6 billions of DKK (2.245 billions of SEK) depending on target specification with respect to overall reductions or decreases in load to specific basins. The benefit from nitrogen reduction (abatement benefit) to this level (given an optimal harvest policy) is about 81 million DKK annually, which is relatively small compared to the cost of nitrogen reduction. However, this benefit is significant to the cod fisheries. It almost doubles the profit of the cod fisheries in 2005 and approximately equals to 26% of the profit of the cod fisheries in 2010. The results imply that the benefits of nitrogen loadings or nitrogen emission (e.g. benefits from agriculture) is relatively high compared to the damage of nitrogen emission to the cod fisheries.

**(Figure3 is about here)**

Figure 3 shows marginal benefit of the cod fisheries from nitrogen reduction (MB) in comparison with the marginal abatement cost (MC) for different nitrogen reduction targets to the Baltic Sea from Gren *et al* (2008). At the current level of nitrogen loadings, MB is around 1119 DKK per ton of nitrogen reduction. MB and MC intersect at the target of about1% nitrogen input reduction. At this nitrogen reduction level, MB would equal MC and be approximately 1000 DKK per ton of nitrogen input reduction. This reduction level is relatively small since our model includes only benefits from cod fisheries. Other fisheries such as herring or salmon may get benefits from nitrogen reduction, too. In addition, sectors as recreational fisheries and the tourism sector may as well get benefits from better water quality by reducing nitrogen loadings. If all benefits are included, the MB curve would shift upward and the cross with MC to the right in figure 3. In other words, the optimal nitrogen input reduction level would be higher in practice.

## 6. Conclusion

In this paper, we introduce a bio-economic model for a renewable resource influenced by stock-flow pollution.. We expand the bio-economic model to include nutrient enrichment in the biological part using the dynamic production function approach where ecosystem services are inputs (Barbier, 2007). We show how the optimal fishery policy depends on nutrient enrichment level. Our main purpose was to derive a marginal damage function of nutrient enrichment that can be compared with the marginal net-benefit function of nutrient enrichment. This provides the basis for polices that balance the use of nutrient in land-based industries (for example agriculture). The bio-economic model is empirically applied for Eastern Baltic cod fisheries under the influence of nitrogen loadings. The model shows that nitrogen loadings is too high and need to be reduced in order to get the optimal cod stock level. If harvest is set equal to the optimal yield, given a discount rate of 4% per year, the marginal benefit of the cod fisheries would equal the marginal cost of about 1% of nitrogen input reduction. At this reduction level, the marginal benefit would be about 1,000 DKK per ton of nitrogen. The maximum benefit of the cod fisheries from nitrogen input reduction is around 82 million DKK per year at the target of 22% nitrogen input reduction. This benefit almost doubles the profit of the cod fisheries in 2005 and equals around 26% of the profit in 2010.

There are several options for improvement of the analysis. The relationship between nutrient loadings and recruitment is of course uncertain. There is a need to research this relationship in greater detail. Data could be improved e.g. we only had access to the cost of part of the Baltic Sea cod fleet. Other sectors could be included, e.g. tourism. Since the tourism sector is adapted to the changing environment there is data available that can be applied to assess the marginal damage using the production function approach. Further research needs include also in general the relationship between the status of the marine environment and the production of the marine resources.

