Ecosystem Externalities of Fishing

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Abstract

Ecosystem externalities arise when one use of an ecosystem have an impact on other uses through the functionality of the ecosystem. We investigate the ecosystem externality created by fishing different species in an ecosystem using simulations of a size-spectrum ecosystem model. The model is based on general ecological principles and calibrated to the North Sea. Two fleets are considered: a “forage fish” fleet targeting species maturing at small sizes, and a “large fish” fleet targeting piscivorous species. Based on marginal analysis of the present value of rent we develop a benefit indicator that explicit divides the consequences into external and internal benefits. The analysis demonstrates that the forage fish fishery have a notable economic impact on the large fish fishery, but not the other way around. The impact can be both negative and positive calling for the right balance between the two fisheries. The present management of the North Sea seems not far from the right balance; however the present exploration level are to high.

Keywords: Ecosystem function, Ecosystem service, Forage Fish, Economics, Benefit indicator, Marine Ecosystems, Ecosystem Approach to Fisheries Management

1. Introduction

When one fish stock in an ecosystem is fished the impact of fishing will influence other stocks than the target stock. For example, fishing piscivorous...
species is expected to have a beneficial effect on their prey species whereas fishing of forage fish can have a detrimental effect on their predators. In economic terms this means that a fishing fleet not only affects its own economy, but, through the ecosystem, will impose externalities on other fleets and ecosystem users. De Groot et al. (2002) advocates for a distinction between ecosystem functions and ecosystem services. An example of an ecosystem function is the small zooplanktivorous forage fish, which functions as food source for larger piscivorous fish. Ecosystem services are the benefits people obtain from ecosystems. From an economic perspective this distinction between function and services is important to avoid double counting when valuing ecosystems. The ecosystem functions are restrictions on the services the ecosystem can supply; the use of one service (e.g. fishing piscivorous fish) will, through the ecosystem functions, change the supply of other services (e.g. fishing forage fish). This dependency of ecosystem services on functions creates opportunity costs on the use of specific services. Our aim is to examine the constraints the ecosystem functions imposed on the ecosystem services, by an economic valuation of how a change in one service influences other services of the system.

To account for the ecosystem functions an ecosystem model is required that resolves the multi-species nature of the ecosystem. Purely data-driven approaches, e.g. analysis of catch data, are unable to provide an understanding of the drivers and dynamics within the ecosystem. A formal approach that integrates ecology and economics is needed to capture the feedbacks in the ecosystem functions. One approach in the fishery economic literature has been to use simple conceptual models to obtain qualitative insights about ecosystems (Hannesson, 1983, 2002). The most common approach has been to investigate the interaction of two or more trophic levels using predator-prey models of the Lotka-Volterra type, e.g Wilen and Wilen (2012). In a critique of these approaches Tschirhart (2009) calls for integrated ecological-economic models that incorporate the ecological process of competition and predator-prey interaction instead of only the outcome of these process as in the Lotka-Volterra approach. This requires ecological models that include description of technical interdependency of ecosystem’s components, that is, the ecosystem functions described mechanically (Tschirhart, 2009); only by applying more sophisticated ecosystem models can externalities in the ecosystem be properly addressed (Crocker and Tschirhart, 1992).

Our viewpoint is that model development and choice of model approach have to reflect the questions and/or (policy) issue that need to be answered.
Our issue is to address the overall functioning of marine ecosystems by investigating the interaction between exploitation and marine ecosystem functions in a general strategic perspective. That is, we ask questions such as: Is the current exploitation pattern in accordance with the ecosystems overall and long run optimal use? Which size groups should be targeted? And in particularly, what are the ecosystem wide effects and opportunity costs of fishing at different trophic level?

From an economic perspective the ecosystem can be viewed as a production system where the final product is the fish. The production unit is the individual fish and the production is the growth in size of this fish. To grow, the fish has to consume other smaller organisms, typically other fish. The fish therefore act as both an intermediate product and the final product, i.e. the service. If the ecosystem is modelled as a production system, the trade-offs of fishing the small fish as final product or leaving it as an intermediate product will appear as opportunity costs in the production system. Ecosystem models based on Lotka-Volterra type of equations treats each species as a single unit and is therefore unable to account for the growth and production of individual fish. Here we employ size-spectrum models that move beyond the simple Lotka-Volterra approach by explicitly modelling the growth of individual fish as a consequence of predation on smaller fish. There is a growing literature describing different types of size spectrum models (Benoit and Rochet, 2004; Pope et al., 2006; Hall et al., 2006; Hartvig et al., 2011) and their application to understand how marine ecosystems respond to fishing (Andersen and Pedersen, 2010; Andersen and Rice, 2010). The advantage of the models is that they are based on a few simple and generally accepted assumptions at the level of the individual organisms and that their dynamics is explicit driven by predation and individual growth. Individuals in the model are characterized by their size (weight). Since fishing gear is size-selective and the prices of landed fish also depends on size, the models are ideally suited for economic calculations. Recently size-spectrum models been used as a basis for economic valuations (Ravn-Jonsen, 2011). However, in the employed model individual fish had only one attribute namely their size, which made it unsuited to study the consequences of fishing on different species. Here the model is extended with a trait attribute representing fish with different size of maturation, which is used as a proxy for species.

