Economic Consequences of Marine Protected Areas: The case of the North Sea sandeel Fishery

Ayoe Hoff[1], Jesper Levring Andersen[1], Asbjørn Christensen[2], Henrik Mosegaard[2]

[1]Institute of Food and Resource Economics, University of Copenhagen, Rolighedsvej 25, 1958 Frederiksberg C, DK-Denmark (Contact: ah@foi.dk).

[2]DTU-Aqua, Charlottenlund Castle, Jægersborg Allé 1, 2920 Charlottenlund, DK-Denmark.

Abstract

Marine Protected Areas (MPAs) have for some time been considered a tool in fisheries management and marine environmental protection. Potentially much can be gained from MPAs, most importantly the protection of vulnerable species, habitats, and ecosystems, as well as ensuring long term sustainable harvesting of economically valuable species. The EU FP-6 project PROTECT (Marine protected areas as a tool for ecosystem conservation and fisheries management) had the primary aim to provide assessment tools for the biological as well as socio-economic effects of MPAs. In this connection, a flexible optimization model BEMCOM (Bioeconomic model to evaluate the consequences of marine protected areas) was developed to provide direct indications for the economic effects for the fisheries of introducing MPAs. BEMCOM answers the question 'what's best', i.e. finds the overall economically optimal effort allocation between the harvesting fleets given possible restrictions on e.g. catches.

The BEMCOM model will be presented and applied to the case of the Danish sandeel fishery in the North Sea. Different parties have suggested closing parts of this fishery in the North Sea of concern for the ecosystem, the sand bank habitats or fisheries for other species that feed on sandeels. How such closures may affect the economics of the Danish fleet targeting sandeel has been assessed with BEMCOM by comparing the present regulation with the case where the Dogger Bank, the main sandeel habitat in the North Sea, is closed for fishing. It is shown that this closure reduces the net profits for the Danish industrial fleet with 21%, indicating that the fleets do not, as might be expected, re-allocate the effort to other fishing areas or species.

Introduction

Marine Protected Areas (MPAs) may be established for a variety of reasons, e.g. as an aid in fisheries management, to protect vulnerable species, nursing grounds or whole ecosystems, or to protect sites of cultural or historical importance. Typically MPAs put some restrictions on fishing in the included areas, and the socio-economic effects of this on affected fishing fleets have yet to be understood fully. The EU FP-6 project PROTECT[1] had the primary aim to provide assessment tools for the biological as well as socio-economic effects of MPAs. In this connection, the bio-economic optimization model BEMCOM (BioEconomic Model to evaluate the COnsequences of Marine protected areas) was developed to provide direct indications for the economic effects for the fisheries of introducing MPAs. BEMCOM is set up as a flexible modelling framework, which is programmed in a generic way in order to investigate different management strategies with respect to marine protected areas in a variety of case studies. Being very flexible BEMCOM operates with several dimensions (time-scale, fishing areas, fleets, species etc.) where some of these have an extensive number of alternatives. Fishing area may, for example, be disaggregated down to ICES square. Such a high level of detail is necessary in order to address the questions related to the economic consequences for fishing fleets of MPAs. BEMCOM answers the question 'what's best', i.e. finds the overall economically optimal effort allocation between the harvesting fleets given possible restrictions on e.g. catches. By 'overall' is in the present context meant that BEMCOM allocates effort by optimising the total profit of all fleets involved in the fishery. This may not necessarily lead to optimisation of individual fleet or vessel profit, but will give a picture of the highest possible gains to society from a sustainable fishery.

The North Sea sandeel fishery has through time primarily been conducted by Danish fishermen. In 2005 Denmark had 94 % of the EU sandeel quota[2], and caught the major part of total EU landings[3]. Different parties have suggested closing parts of this fishery in the North Sea of concern for the ecosystem, the sand bank habitats and/or fisheries for other species that feed on sandeels (Engelhard et al., 2008). On the Dogger Bank, where the highest proportion of the North Sea sandeel catches are taken, sandeel are predated upon by a number of human consumption species important for the European demersal trawl fleet. Low sandeel abundances, caused by excessive fishing, may affect the stocks of these predatory species and as such have further consequences for the European fishing fleet. To illustrate the potential of BEMCOM the model has thus been used to assess how a closure of Dogger Bank may affect the economics of the Danish fleet targeting sandeel by comparing the present regulation with the case where the Dogger Bank is closed for fishing.

[1] Marine protected areas as a tool for ecosystem conservation and fisheries management, EU-FP6 Contract no. 513670.

[2] Since 2006, the sand eel TAC has been set in May based on a real time monitoring of the sandeel population.

[3] The remaining part of the sandeel TAC in the North Sea is distributed with 2% to United Kingdom and 4% is unallocated.

The paper is introduced with a description of the BEMCOM model, followed by an outline of the dimensions used in the model for the North Sea sandeel fishery. Then the data used in the model are described and subsequently the restrictions used when modelling the fishery. Finally the results of the model calculations are presented and discussed.

The BEMCOM model

BEMCOM covers 7 dimensions to be able to reflect a fishery in a realistic way. These dimensions are:

- Year	*y =*	*1,…,Y*
- month/quarter	*m =*	*1,…,M*
- vessel/fleet segment	*f =*	*1,…,F*
- primary fishing ground (area)	*g =*	*1,…,G*
- sub-fishing areas (squares)	*a =*	*1,..., A*
- Species	*s =*	*1,…,S*
- Cohort	*c =*	*1,…,C*

Each dimension has several alternatives dependent on the analysed case study. It must be noticed that primary fishing grounds are distinguished from sub-fishing areas. Primary fishing grounds are e.g. the North Sea or larger parts of this, while sub-fishing areas are sub-divisions of the primary fishing areas, i.e. ICES squares. This division is necessary in order to include detailed activity of a vessel, but at the same time maintaining focus on the overall fishing grounds considered in a case study. Moreover some information may only be available for the overall fishing ground (for example stock information), while other information is available at a finer scale (for example catch data).