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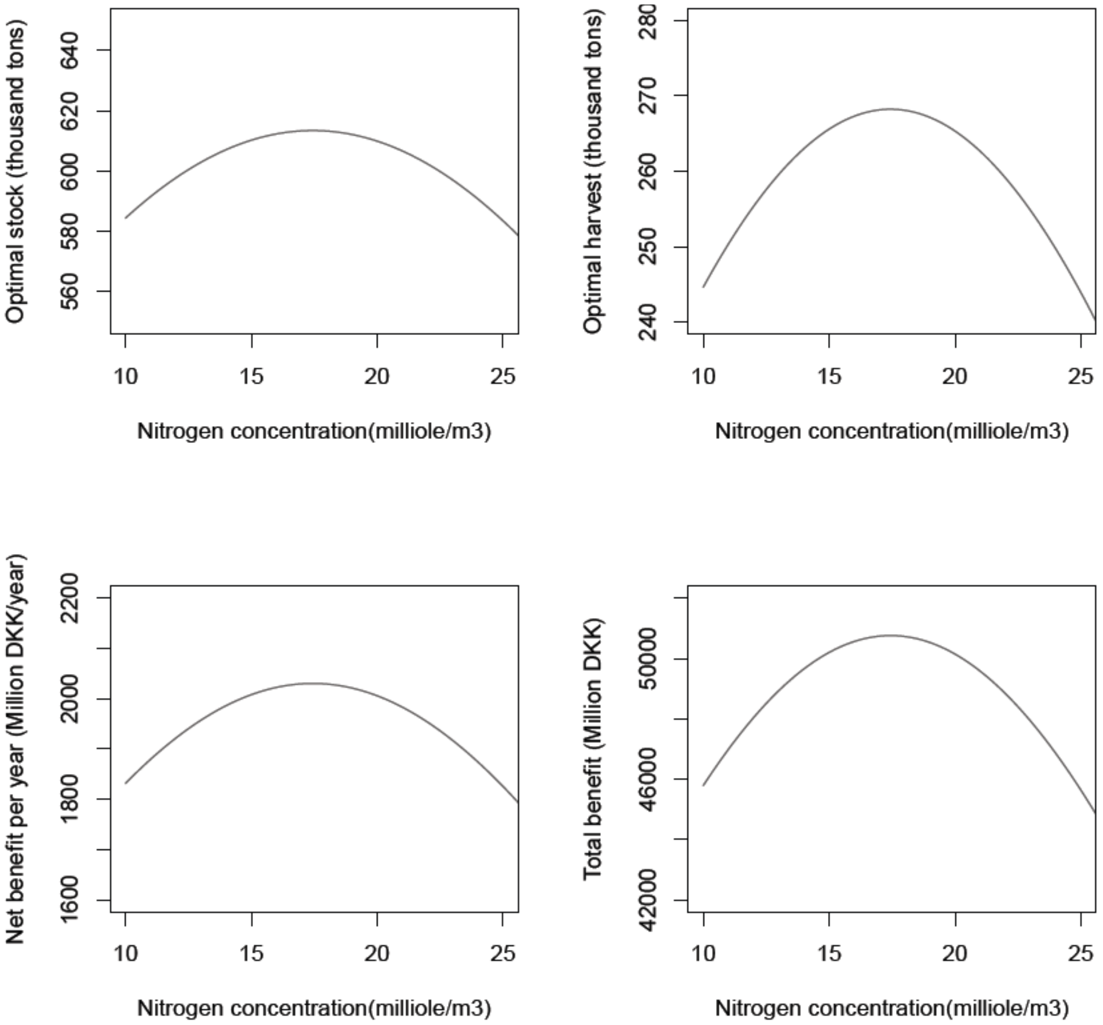

**Figure 1.** Optimal stock, harvest, net benefit per year and total benefit under different nitrogen concentration levels (r=4%)