The size-spectrum model is used as the ecological basis for an investigation of the interaction between exploitation and marine ecosystems in a general strategic perspective. To simplify the problem the fishery is divided into
two fleets: one targeting forage fish, and one targeting large piscovorous fish. In this context forage fish refer to fish that are prey all their life. The forage fish fleet is then characterized by catching small fish from fish species that mature at small sizes and the harvest is used for industrial reduction into fish meal and oil. The large fish fleet catches piscovorous fish, that are fish species that mature as relative large, which are sold it for human consumption. The aforementioned questions are addressed through marginal economic analysis.

We derive a benefit indicator which is the marginal change in present value of rent when the system is brought from one steady state situation to another, taking the dynamic effects of the ecosystem during the change explicitly into consideration. A change of state is brought about through a change of the fishing pressure of one of the fishing fleets. The consequences of a change is characterized by the internal benefit on the fleet that imposes the marginal change, and the external benefit experienced by other fleets. We show that the forage species fishery have a notable economic impact on large species fishery, but not the other way around. The impact can be both negative and positive, depending on the level of exploitation of the system. To achieve an optimal exploitation the two fishery have to be adjusted to each other, and we find that the current level of exploitation of the North Sea is close to have the right balance between the two fisheries, however, the present exploitation level are to high to be optimal.

The model provides insight in the economic consequences of fishing, especially related with the forage fish fishery. This knowledge is important and is in most situations missing when formulating fishery policies, i.e. fisheries policies are ad hoc and second best.\textsuperscript{1} The model is calibrated for the North Sea, however the model build on characteristics general valid cross marine ecosystems. We contribute to the literature on marine ecosystem modeling and management about the function and value of forage fish (e.g. Cury et al., 2011; Wilen and Wilen, 2012; Pikitch et al., 2012) where our results add to the discussion by providing values based on ecological and economic theory. The developed benefit indicator method provide information of the net benefit on marginal changes, thereby gives information on management actions in non-optimal situations. The method is developed for analyze of numeric models; complicated simulation models that otherwise is left with scenario

\textsuperscript{1}E.g. in EU, annual quota are decided based on single species assessment models where impact on other species are not included.
analysis can with this tool provide information of marginal changes based on capital theory.

The structure of the paper is: The benefit indicator is derived in section 2, the economic model developed in section 3, the biological model briefly explained in 4, results are presented in section 5 and discussed in section 6. In the electronic supplementary material\(^2\) there is additional information on: A estimation of cost parameters, B estimation of price function, C details of the biological model, D sensitivity analysis of some cost parameters, and E sensitivity of the choice of control variable.

2. Benefit indicator

Our aim is to value the ecosystem effects of fishing. We therefore divide the consequences of fishing in two parts: 1) the consequences for the fleet doing the fishery and 2) the consequences for the other fleets indirectly affected. We use the term *internal benefit* as the net-benefit to the fleet doing the fishery, and *external benefit* as the externality imposed on the other fleet.

Each fleet has one control variable: the overall fishing mortality rate \((\mathcal{F}_f, \mathcal{F}_l)\) where \(\mathcal{F}_f\) is for the fleet targeting forage fish and \(\mathcal{F}_l\) for the fleet targeting larger fish. We define *continue as usual* as keeping a constant \(\mathcal{F}\) and an action is to change the \(\mathcal{F}\). For the purpose of generalization of the method the two fleets are called \(i\) and \(j\) where \((i, j)\) can be either \((f, l)\) or \((l, f)\).

Assume two ecosystem services: fishery \(i\) and \(j\). The services are the harvest \(y_i\) and \(y_j\)—appraised by the rent (net value) \(\pi_i\) and \(\pi_j\). Both harvest and rent are varying through time; to include the time perspective, the benefit of fishery \(i\) is summarized in \(Y_i\) and \(V_i\) as the present value of respectively harvest and rent using the social discount rate \(\rho\) (equivalent for fleet \(j\)):

\[
Y_i := \int_0^\infty y_i(t) e^{-\rho t} dt \\
V_i := \int_0^\infty \pi_i(t) e^{-\rho t} dt
\]

We look at a baseline situation where the ecosystem is in equilibrium with its fisheries and the outputs constant. We consider a change in the harvest

\(^2\)The supplementary material: [URL for the supplementary material]
of fleet \( i \) prompted by a change in \( F_i \); the system will then no longer be in equilibrium. Because of the restriction imposed by the functionality of the ecosystem, the change in fleet \( i \)'s harvest will lead to changes in harvest and rent for fleet \( j \) as well. As fleet \( j \) is \textit{continue as usual} the changes in this fleet is an externality.