In order to realistically simulate a given fishery BEMCOM includes biological, economic and production variables that together constitute a detailed description of the case study in question. The economic variables, which are all at the vessel level, comprise:

- profit	*P*
- Revenue	*R*
- total costs	*TOTC*
- variable costs	*VC*
- fuel and lubricants costs	*FUELC*
- provision costs	*PC*
- ice costs	*IC*
- sales costs	*SC*
- crew costs	*CC*
- fixed costs	*FC*

- maintenance costs *MAIN*
- insurance costs *INSUR*
- other fixed costs *OTH*
- fish prices *P*

The biological variables are:

- fish stocks $N_{c>1}$
- Recruitment $N_{c=1}$
- landings distribution on cohorts $lf_{f,g,s,c}$
- discard fraction of catches $df_{f,a,s,c}$

Finally the production variables, also at the vessel level, are:

- Catches *C*
- Effort *E*
- fleet size (number of vessels) *NV*
- Landings *L*
- landings weight *WL*
- Discards *D*

All these variables are determined within the model framework, when the objective function is optimised. At present the objective function is the present value profit for the total fleet over the time period considered, which is optimised with respect to allocation of fishing effort $E_{y,m,f,a}$ over fleets and sub-fishing areas in each time period (month/quarter/year) considered:

(1) $$\max_{E_{y,m,f,a}} \quad TOTP = \sum_{y,f} NV_{y,f} \cdot P_{y,f} \cdot \frac{1}{(1+\rho)^y}$$

Here ρ is the interest, or discount, rate, $NV_{y,f}$ is the number of vessels in fleet segment *f* in year *y*, and $P_{y,f}$ is the profit in year *y* for an average vessel[4] in fleet segment *f*, given by:

(2) $$P_{y,f} = R_{y,f} - TOTC_{y,f}$$

Where $R_{y,f}$ and $TOTC_{y,f}$ are the revenue respectively total cost in year *y* for an average vessel in fleet segment *f*. The latter is given by the sum of variable (*VC*) and fixed (*FC*) costs:

[4] By 'average vessel' is meant that all vessel information are based on average values for the fleet segment in question.

(3) $TOTC_{y,f} = VC_{y,f} + FC_{y,f}$

The variable cost is given by the sum of fuel cost, provision cost, ice costs, sales costs and crew costs:

(4) $VC_{y,f} = FUELC_{y,f} + PC_{y,f} + IC_{y,f} + SC_{y,f} + CC_{y,f}$

The revenue is given by the sum of landings in numbers ($L_{y,m,f,a,s,c}$) times weight per age-class ($wt_{s,c}$) times price ($p_{y,f,g,s,c}$) summed over months, fishing grounds, species and age-classes, i.e. the sum of the landings value for fleet *f* of each species caught at each age-class in each sub fishing area in each month:

(5) $R_{y,f} = \sum_{m,g,a(g),s,c} L_{y,m,f,a,s,c} \cdot wt_{s,c} \cdot p_{y,f,g,s,c}$

The landings $L_{y,m,f,a,s,c}$ (measured in number of fish) are determined by the Landings Per Unit Effort (*LPUE*)[5], the effort (*E*) of the vessel, the stock size *SB*, and the landings distribution fraction (*lf*) on cohort *c*:

(6) $L_{y,m,f,a,s,c} = LPUE_{y,m,f,a,s} \cdot E_{y,m,f,a} \cdot lf_{f,g,s,c}$

The stock dependency enters via *LPUE* that varies over time with stock and catches according to:

(7) $LPUE_{y,m,f,a,s} = LPUE_{y=0,m,f,a,s} \left(\frac{SB_{y,s,g}}{SB_{y=0,s,g}} \right)^{\gamma_{f,s,g}} \quad ; \; \gamma_{f,s,g} \geq 0$

I.e. the landings per unit effort are assumed to vary with the stock abundance (see also Hoff and Frost, 2008, for a further discussion of this relationship).

The price in equation (5) is assumed to vary inversely with the yearly quotas, thus illustrating increasing demand with decreasing availability and vice versa:

(8) $p_{y,f,g,s,c} = p_{y=0,f,g,s,c} \cdot \left(\frac{Q_{y,g,s}}{Q_{y=0,g,s}} \right)^{\alpha_{g,f,c}} \quad ; \; \alpha_{g,f,s} \leq 0$

The total catches $C_{y,f,a,s,c}$ (measured in numbes) are given by landings (equation 6) plus discards (both measured in numbers):

[5] *LPUE* must not be distinguished by the Catch Per Unit Effort (*CPUE*) that may differ from *LPUE* if some discard takes place. What can be deduced from landings data is *LPUE*.

(9) $C_{y,f,a,s,c} = \left(\sum_m L_{y,m,f,a,s,c} \right) + D_{y,f,a,s,c} \quad ; \quad D_{y,f,a,s,c} = df_{f,a,s,c} \cdot C_{y,f,a,s,c}$

The catches are used to project the fish stocks (measured in numbers) from year to year, using the Pope Approximation (Sparre, 1998):

(10) $N_{y,g,s,c} = N_{y-1,g,s,c-1} \cdot \exp(-MORT_{g,s,c-1}) - C_{y-1,g,s,c-1} \cdot \exp(-M_{g,s,c-1}/2) \; ; \; c > 1$

Recruitment to cohort *c=1* can be assessed with various formulas, for example Beverton-Holt or Ricker. For sandeel in the North Sea recruitment is represented by number of juveniles settling on habitat *g* around March in year *y*, which is given by (Christensen et al., 2009):

(11) $R_{y,g} = \sum_{habitat\ g',c>0} (T_{g,g'} \cdot S_{y,g,g'} \cdot Q_c) \cdot N_{y,c,g'}$

Here $T_{g,g'}$ is the larval transport (drift) from habitat *g'* to habitat *g*, $Q_{y,g',c}$ is the fecundity (eggs per sandeel) at age *c*, and $S_{y,g,g'}$ is the larval survival fraction under transport from habitat *g'* to habitat *g*. The latter is density dependent and decreases with increasing density.