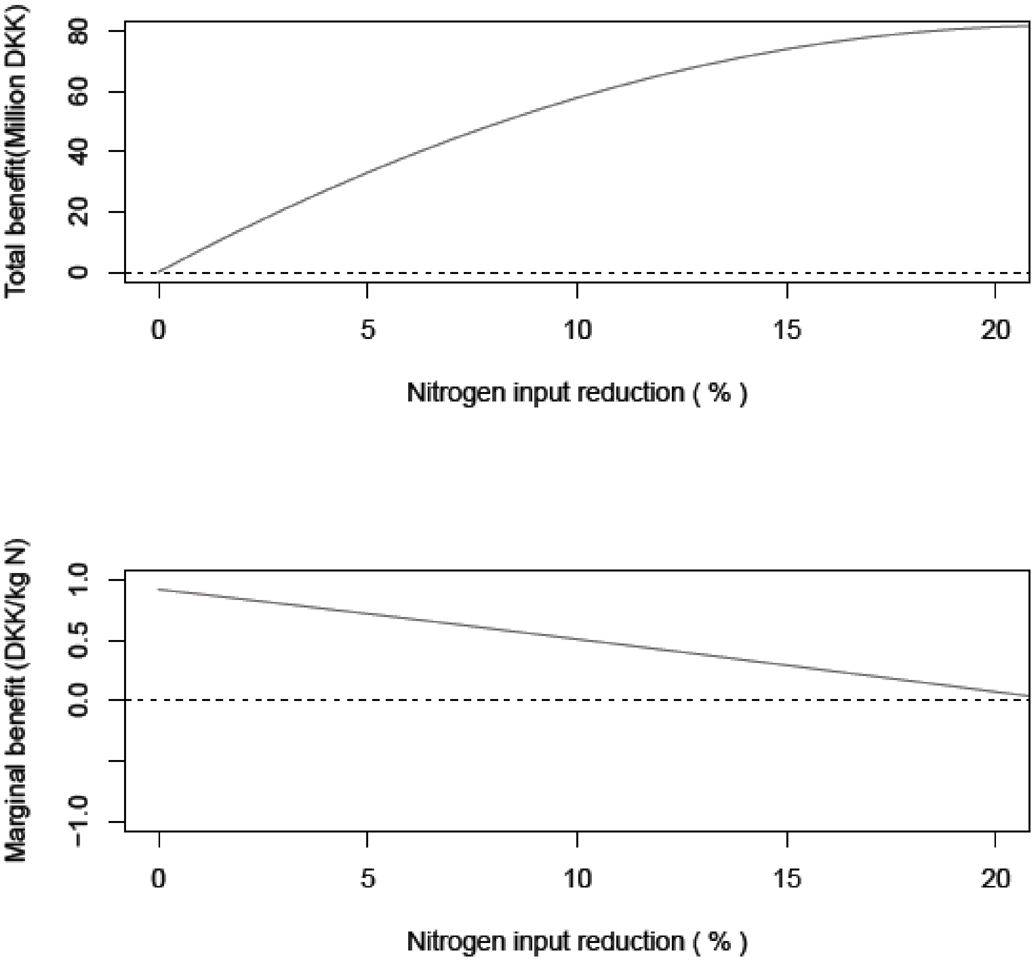

**Figure 2.** Total and marginal yearly benefits from nitrogen input reduction

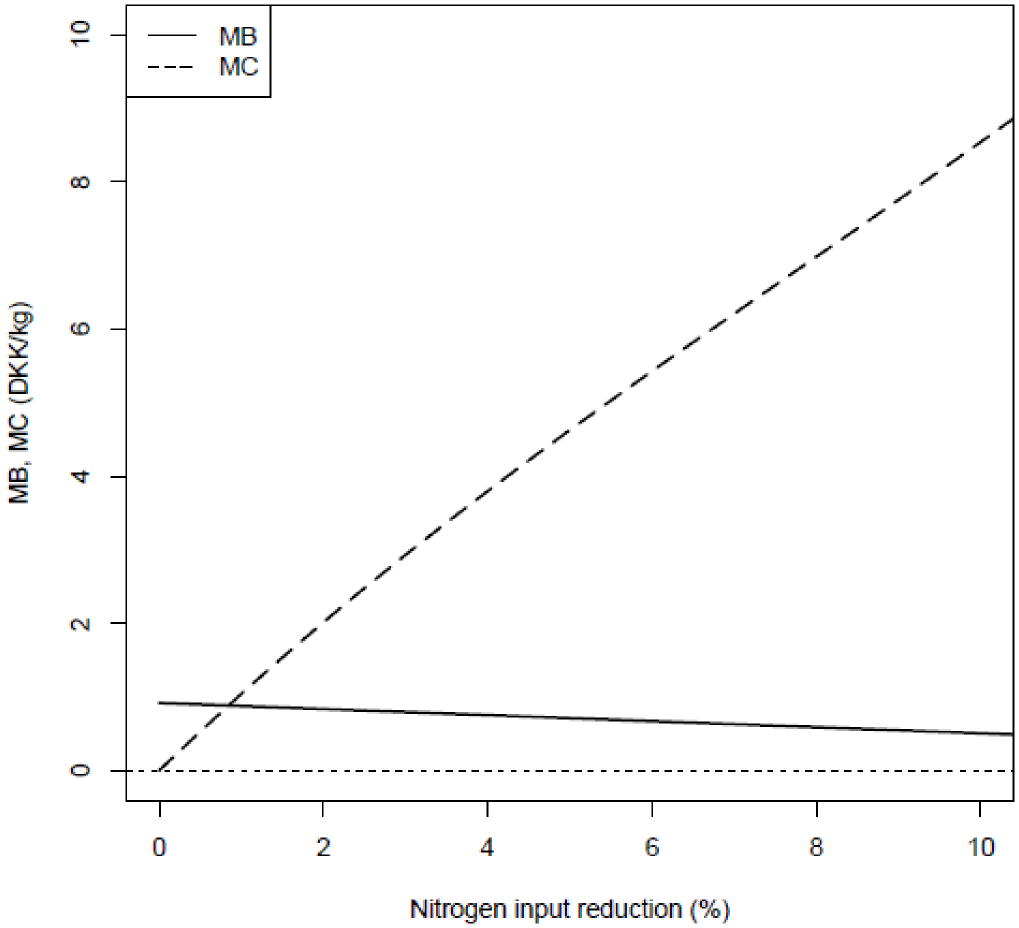

**Figure 3.** Marginal cost (MC) and Marginal benefit (MB) for different nitrogen reduction targets[10].

Source for MC: data from (Gren, Jonzon and Lindqvist, 2008) and own calculations

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[10] MC was original calculated in Million SEK, we use exchange rate in 1st December 2008: 1 SEK = 0.711725 DKK.

**Table 1:** Biological and environmental data from 1995 to 2009

| Year | SSB (1000 tones) | Recruits (millions) | N (mM/m3) | Year | SSB (1000 tones) | Recruits (millions) | N (mM/m3) |
|---|---|---|---|---|---|---|---|
| 1966 | 172.018 | 430.264 | Na | 1988 | 299.273 | 224.300 | 21.3975 |
| 1967 | 228.679 | 370.921 | Na | 1989 | 240.273 | 122.489 | 22.3235 |
| 1968 | 233.958 | 354.063 | Na | 1990 | 216.024 | 128.357 | 17.3061 |
| 1969 | 222.659 | 306.727 | 15.3622 | 1991 | 151.586 | 82.752 | 12.3441 |
| 1970 | 208.842 | 240.011 | 15.2414 | 1992 | 92.864 | 136.406 | 18.1909 |
| 1971 | 184.181 | 264.787 | 13.1179 | 1993 | 112.710 | 181.985 | 21.2248 |