As the change in \( V_j \) will depend on \( \Delta y_i(t) \) we use the concept from cost-effectiveness analysis (Garber and Phelps, 1997; Kronbak and Vestergaard, 2013) and evaluate \( \Delta V_j / \Delta Y_i \). We define the benefit indicator of fleet \( j \)'s rent per unit of fleet \( i \)'s harvest in the limit \( \Delta Y_i \to 0 \):

\[
B_{j/i} := \frac{\partial V_j}{\partial Y_i}
\]  

(3)

where the present value of rent \( V_j \) and harvest \( Y_i \) is measured departing from an ecosystem in equilibrium with \((F_i, F_j)\) and only \( F_i \) is changed. The benefit indicator of the fishery itself \( B_{i/i} \) can be calculated in a similar fashion. \( B_{i/j} \) does not measure an externality, but should be viewed as the net-benefit to the fishery of removing one more fish, ignoring the externality of the fishery on other fisheries.

The total benefit indicator per unit of fleet \( i \)'s harvest is:

\[
B_{\bullet/i} := B_{i/i} + B_{j/i}
\]  

(4)

which is the total net benefit of removing one more fish including opportunity costs. Here only two services are considered but the expression can be generalized to arbitrary number of services by summing over all services. The benefit will be a function of the current state of the services, and if the total benefit is positive, it will, from an economic point of view, be beneficial to increase the harvest and \textit{vice versa}. If \( B_{\bullet/i} = 0 \) for both fleets, it will be a situation where a marginal change of fishery will leave the present value of rent flow unchanged. Such a point is a candidate for a situation with optimum ecosystem services.

2.1. Implementation

The control variables in the ecosystem model (described in section 4) is the fishing mortality rate \( F \) of the fleets \( i \) and \( j \). The actual estimation of \( B_{j/i} \) has to be made numerically:
\[ B_{j/i} = \frac{\partial V_j}{\partial Y_i} = \frac{\partial V_j}{\partial F_i} \frac{\partial F_i}{\partial Y_i} \]  

\[ \approx \frac{\Delta V_j}{\Delta F_i} \left( \frac{\Delta Y_i}{\Delta F_i} \right)^{-1} \]  

The estimation is preformed by letting the model run until converged to equilibrium\(^3\). Departing from this equilibrium two experiments A and B are preformed: the fishing mortality of fleet \( j \) is fixed while the fishing mortality in fishery \( i \) is changed: \( F_i(A) = (1 - \epsilon)F_i \) and \( F_i(B) = (1 + \epsilon)F_i \). The change in fishing mortality cause fluctuations in the ecosystem model. The experiment run for \( T = 50 \) years where the system have converge to a new equilibrium. We use \( \epsilon = 10^{-6} \) as a suitable compromise between precision and numerical noise.

The harvest flows, \( y_i(A) \) and \( y_i(B) \), and rent flows, \( \pi_j(A) \) and \( \pi_j(B) \) are recorded (the bold symbols indicates that the flows are functions of time represented as vectors). All are vectors of length \( T/\Delta t \), where \( \Delta t \) is the time step in the model. The change in present values are then calculated as:

\[ \Delta V_j = PV(\pi_j(B) - \pi_j(A)) \]  

\[ \Delta Y_i = PV(y_i(B) - y_i(A)) \]  

The integrals involved in the present values are estimated numerically as:

\[ PV(\pi) = \sum_{t \in \{0, \Delta t, 2\Delta t, \ldots, T - \Delta t\}} \rho^{-1} \left( e^{-t\rho} - e^{-(t+\Delta t)\rho} \right) \pi_t + e^{-T\rho} \frac{\pi_{T-\Delta t}}{\rho} \]  

here \( \sum (\cdots) \) calculates the present value from \( t = 0 \) to \( t = T \) and \( e^{-T\rho} \pi_{T-\Delta t} \rho^{-1} \) estimates the present value from \( t = T \) to \( t = \infty \).

3. Economic model

3.1. Two views on production in fishery

In a traditional fisheries models the harvest is calculated by summing contributions from all fished size groups. In the size-spectrum model this is
performed as an integral over the abundance distribution $N(w)$ weighted by the size-selectivity of the fishing gear $\omega(w)$:

$$ Y = \mathcal{F} \int_0^\infty \omega(w)N(w)w \, dw $$

(10)

where $\mathcal{F}$ is the overall fishing mortality.

Fisheries economists, on the contrary, tend to use a production model where the harvest $y$ is the production of a fishing vessels with the factor inputs effort $E$ and stock $S$, where the fish stock is seen as an environment variable.\(^4\) The traditional approximation is to apply a Cobb-Douglas production function (e.g. Clark, 1990, eq (2.8))

$$ y = qE^\alpha S^\gamma $$

(11)

The total production of the fleet is the sum of the production of each vessel. Assuming identical vessel and effort levels, it will have the same form:

$$ Y = \sum_n q \left( \frac{E_{\text{total}}}{n} \right)^\alpha S^\gamma $$

$$ = q' E_{\text{total}}^\alpha S^\gamma $$

(12)

where $n$ is the number of vessels and $q' = n^{1-\alpha}q$. Hence the total harvest function will be a scaled version of (11).