The projected stock (equation 10) is finally used to evaluate the stock biomass used to scale the *LPUE* (equation 7):

(12) $SB_{y,s,g} = \sum_c N_{y,s,g,c} \cdot wt_{s,c}$

To illustrate the dynamics of this model the case of the Danish sandeel fishery in the North Sea is considered, with special emphasis on a possible closure of the Dogger Bank for fishing.

Dimensions for the North Sea sandeel fishery model

The Danish fishery for sandeel is covered by large trawlers and industrial trawlers. In the present context vessels for which sandeel constitutes more than 25% of the total landings measured in weight are considered. This leads to including 5 fleet segments in the analysis; (i) Trawlers 18-24 meters, (ii) Industrial trawlers[6] 24-40 meters, (iii) Mixed trawlers 24-40 meters, (iv) Industrial trawlers >40 meters, and (v) Mixed trawlers >40m.

The primary fishing areas covered by these fleet segments are the five sandeel banks in the North Sea that can be identified. These are the Central Bank (C), Dogger Bank (D), North Eastern Bank (NE), South Eastern Bank (SE) and Western Bank (W). Individual sandeel stocks are considered for each of these banks. Furthermore, each bank is divided into ICES-squares as sub-fishing areas, and in total the five banks covers 72 ICES squares, which are thus included in the model. Furthermore the remaining part of the North Sea (4ABCOTH) is included as a primary fishing area for other

[6] A vessel is included in this group, if at least 80% of its revenue originates from catches of industrial species.

industrial and consumption species, as well as other areas (OTH), but these two primary areas are not divided into sub-fishing areas.

The species caught in these fishing areas are sandeel (SAN), other industrial species collected into one group (IND) and consumption species also collected into one group (CON). The model only considers the biological development for sandeel in the present context, as it is the development of this species that may be most affected by the closure of Dogger Bank. The sandeel population is divided into 5 age classes, *c=0,...,4*.

Eight years (2006-2013) are included in the analysis. Seeing that this time span covers almost three lifecycles for sandeel, it is considered sufficient to illustrate the consequences of closed areas on the sandeel stocks and the fishery. Each year is divided into twelve months, which allows a detailed description of the sandeel fishery season lasting from approximately April to July. Modelling the allocation of average effort per vessel to the different fishing areas is thus done on a monthly basis, while the biological part (stock projections) is on a yearly basis.

Data for the North Sea sandeel fishery model

As mentioned above individual sandeel stocks are modelled for each of the five banks. Initial stock data, used to initialise equation 10 is given in Table 1. Data relating to recruitment[7] (equation 11) is rather extensive and would thus take up too much place in the present context. The recruitment data used is presented in Christensen et al. (2008, 2009).

Table 1. Initial stock data for sandeel on the five North Sea Banks (thousand individuals)

Age/Area	W	SE	D	C	NE
0	9.245.833	37.738.255	243.975.914	67.279.321	25.340.174
1	4.946.529	16.080.165	102.883.149	26.536.422	14.268.828
2	708.709	2.303.811	14.740.522	3.801.865	2.044.334
3	190.847	620.377	3.969.669	1.023.881	550.574
4	63.615	206.800	1.322.295	341.168	183.429

Source: ICES Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK, 2007)

Weight at age data, used to calculate spawning biomass (equation 12) is given in table 2.

[7] Data relating to recruitment are transport survival between habitats, predation risk when moving between habitats and carrying capacity of the different habitats.

Table 2. Weight (kg) per individual at age

Age/Area	W	SE	D	C	NE
0	0.0016	0.0016	0.0016	0.0016	0.0016
1	0.0075	0.0037	0.0041	0.0055	0.0056
2	0.0176	0.0128	0.0130	0.0149	0.0147
3	0.0248	0.0194	0.0201	0.0224	0.0223
4	0.0292	0.0262	0.0264	0.0278	0.0277

Source: ICES Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK, 2007)

Landings distribution factors *lf*, used to distribute landings on age classes (equation 6) are given in table 3. These are based on historical catch data for 2005 and 2006 (WGNSSK, 2007). Individual catch data for the five North Sea banks is not available so the catch distribution on each bank is set equal to the overall catch Distribution in the North Sea.

Table 3. Landings distribution on age classes (lf)

Age/Area	W	SE	D	C	NE
0	0	0	0	0	0
1	0.810692	0.810692	0.810692	0.810692	0.810692
2	0.15557	0.15557	0.15557	0.15557	0.15557
3	0.020608	0.020608	0.020608	0.020608	0.020608
4	0.01313	0.01313	0.01313	0.01313	0.01313

Source: ICES Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK, 2007)

As seen in equation (7) the landings per unit effort (*LPUE*) is assumed to vary according to the variation of the sandeel stocks on each bank. It is in the present context assumed that the variation factor γ equals 1 for all banks. Contrary to this, the *LPUE* of other industrial and consumption species is considered independent of the sandeel *LPUE* and constant throughout the analysed period. This is a reasonable assumption, because the sandeel fishery is generally performed separately from the fishery for other species. All LPUE calculations are initialised using historical catch and efforts data for each of the included sub-fishing areas (ICES squares). These data are obtained from the Danish Directorate of Fisheries based on logbook data. As this initial LPUE dataset contains number of sub-fishing areas times number of fleets times number of species >1100 entries it has been decided not to include it in the present context. The data can, however, be obtained via the contact author.

For the considered fleet segments, data related to vessel characteristics, activity and catches are provided by the Danish Directorate for Fisheries. Fish prices have been calculated from historical catch weight and value data for the fleet segments. Prices are assumed constant for the North Sea and surrounding areas, and also assumed constant over the simulation period (thus assuming that α equals zero in equation 8) and equal 2005 prices, which are shown in table 4.