| 1972 | 198.996 | 322.278 | 14.8874 | 1994 | 191.730 | 127.263 | 21.0654 |
| 1973 | 211.991 | 432.140 | 16.3683 | 1995 | 236.994 | 119.558 | 21.6316 |
| 1974 | 262.952 | 506.893 | 15.9865 | 1996 | 163.779 | 115.509 | 22.145 |
| 1975 | 339.545 | 303.683 | 18.2519 | 1997 | 135.620 | 88.058 | 20.2688 |
| 1976 | 355.564 | 293.397 | 15.7158 | 1998 | 109.078 | 149.121 | 20.5933 |
| 1977 | 326.914 | 479.002 | 16.3753 | 1999 | 90.298 | 152.307 | 23.0713 |
| 1978 | 379.201 | 829.398 | 13.9564 | 2000 | 115.853 | 174.929 | 20.9427 |
| 1979 | 579.671 | 615.355 | 19.0587 | 2001 | 104.135 | 135.682 | 20.9891 |
| 1980 | 696.743 | 425.886 | 18.6566 | 2002 | 82.992 | 122.186 | 21.4832 |
| 1981 | 666.132 | 689.813 | 18.5581 | 2003 | 80.153 | 111.907 | 19.6571 |
| 1982 | 670.941 | 693.590 | 20.1841 | 2004 | 78.901 | 107.209 | 20.0716 |
| 1983 | 645.258 | 472.374 | 22.1226 | 2005 | 63.750 | 160.148 | 21.1544 |
| 1984 | 657.667 | 302.921 | 21.2992 | 2006 | 78.656 | 127.414 | 21.3767 |
| 1985 | 544.911 | 253.078 | 25.5562 | 2007 | 93.942 | 160.234 | 20.7835 |
| 1986 | 399.371 | 260.214 | 23.7282 | 2008 | 111.253 | 204.938 | 21.9704 |
| 1987 | 320.470 | 368.089 | 21.9113 | 2009 | 186.327 | 198.143 | 22.1991 |