The two views on production can be united by defining the stocks as:

$$ S := \int_0^\infty \omega(w)N(w)w \, dw $$

(13)

and the overall fishing mortality rate as

$$ \mathcal{F} := q' E_{\text{total}}^\alpha S^{\gamma-1} $$

(14)

In this manner the economic production view (12) and the model (10) will give the same production $Y$.

The function $S^{\gamma-1}$ in the overall fishing mortality rate (14) will, with an expectation of $\gamma \in [0, 1]$, be a convex decreasing function, indicating there is declining productivity with respect to increasing stock.

\(^4\)Stock is not a traditional production factor for the individual fisher as it is not under his control. It is more like an exogenous environment. However at an aggregated, that is from a social view point, the stock is endogenous and can be seen as a traditional production factor.
3.2. Generic cost efficient model

Effort is an ambiguous concept, economist will prefer to work with physical input factors like labor, fuel, provision etc. (see e.g. Squires, 1988)

\[ y = q_1 x_1^{\alpha_1} x_2^{\alpha_2} \cdots k^{\beta} S^{\gamma} \]  

(15)

where \( x_i \) is variable input factors and \( k \) capital. Given (15), with corresponding prices \( p_i \) and the fisher assumed to minimize cost, the variable cost function is:

\[ G(p; y, k) = x \cdot p \bigg| \frac{x_i}{x_j} = \frac{\alpha_i p_i}{\alpha_j p_j} \quad \forall \ (i, j) \]  

(16)

The equations (15) and (16) give a production cost relationship:

\[ y = q_2 G^{\alpha} k^{\beta} S^{\gamma} \]  

(17)

where

\[ \alpha = \sum \alpha_i \]  

(18)

\[ q_2 = q_1 \alpha^{-\alpha} \prod_i \left( \frac{\alpha_i}{p_i} \right)^{\alpha_i} \]  

(19)

The production function (17) can replace (11) to allow for estimation of a production function based on accounting statistics for the individual vessel, without introducing the effort concept. It may seem equivalent to have a fixed price on effort, however by assuming minimized cost, we allow for substitution when relative prices between factors change (see supplementary material A).

Our objective is to analyze the ecosystem model from a strategic perspective, that is, from a long term perspective. We therefore will derive a cost function under the assumption that all the factor input of the fishing fleet are totally variable and we therefore can minimize cost, operation cost as well as capital costs.

With \( p_k \) as the price of capital the total cost per vessel \( C = G + kp_k \). If we assume the ecosystem is in a steady state with a total harvest of \( Y \) the cost minimizing problem is to find the number of vessels \( n \), operation cost \( G \) and capital \( k \):

\[ (n, G, k) = \text{argmin}_{n,G,k} \left. \frac{1}{Y} \right|_{Y=nqG^{\alpha} k^{\beta} S^{\gamma}} (G + kp_k) \]  

(20)
This can be solved in two steps: First find the capital level where unit cost is minimized and then find the number of vessels. Minimizing unit costs implies input factors are applied in the ratio

\[
\frac{G}{kp_k} = \frac{\alpha}{\beta}
\]  

(21)

and, as we are looking for longterm optimal level of capital, that \(\alpha + \beta = 1\). The total cost per vessel is then:

\[
C = G + p_k k = G \left(1 + \frac{\beta}{\alpha}\right)
\]  

(22)

And the unit costs

\[
\frac{C}{y} = \frac{G \left(1 + \frac{\beta}{\alpha}\right)}{q \left(\frac{\beta}{\alpha p_k}\right)^{1/\beta} G^{\alpha + \beta} S^\gamma} = AS^{-\gamma}
\]  

(23)

Where

\[
A = q^{-1} \beta^{-\beta} \alpha^{-\beta - 1} p_k^\beta
\]  

(24)

In conclusion we can, if we are doing analysis from a strategic perspective and assume an ideal cost minimizing fleet, expect that the unit cost of harvesting will be of the form (23) if changes in harvest in the short run perspective are small. As there in section 3.1, with the definition of stock (13), is established a coherence between biological production function (10) and the production function (17); \(F\) can be used as control variable in the model and the cost calculated with (23).