Table 4. Fish prices in 2005 (DKK/kilo)

	Sandeel	Consumption	Other industrial
Trawler 18-24m	0.74	12.53	0.85
Trawler 24-40m industrial	0.70	3.26	0.80
Trawler 24-40m mixed	0.76	2.70	0.84
Trawler above 40m industrial	0.69	2.21	0.81
Trawler above 40m mixed	0.70	2.96	0.82

The assumption of constant prices through time can be discussed seeing that the prices on industrial species have changed considerably during the last couple of years (FOI, 2007). It must, however, be assumed that the price variation follows the variation in quotas/stocks, and as it has been observed that the sandeel stocks are oscillating around constant values in the model runs, the constant price assumption is considered a valid first approximation.

Cost information (used in equations 2-4) for the included vessels is based on data from the Danish fisheries account statistics published by the Institute of Food and Resource Economics. The information is collected for a stratified sample of vessels, corresponding to one-third of the commercial Danish fishing fleet. It is assumed that the costs do not vary during the year. Neither are costs assumed to vary within the analysed period, seeing that it is highly problematic to foresee future development in costs, for instance fuel prices. This is of course a questionable assumption, but it is believed an adequate first approximation. Information from the 2005 account statistics (FOI, 2006) is thus used in the present context. The costs are divided into variable and fixed costs, where the former varies with the activity (effort) or catch revenue, while the latter must be paid irrespective of vessel activity. All costs are calculated as average costs for a vessel within each of the included fleet segments. These are presented in table 5.

Table 5. Cost data for the fleet segments fishing sandeel in the North Sea

	Variable costs (DKK/day at sea)			Variable costs (% of catch revenue)		Fixed costs (DKK/year)		
	Fuel	**Ice/provi-sions**	**Mainte-nance**	**Sales**	**Crew**	**Rent of plant and equip.**	**Insurance**	**Miscella-neous**
Trawler 18-24m	2,588	218	1,372	0.0984	0.2763	5,688	135,077	113,656
Trawler 24-40m industrial	5,576	1,177	2,143	0.1129	0.2609	8,989	250,193	172,282
Trawler 24-40m mixed	4,873	334	2,486	0.1011	0.2930	9,248	224,524	173,664
Trawler above 40m indu.	12,479	3,270	6,312	0.1206	0.2661	27,336	388,689	309,886
Trawler above 40m mixed	7,867	598	4,969	0.0378	0.2215	46,428	324,149	690,229

Source: FOI (2006).

Finally the interest rate used to evaluate the total present value profit (equation 1) is set to 5%.

Technological assumptions and restrictions

BEMCOM is an optimisation model, seeking the most profitable solution. Model runs will therefore often result in a solution, which is not considered consistent with reality. In order to obtain more realistic results, several technical restrictions have therefore been included in the model.

It is assumed that the sandeel fishery, as well as the fishery of other industrial species and consumption species is limited by quotas. Without these restrictions, the model would propose a solution with unrealistic catch levels, which in principle could lead to extinction of species. For sandeel, the quotas are specified on bank level and scaled each year, relatively to the 2005 level, according to the estimated sandeel biomasses, i.e. increasing with increasing biomass and vice versa. For the other industrial and consumption quotas, these are given on fleet level and assumed constant throughout the simulation period at the 2005-level. Thus, no reallocation between fleets of these quotas is assumed to be possible.

The sandeel fishery is conducted with almost no bycatches as mentioned previously. Effort measured as days at sea per vessel is therefore divided in the model between effort used to catch sandeel and effort used to catch other industrial and consumption species. The effort used to catch sandeel is restricted for each fleet on each bank by the maximum number of days at sea observed in 2005. This is done to prevent the fleets from concentrating all effort on a single bank with high sandeel concentration, which would of course be unrealistic in reality.

The total effort, i.e. the sum of the effort used to catch sandeel and the effort used to catch other species, is furthermore bounded from below and above for each fleet in each month by the minimum and maximum effort observed in 2005. The maximum is less than the total number of days in a month, because time is also used for repairs, weekends and vacation. The minimum restriction is included to prevent that the model ends up with some fleet segments not being allocated any effort at all (while still maintaining fixed costs), seeing that BEMCOM is an optimisation model and as such allocates effort to fleet segments with the highest profit.

The number of vessels in each fleet segment is in the model considered constant throughout the simulation period and equal to the number of vessel observed in 2005. These are given in Table 6.

Table 6. Number of vessels in 2005

	Number of vessels
Trawler 18-24m	10
Trawler 24-40m industrial	32
Trawler 24-40m mixed	7
Trawler above 40m industrial	15
Trawler above 40m mixed	13

As mentioned in the introduction, the Danish catches constitute the major part of the total sandeel catches in the North Sea. However, in order to evaluate the stock development of sandeel on the five banks, it is necessary to estimate total catches, which is done by scaling up the Danish sandeel catches by a factor 1/0.83, seeing that the Danish catches have been estimated to constitute 83% of the total catches[8], according to data presented by ICES Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK, 2007).

Scenarios and results

Two scenarios have been analysed to illustrate how BEMCOM may be used to assess the effect of MPAs on the sandeel fishery in the North Sea.

The first scenario is the base scenario, illustrating the status-quo situation where no changes in management are made, i.e. the management in 2005 is assumed to continue. This scheme allows sandeel fishery on all banks in the North Sea. Given the quota and effort restrictions listed above, the model assesses the overall economically optimal distribution of catches between sandeel and other species, and thus the overall economically optimal allocation of effort, disaggregated down to ICES square, for the North Sea and for areas included outside the North Sea. This is done for the analysed period, i.e. 2006-2013.