**Table 2.** Data for the Bornholm cod fisheries

| Year | Total variable cost (mill. DKK) | Total landing (1000 tons) |
|---|---:|---:|
| 1995 | 86.611 | 14.467 |
| 1996 | 111.505 | 17.009 |
| 1997 | 165.785 | 14.107 |
| 1998 | 124.007 | 10.914 |
| 1999 | 166.505 | 13.759 |
| 2000 | 117.572 | 10.159 |
| 2001 | 110.546 | 9.512 |
| 2002 | 79.579 | 7.032 |
| 2003 | 77.752 | 8.293 |
| 2004 | 68.331 | 7.323 |
| 2005 | 71.445 | 7.209 |
| 2006 | 70.390 | 7.696 |
| 2007 | 58.972 | 4.924 |
| 2008 | 45.204 | 5.541 |

**Table 3.** Estimation of the Eastern Baltic cod stock-recruitment function using the quadratic model and the data for 1966-2009

| Symbol | Variables | Estimation (Standard error) |
|---|---|---|
| *a* | Spawning stock ($S_{t-2}$) | -0. 0016263* (0.000668) |
| *b* | Nitrogen ($N_{t-2}$) | 0.2015826** (0.0458933) |
| *c* | Nitrogen square ($N_{t-2}^2$) | -0.0058455** (0.0019295) |
|  | $R^2$ | 0.53 |
|  | F statistic | 14.92 |
|  | DW statistic | 1.668 |
|  | Rho | 0.688 |

The dependent variable is $R_t/S_{t-2}$ and n=39. The models have been estimated with first order autocorrelation, using the Prais-Winsten transformed regression estimator. * $p<0.05$, **$p<0.01$.

**Table 4.** Estimation of equation (30); the natural growth for the Eastern Baltic cod using data for 1966-2009

| Symbol | Variables | Estimation (Standard error) |
|---|---|---|
| $o$ | Constant | 1.140578** (0.100894) |
| $q$ | Spawning stock ($S_t$) | -0.0012049** (0.0002328) |
| | $R^2$ | 0.33 |
| | F statistic | 26.78 |
| | DW statistic | 1.463 |

The dependent variable is $\delta$ for the model and n=44, ** p<0.01.

**Table 5.** Estimation of the variable cost function for the Bornholm cod fishery using data for 1995-2008.

| Symbol | Variables | Estimation (Standard error) |
|---|---|---|
| $ln\alpha_b$ | Constant | 4.08** (0.787) |
| $\beta_1$ | Spawning stock (*S*) | -0.4* (0.183) |
| $\beta_2$ | Harvest ($h_b$) | 1.04** (0.176) |
|  | $R^2$ | 0.76 |
|  | F statistic | 17.55 |
|  | DW statistic | 1.31 |

The dependent variable is total cost and n=14. The model has been estimated using log-linear regression.*p<0.05, **p<0.001

**Table 6.** Optimal stock and corresponding harvest, and net yearly benefit in optimum (*r*=0.04)

| Nitrogen scenarios | Optimal stock (1000 tons) | Optimal harvest (1000 tons) | Net benefit (Million DKK/year) |
|---|---|---|---|
| 2009 level | 593.67 | 257.56 | 1934.16 |
| 20% reduction | 605.38 | 267.21 | 2015.54 |
| Optimal level | 605.45 | 267.26 | 2015.98 |