3.3. Cost function parameter

The parameters for the cost functions for the two fleets (Tab. 1) are estimated for the North Sea on the basis of accounting statistics, landing statistics and ICES (International Council for Exploration of the Sea) stock assessment summeries (ICES, 2010b) (see supplementary material A). The unit costs function (23) has two parameters \(A, \gamma\) and one variable \(S\). The value of \(\gamma\) is independent of how \(S\) is measured as long as it is proportional to density of fish in the sea. However the value of \(A\) will depend on the way \(S\) is measured and there is no way to get from spawning stock biomass, the metric of ICES, to density of fish per m\(^3\), the metric of the model. The approach
taken is to calibrate the function to give a unit cost like the one observed in the data. However the rent in todays fishery is zero (supplementary material A Tab. 2 and 3). The fishery where transferable quotas was first introduced in Denmark was herring and mackerel fishery (as test from 2003, permanent 2007), this is today probably the most cost efficient fishery, and we assume that the other sectors can be as efficient if proper managed. Hence the constant $A$ is found by setting the rent to 15.57% of the revenue in a fishery that resembles to days fishery in the North Sea.

### 3.4. Price function

The price function is estimated from data from the Danish Landing Statistics (estimations details in supplementary material B.). Two price functions are needed: $p_f$ for the forage fish fleet and $p_l$ for the large fish fleet. The forage fish fleet lands fish for reduction into fishmeal. Since there is no size sorting in the landings we assume a flat price with respect to the size of the landed fish:

$$p_f(w) = P$$

The large fish fleet lands fish for for human consumption. Here prices depend on size, grade and species. In the model size is present as dimension, and it is therefore appropriated to give a price as a function of size:

$$p_l(w) = \begin{cases} 
\theta \left(1 - \exp\left(-\frac{(w-b)}{a}\right)^k\right) & w \geq b \\
0 & \text{else}
\end{cases}$$

Variance statistics (Tab. 1) is based on re-sampling (Efron and Tibshirani, 1993) leading to a coefficient of variation below 0.004.

### 4. Ecosystem model

The aim of a the trait-based size-spectrum model is to calculate the abundance of individuals $N(w,W)$ as a function of the size of individuals $w$ and the asymptotic (maximum) size that the individual may reach $W$ (Fig. 1 panel A). The representation of the trait $W$ as a continuous variable makes it possible to circumvent the need to represent specific species; the diversity of the fish community is instead characterized by the attribute of their asymptotic size $W$. All parameters in the size spectrum models are related to individual weight which makes it possible to formulate the model with a
Table 1: Parameter estimates for price and cost functions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Std Error</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>0.1610</td>
<td>0.0053</td>
<td>€ kg$^{-1}$</td>
</tr>
<tr>
<td>$\varrho$</td>
<td>4.830</td>
<td>0.51</td>
<td>€ kg$^{-1}$</td>
</tr>
<tr>
<td>$b$</td>
<td>0.0295</td>
<td>0.00096</td>
<td>kg</td>
</tr>
<tr>
<td>$a$</td>
<td>5.38</td>
<td>0.25</td>
<td>kg</td>
</tr>
<tr>
<td>$k$</td>
<td>0.5230</td>
<td>0.0039</td>
<td></td>
</tr>
<tr>
<td>$\gamma_f$</td>
<td>0.175</td>
<td>0.037</td>
<td></td>
</tr>
<tr>
<td>$\gamma_l$</td>
<td>0.280</td>
<td>0.016</td>
<td></td>
</tr>
<tr>
<td>$A_f$</td>
<td>0.05748</td>
<td>Calibrated</td>
<td>€ kg$^{-1}$</td>
</tr>
<tr>
<td>$A_l$</td>
<td>0.2759</td>
<td>Calibrated</td>
<td>€ kg$^{-1}$</td>
</tr>
</tbody>
</table>

small set of general parameters, which has prompted the label “simple” to the model framework (Pope et al., 2006). The equations and parameters of the models are described in supplementary material C.

Fishing in the model is represented by the by the product of overall fishing mortality $F$ and selectivity as a function of size and trait $\omega(w,W)$. The two fleets are characterized by which range of asymptotic sizes they target; the forage fish fleet targets species with $W < 512$ g (solid lines Fig. 1A) and the large fish fleet target $W \geq 512$ g (dashed lines Fig. 1A). Overall fishing mortality rate of the two fleets ($F_f, F_l$) are control variable in the model. The size-selectivity is modeled as a trawl selectivity curve with an S-shaped function (Fig. 1 B). The output of the ecological model is the harvest with respect to size (Fig. 1 C), which gives the price when multiplied by price and integrated over all sizes.