The second scenario analyses the consequences of closing the sandeel fishery on Dogger Bank throughout the year. As discussed above, Dogger Bank and its boundaries are important spawning grounds for many commercial species and important feeding grounds for several species of seabirds. Dogger Bank has therefore been recommended as one possible focus area in connection with establishment of ecosystem conservation MPAs in the North Sea (WWF 2004, Greenpeace 2004). The effect on the fishery of closing Dogger Bank is moreover interesting as it is the habitat with the highest abundance of sandeel in the North Sea. To model the Dogger Bank closure, the catch per unit effort has therefore been set permanently to zero in all ICES squares comprising Dogger Bank, resulting in the sandeel fishing effort being equal to zero on the bank throughout the analysed period (see also equations 6 and 7). Except for this added restriction of zero effort on

[8] Not to be confused by the fraction the Danish sandeel quota constitutes of the total allowable catch for EU.

Dogger Bank, the remaining quota and effort restrictions used in the base scenario are also used in the scenario where Dogger Bank is closed. The involved fleets can therefore either choose to redistribute their effort for sandeel to the remaining banks in the North Sea of substitute the sandeel effort with effort on other species.

Running these scenarios produce a very detailed amount of output for instance in form of fleet catches and effort distribution down to ICES square level. Given that such a detailed amount of output would be both space and time consuming to present, and furthermore would distort the overall picture resulting from the simulations, it has been decided to present aggregated values of the following indicators:

- Sandeel stock (SB) on the five banks in the North Sea
- Effort used to catch sandeel
- Effort used to catch other species
- Profit

The development on the five banks of the sandeel spawning biomass (SB) during the optimisation period in the base scenario is shown in Figure 1. The figure shows that the sandeel biomass on each bank oscillates around average values that are highest on Dogger Bank (D) and lowest on the South Eastern (SE) Bank, cf. table 7. The oscillations indicate that the sandeel populations on the five banks are not threatened with the fishing pressure applied in the base scenario, i.e. the fishing pressure observed at present in the North Sea, not even when the fleets operate with an effort level that optimises the total profit of all included fleets.

Figure 1. Development in sandeel spawning biomass, base scenario (100,000 tonnes)

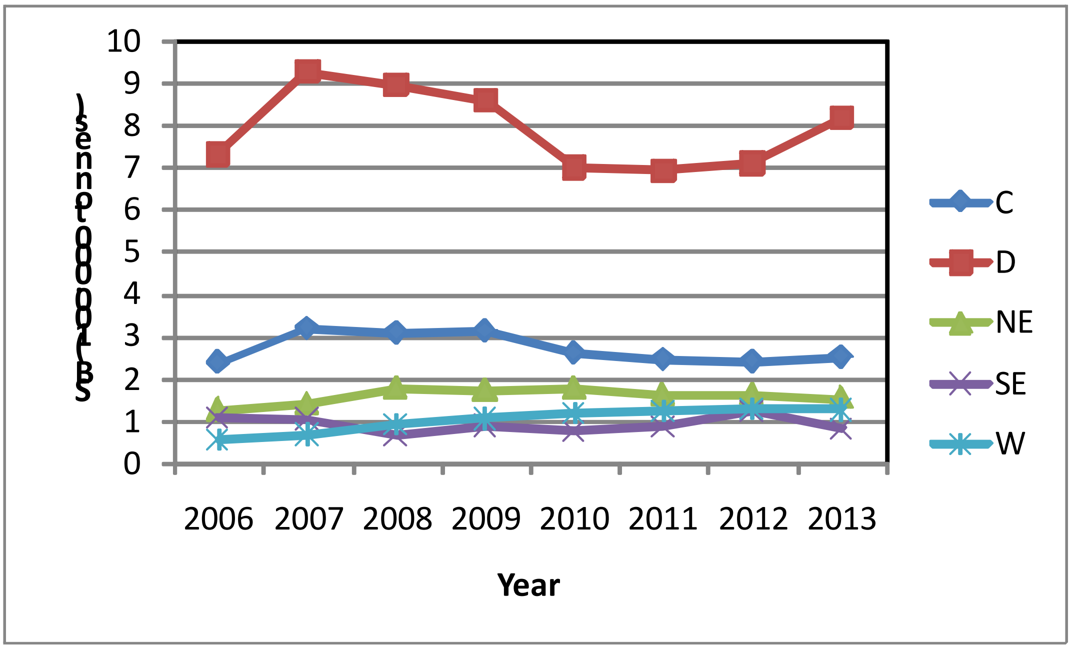


Table 7. Average biomass values on the North Sea banks from 2006-2013, base scenario (100,000 tonnes)

Bank	C	D	NE	SE	W
Average SB	2.72	7.93	1.60	0.92	1.02

Figure 2 shows the spawning biomasses with Dogger Bank closed (scenario 2) relative to the biomasses in the base scenario while table 8 shows the average of these biomasses over the simulation pperiod. It is observed that the sandeel stock on Dogger Bank increases relative to the base scenario as would also be expected. However, the sandeel stocks especially on the South Eastern Bank (SE) and to some lesser degree on the Central Bank (C) decrease during the period, indicating that the fishing pressure is moved towards these areas, when Dogger Bank is closed.

Figure 2. Sandeel spawning biomass (SB_1) when Dogger Bank is closed relative to base scenario (SB_0)