5. Results

To illustrate the calculation of the benefit indicator the state of the current North Sea fishery is examined. We assume that the mean landings over the period 2001–2009 represent the sustainable harvest the North Sea can deliver in its present state. The mean landing is 1 990 304 ton year$^{-1}$ (ICES, 2010a), half is assumed to be forage fish fishery and half large fish fishery. We depart from a model system in equilibrium and delivering these services and calculate the benefit indicators with a social discount rate of $\rho = 0.03$ year$^{-1}$.
Figure 1: Run of the model with a fishing effort of the two fleets corresponding to the current exploitation of the North Sea. Solid lines represent forage fish fleet, dashed lines the large fish fleet. A: density of fish $N_i(w)$ as a function of individual weight $w$. Each thin line represents a population characterized by the maximum size $W$ of individuals in the population. The thick black line is the sum of all the populations. The gray line is the background spectrum represents the plankton community that provides food for the smallest individuals. B: Fishing size-selection function $\omega(w)$. C: The density of harvest. The total harvest is the integral under the curves, however, as the abscissa is representing the size on a logarithmic scale, for the areas of the curves to be comparable they are scaled with the logarithm of their size: the plotted line is $\mathcal{F}_\phi N_w \Delta w$. 
A change in the fishing mortality of the forage fleet has an impact on production and rent of both fleets (Fig. 2). Initially harvest of the forage fish fleet shows a big increase followed by a reduction leveling out around half of the initial increase. The rent of the forage fish fleet increases initially, but eventually levels out close to zero. The reason that the rent ends up around zero, despite the increase in harvest, is a slight decrease in the density of fish; even though the elasticity of unit cost with respect to density is only \( \gamma = 0.175 \), the result is a slight increase in unit cost that affects harvest of the whole fleets. The consequence for the large fish fleet of the change in fishing mortality of the forage fish fleet is a slight drop in harvest followed by a sustained increase in harvest volume. Despite the increase in harvest of the large fleet the rent is decreased. This decrease is due to a decreased size of the fish in large fish fleet’s harvest leading to a lower market value. The benefit indicator for the two fleets per forage fish is calculated according to (3). The internal benefit of the forage fleet shows a slight increase, which is offset by a much larger external negative benefit of the large fish fleet. The total benefit of an increase in the forage fishing in the North Sea today is therefore clearly negative.

In Fig. 3 the consequences of a change in the large fish fleet’s fishing mortality rate can be evaluated in a similar manner (Fig. 3). The production of the large fish fleet show the same pattern as the forage fish fleet with an initial high extra harvest followed by oscillations and settling around half the initial amount. The harvest of the forage fish increases initially due to the decreased predation pressure, but later it settles around zero as the predators are increasing in number again, however at a slightly smaller level. The change in rent of the forage fish fleet is negligible while the rent of the large fish fleet show an initial increase followed by a drastic decrease. This decrease in rent, despite increase in harvest is caused by two things: a slight decrease in fish density, which increase the unit costs, and a decrease in size of the harvested fish, which decrease the marked value. The total benefit of an increase in the large fish fleet in the North Sea today is negative and in magnitude higher than the externality imposed by the forage fish fishery. Since both benefit indicators of the present use of the North Sea are negative (Tab. 2) the benefit of the ecosystem service from the North Sea can be improved by reducing both fleets’ harvest.

[16]

Fig. 4 presents the internal and external benefit indicator calculated with a social discount rate of \( \rho = 0.03 \) year\(^{-1} \). The zero contour lines in the two
\[ \Delta Y_f = 1.139 \cdot 10^{-8} \text{g} \text{m}^{-3} \]

\[ \Delta V_f = 5.139 \cdot 10^{-14} \text{e} \text{m}^{-3} \]

\[ B_{f/f} = 4.511 \text{e} \text{ton}^{-1} \]

\[ \Delta V_l = -8.160 \cdot 10^{-13} \text{e} \text{m}^{-3} \]

\[ B_{l/f} = -71.63 \text{e} \text{ton}^{-1} \]

\[ B_{f/l} = -1.093 \text{e} \text{ton}^{-1} \]

\[ B_{l/l} = -3 \text{e} \text{ton}^{-1} \]

\[ B_{f/l} = -1.096 \text{e} \text{ton}^{-1} \]

Figure 2: Illustration of the benefit indicator method for the calculation of the benefit due to a change in the forage fish fishery. The starting point of the calculation is a steady state. At time \( t = 0 \) the forage fish fishing mortality is slightly changed, while the fishing mortality of the large fish fleet is unchanged. The change in fishing mortality leads to a change in production (upper panel) and rent (lower panel) of the forage fish fleet (solid lines) and the large fish fleet (dashed).

Table 2: The benefit indicators at the present use of the North Sea.

<table>
<thead>
<tr>
<th>With respect to</th>
<th>Forage fish fleet</th>
<th>Large fish fleet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Benefit</td>
<td>( B_{f/f} )</td>
<td>4.5 ( \text{e} ) ton(^{-1} )</td>
</tr>
<tr>
<td>External Benefit</td>
<td>( B_{l/f} )</td>
<td>-71.6 ( \text{e} ) ton(^{-1} )</td>
</tr>
<tr>
<td>Total Benefit</td>
<td>( B_{f/l} )</td>
<td>-67.1 ( \text{e} ) ton(^{-1} )</td>
</tr>
</tbody>
</table>
Figure 3: Illustration of the benefit indicator method due to a change in the large fish fishery. The change in fishing mortality leads to a change in production (upper panel) and rent (lower panel) of the forage fleet (solid lines) and the large fish fleet (dashed).

internal panels cross each other in point A. This is the solution if society optimizes the benefit from the two services, but ignoring the externality. At point A there is are negative externalities of $-132 \text{ € ton}^{-1}$ inflicted on large fish fleet for the marginal fish caught by forage fish fleet, and of $-12 \text{ € ton}^{-1}$ on forage fish fleet for the marginal fish caught by large fish fleet.