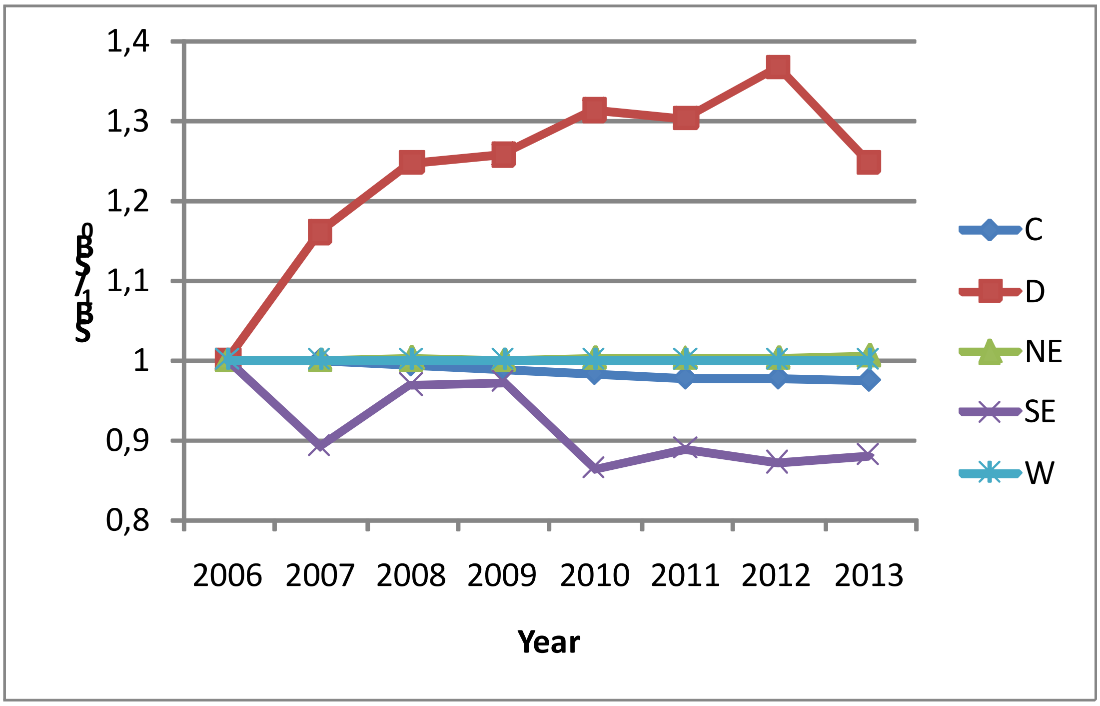


Table 8. Average biomass values on each bank from 2006-2013, Dogger Bank closed (100,000 tonnes)

Bank	C	D	NE	SE	W
Average SB	2.683	9.785375	1.6075	0.840125	1.02925

The development in total number of days at sea used to catch sandeel by the included fleets on the five banks during the analysed period is shown in Figure 3 for each of the two scenarios. The figure adds the number of seadays used on each bank for each of the two scenarios such that the upper bar/line for each scenario is the total effort used. Figure 4 shows the total number of seadays used in the simulation period (added over all years and fleet segments) for each of the two scenarios. Finally Table 9 shows the total number of seadays used to catch other industrial and consumption species in the North Sea during the analysed period.

Figure 3. Comparison of number of sea days between base scenario and Dogger Bank closure

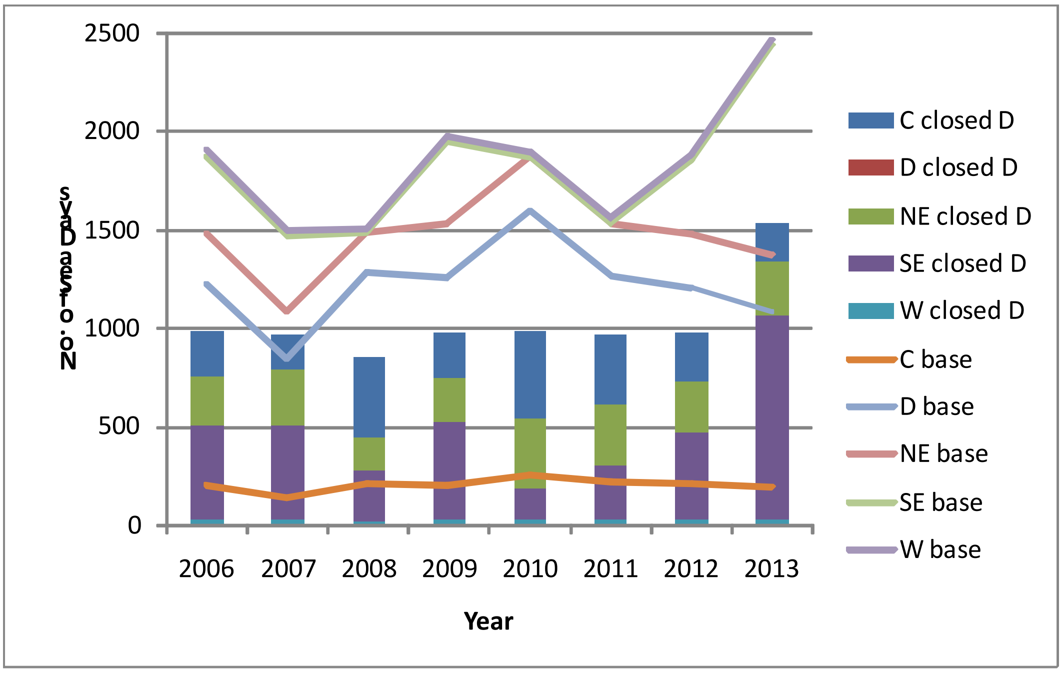
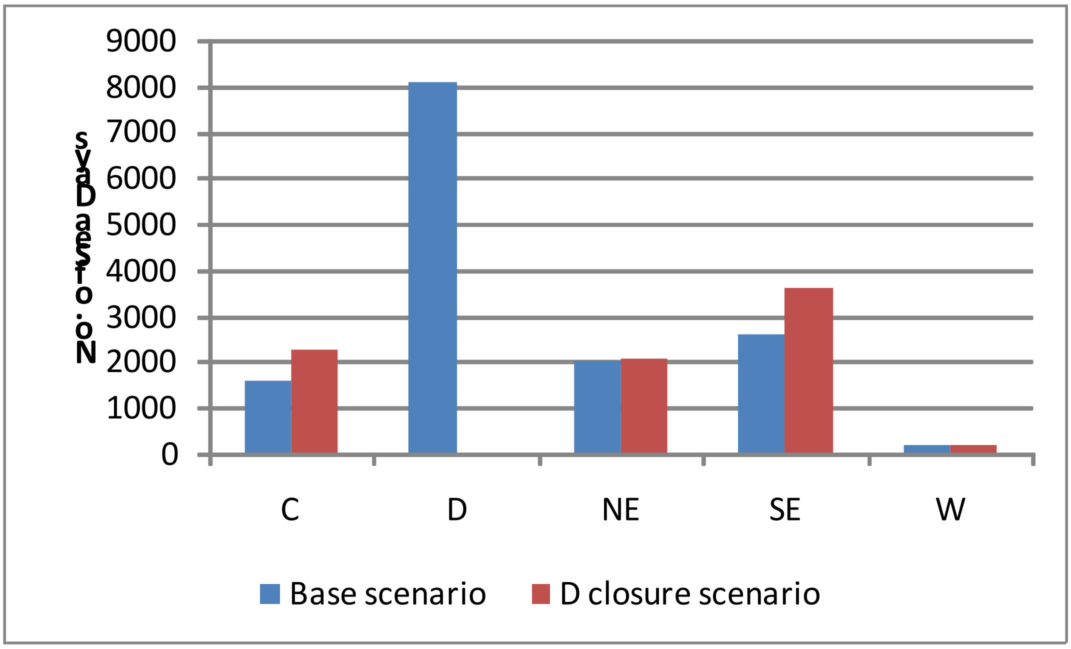


Figure 4. Comparison of total number of days at sea from 2006 to 2013 between base scenario and Dogger Bank closure scenario



Figures 3 firstly shows that the overall economically optimal effort for sandeel in the North Sea lies between 1.500 and 2.500 sea days per year for the Danish fleet in the base scenario. Contrary to this the optimal number of seadays used to catch sandeel decreases to below 1.000 except in the last year in the scenario where Dogger Bank is closed. Comparing this with figure 4, shows that the reason for the sharp decline in effort shown in figure 3 is that the number of seadays used on Dogger Bank in the base scenario is only to a small degree reallocated to the other banks when Dogger Bank is closed. A slight increase in effort is observed on the South Eastern Bank (SE) and Central Bank (C), corresponding with the decreasing stocks on these banks, cf. Figure 2. Finally a general jump in effort is noticed in the end year 2013 in both scenarios. This is caused by the simulation drawing to an end, with no restrictions in the ensuing years, causing the model to simulate a rather high fishing pressure in the last year. This is of course a problem with the model that should be considered in future work, but the result does not influence on the conclusions drawn in the present context.

Finally table 9 shows that the effort not used to catch sandeel in the closure scenario is not reallocated to catch other species either, as the number of seadays used to catch other species are more or less the same for the two scenarios. The reason for this is believed to be that it is not profitable to switch the effort to fishing industrial and other species, even though these give higher prices, probably because of the relatively low Landings Per Unit Effort values for these species. Altogether, it can therefore be concluded that the effort used by the Danish fleet in the North Sea and surrounding areas is to a high degree reduced as a result of the closure of Dogger Bank, and that effort re-allocation to other banks and areas is only observed to a minor degree.

Table 9. Total number of days at sea used to catch other industrial and consumption species, base scenario

	Area	2006	2007	2008	2009	2010	2011	2012	2013
Base scenario	North Sea	6,969	6,969	6,969	69,69	6,968	6,968	6,969	6,968
	Other	878	878	878	878	878	878	878	878
Dogger Bank Closed	North Sea	6,969	6,970	6,969	6,969	6,970	6,973	6,969	6,968
	Other	878	885	1006	878	880	885	878	878

The optimal profit (measured in present values) is defined as catch revenue minus variable and fixed costs. Summarising over the analysed period and all fleet segments, the total profit is 1,055 million DKK in the base scenario and 835 million DKK when Dogger Bank is closed, i.e. a reduction of 21%. The development in total yearly net- and present value profit for the Danish fleet in the base scenario is shown in Figure 5. The net profit oscillates around a yearly average value of 155 million DKK during the analysed period. Comparison with Figure 1 shows that the oscillation pattern is much the same as the pattern for the sandeel stock on Dogger Bank (D) in the base scenario, indicating that the sandeel catch on this bank as expected has a high influence on the total catch value. The present value profit on the other hand decreases with around 25% during the period, which is a natural consequence of keeping all prices (species and costs) constant during the simulation period.

Figure 6 shows the total yearly fleet net profit when Dogger Bank is closed relative to the yearly net profit in the base scenario. The figure confirms the overall decrease in profit, seeing that the yearly profits in the closure scenario are all less than the profits in the base scenario. The situation is worst in 2007-2008, followed by an increase in relative profit towards the end of the period.