To find a global optimum the total benefit indicator has to be considered (Fig. 5). The optimum is where the total benefit of the two fleets is zero (point B). This point may be reached by approximately halving the harvest of the two fleets.

The external benefit from the forage fish fleet ($0–150 \text{ € ton}^{-1}$) generally far exceeds the internal benefit ($0–30 \text{ € ton}^{-1}$). This implies that the forage fish fishery should be managed with consideration of the large fish fishery. The zero contour line of the total benefit indicator for the forage fish fishery follow diagonals up left and right from point B (Fig 5). This indicates that the optimal forage fish harvest is dependent on the volume of the large fish fishery’s harvest.

On the contrary, in absolute values, the internal benefit from large fish fleet’s fishery ($0–1000 \text{ € ton}^{-1}$) generally dwarfs the external benefit ($0–12 \text{ € ton}^{-1}$).
Figure 4: The benefit indicators (€ ton\(^{-1}\)) for the North Sea forage fish fleet (top) and large fish fleet (bottom) divided into internal benefit \(B_{i/i}\) and external benefit \(B_{i/j}\). Four points of special interest are marked: the plus sign is the current state of the North Sea, A is where the internal benefit of the two fleets cross, B is where the total benefit of the two fleets cross (Fig. 5), and C is an arbitrarily chosen point where the externality on large fish fleet from forage fish fleet is positive.
Thus the influence of the large fish fleet on forage fish fleet is rather small and it can for practical purposes be ignored. The zero contour line for the large fish fishery in Fig 5 is vertical, indicating that optimum harvest level in the large fish fishery is independent of the forage fish fishery.

A striking result of Fig. 4 is that the forage fish fishery can create a positive externality for the large fish fishery. To understand the mechanism behind this result the population level in three points marked A, B and C in Fig. 4 and 5 are examined (Fig. 6). As the harvest of the forage fish is increased, i.e. moving from point C to B, the abundance of large forage fish within the size range targeted by the fishery decreases. The decreased abundance of forage fish releases the predation pressure on smaller individuals in the size range 1–10 g. The decrease in the abundance of large forage fish affects the large fish in two opposite ways: 1) it removes some of the food for the largest fish (> 1 kg) and 2) it reduces the competition for food for juvenile individuals of the large fish. Moving from C to B the effect of the reduced competition appears most important since the large fish generally increases in abundance. Only moving from B to A are the very large fish (> 5 kg) negatively affected due to lower abundance of food from forage fish. The impact in abundance is modest but since the price of large fish is high this reduction is responsible for the negative externality at high harvest rates.
Figure 6: Abundance of fish as a function of individual size (both axis logarithmic) at the points A-C in Figs. 4 and 5, A dotted, B solid and C dashed. The abundance of forage fish (top) and large fish (bottom) is scaled relative to the unfished situation. The gray regions illustrate each fleet’s selection function.
6. Discussion and Conclusion

We have developed a general methodology to analyse the internal and external consequences of fishing an ecosystem in terms of the benefit indicator. The method has been applied to quantify the externalities that a forage fishery and a fishery for large fish in the North Sea generate for one another. The generalization of the methodology to more than two ecosystem services is straightforward. Even though the model is calibrated to resemble the North Sea, it builds on properties that are generally found cross ecosystems. The results therefore have a general value and may be applied to other systems as well, at least in qualitative terms.

The utilized method is marginal analysis of the present value of the ecosystem services under the restriction of the ecosystem’s function. The method of benefit indicator is, as defined in section 2, linked to the control variable, the overall fishing mortality, as this defines what continue as usual and what a change is. To test how consistent the benefit indicator is to the choice of control variable, the model was reformulated with harvest as control variable. The results are presented in supplementary material E and show consistency with the found benefit indicator, except for the external benefit from forage fish fleet. Here the zero contour line moves up so the value for to days fishery change for \(-71\,€\,\text{ton}^{-1}\) to \(100\,€\,\text{ton}^{-1}\). Nevertheless the general picture and the optimum point are convergent, assuring that the benefit indicator is a proper indicator of the net benefit, though value for external benefit at present exploitation rate have to be taken with precaution.

The intersection of the zero contour lines of the total benefit indicator in Fig. 5 indicates an optimum. For simplicity the decision variables have been reduced to two dimensions, in the real world there are many more possibilities: change of the size selectivity, change of the selectivity with respect to traits, change of fishing mortality over time, etc. It may therefore be possible to increase the benefit by exploring other dimensions of control variable.

In present fishery management an aspect considered important is to secure the reproduction of the fish stock. The ecological model has fixed reproduction, that is, there is no feedback from the abundance of the adult fish to the abundance of offspring. This is in line with classic yield-per-recruit analysis in fisheries science (Beverton and Holt, 1957). Thus the shadow price of reproduction is not part of the benefits calculated in Fig. 4 and 5. This is purposely done to highlight only the trophic system such that all effects
stems from predation and growth of individual. Our analysis can therefore not stand alone, the reproduction aspect has to be considered as well. However, the model indicates benefit from a substantial reduction in harvest, this will at the same time greatly reduce the thread of reproduction failure.

The economic aspects of the model consist of a price function and a cost function. Both functions are based on data from Denmark, however Danish fishery being a part of the global marked, those functions can therefore be expected to be valid as a generic functions. The price function is divided in two, one for forage fish and one for large fish. Large fish is regarded as landed for direct human consumption and we show that price increases with size with minor changes from year to year. We are therefore confident that the price function reflects the willingness of industry to pay with respect to size.

The cost function is described as a power function of the biomass in the sea. The function needs two parameters for each fleet, the exponents $\gamma_i$ and the coefficients $A_i$. The value of the exponents differ between study, e.g. found Sandberg (2006) values in the range between 0.18 to 0.48 for different herring and cod fleets, and Eide et al. (2003) found 0.42 for cod. Compared to those, the values found in present study (0.18 and 0.28) are in the lower end. In supplementary material D the sensitivity of this parameter is tested by increasing the exponents by a factor 1.5. The change of $\gamma$ do not qualitatively change the figures 4 and 5. The value of the benefit to the forage fleet is slightly sensitive to change in the exponent, while large fish fleet is almost insensitive.

As our model do not use the same stock concepts as ICES stock assessments we have calibrated the coefficients in the cost functions so present fishery gives 15.57% rent — as the best regulated fleet in Denmark. This is a rough estimate as the present fishery yields zero rent (supplementary material A Tab. 2 and 3). In supplementary material D the sensitivity of this calibration is tested by calibrating under the assumption of zero rent in present fishery. Again the figures do not change qualitatively, however the value of the benefit to the forage fish fleet is more sensitive to this parameter, while the large fish fleet is only slightly sensitive. The reason for this difference between the two fleets in sensitivity stems from the underlying price structure: while large fish fleet benefit from an increase in price with the increase in size of fish as a result of a relived exploitation level, forage fish fleet have a flat price. Both fleets benefit from an increase in density as a result of a relived exploitation levels in form of decreased unit cost. However
for large fish the change in price dominates over the change in cost. The economics of forage fish are then dominated by the density effect on the cost, and large fish fleet is dominated by the price response to size of fish.

The model result as presented in Fig. 4 and 5 quantify how the fleets affects the other and themselves. The large fish fleet generate no notable externality in the forage fish fishery. It does, however, generate a large intertemporal cost in its own fishery if not managed close to optimum. Because of the specific size structure and price increasing with size in this model, the consequences of a change in size of harvest fish (see Fig. 3) are captured in the model, hence contributes to calculations of the intertemporal cost.

There are situations where the fishery on the forage fish generates a positive externality for the large fish fishery as well as situations where the externality is negative. The explanation for this must be seen in the different function the species have for each other doing their life history. If we focus on a mature forage fish, that is around 100 g, it will have three different functions with respect to the large fish species: 1) the function as a predator on larvae and juveniles, 2) the function as competitor to similar size fish and 3) the function as prey (forage fish). The first two have a negative influence, while the last have a positive. The economic analysis shows that the triple functionality leads to a requirement of a balance between harvest of forage fish and large fish species. Traditional bioeconomic models have been centred around the mature fish and in multi-species models including interaction on the mature level, for example are models of the Lotka-Volterra type restricted to model either predator-prey or competition or mutualism. As a consequence will these models disregard an important part of the ecological functionality.

Concluding remarks

Overall the model show that the exploitation of the forage species has a notable economic impact on the fishery of the large species, but not the other way around. The analysis shows that the naïve perception where the forage species is only viewed as food for large species is too simple. The predation of forage fish species on the juveniles of large species and the competition between forage fish species and juveniles of the large species can, if the density of forage fish is high, dominate over the forage fish function. Thus there has to be a balance between harvesting the forage fish and the large fish. The present management of the North Sea is, at present exploitation rate, not far from having the right balance. However, the model’s optimal point

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\((481 \cdot 10^3 \text{ ton year}^{-1}, 489 \cdot 10^3 \text{ ton year}^{-1})\) is around half the present day's harvest of the North Sea, indicating present exploitation as too high. Improving the utilization of the ecosystem implies an acknowledgment of the externalities that the other fisheries impose on each other.

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Hannesson, R., 2002. The economics of fishing down the food chain. Canadian Journal of Fisheries and Aquatic Sciences 59 (5).


ICES, 2010b. Stock assessment summary database. Internet, retrieved 24/10 2011. URL http://ices.dk/datacentre/StdGraphDB/FishStockDB.mdb