Figure 5. Total yearly profits for the Danish fleet, base scenario

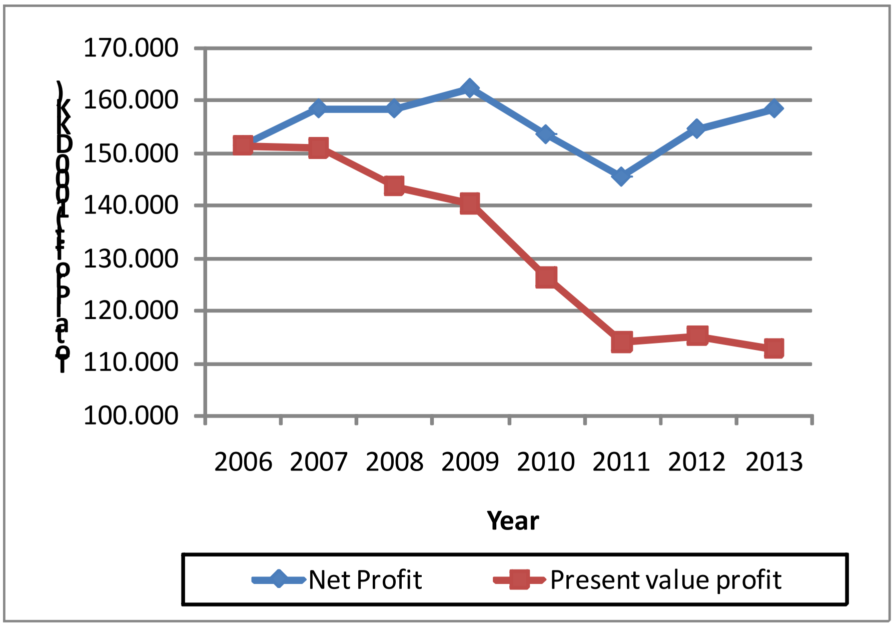
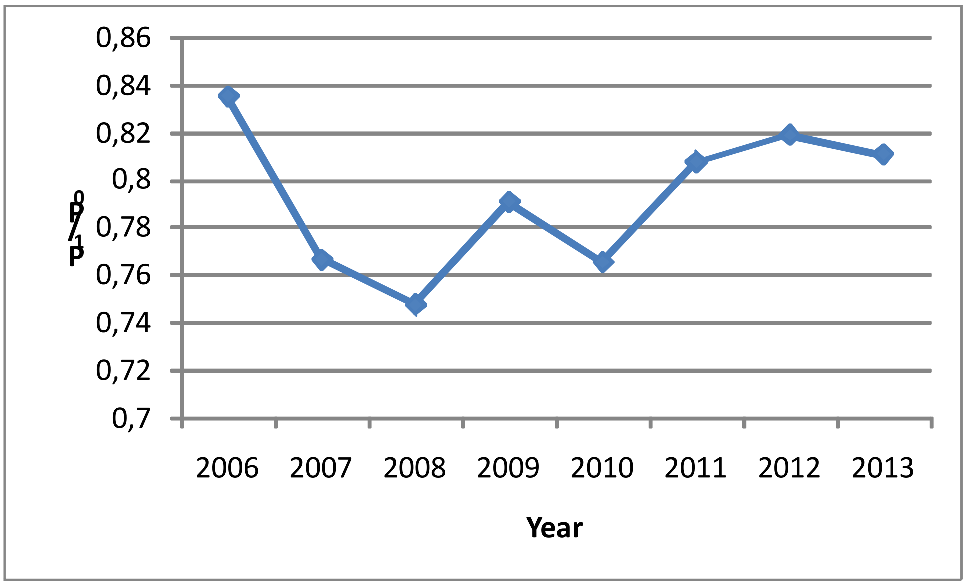
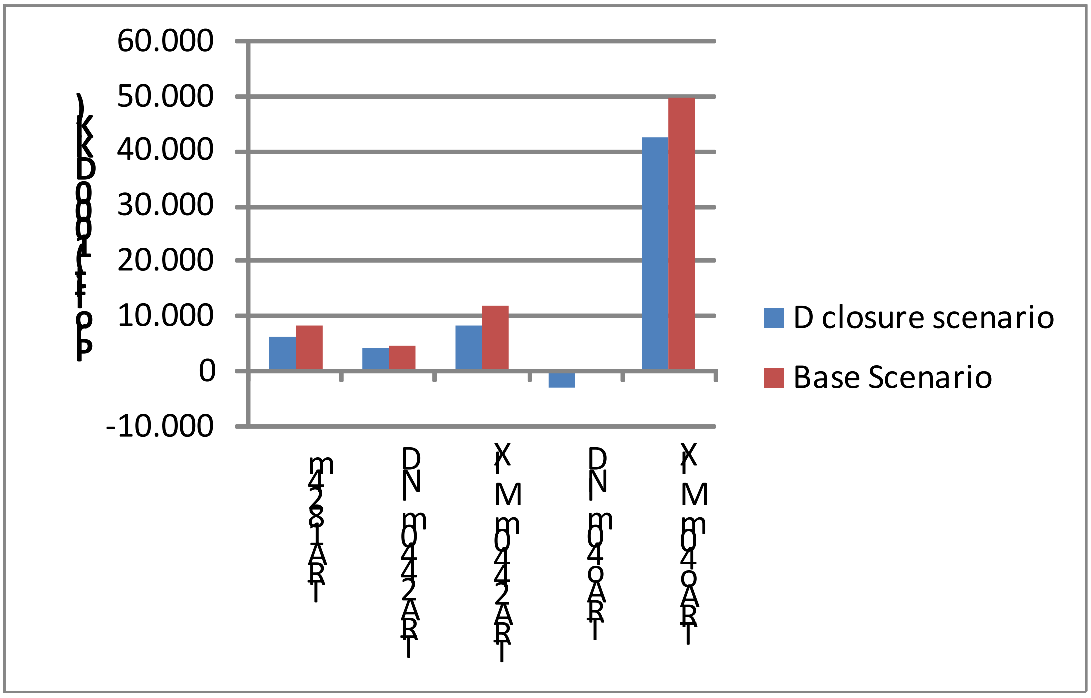


Figure 6. Yearly net profit P_1 with Dogger Bank closure relative to base scenario P_0.



The total present value profit per vessel for each fleet segment is shown in Figure 7 for the two scenarios. All fleet segments have lower profit when Dogger Bank is closed, corresponding with the picture for total profit, and the general decrease in effort discussed above.

Figure 7. Present value profits per vessel with closure of Dogger Bank and base scenario



Summary and Conclusion

Sandeel is one of the most economically important species for the Danish industrial fishery in the North Sea. In the sandeel season from March/April to July, the Danish industrial fleet target sandeel specifically and seldom take this species with bycatch of other species. Given the present discussion of introduction of Marine Protected Areas (MPAs) in the North Sea, it is important to assess possible effects of this on the Danish industrial fleet. The BEMCOM optimisation model has been used for this purpose by comparing status quo management with a case where Dogger Bank is closed. Dogger Bank is the largest habitat for sandeel in the North Sea with respect to sandeel abundance and thus fishing opportunities.

BEMCOM has been calibrated for the North Sea case study using data collected from ICES and DTU-AQUA, The Danish Directorate of Fisheries and the Institute of Food and Resource Economics. Only Danish vessels are included in the analyses, but these vessels also take the major part of sandeel catches in the North Sea, and it is therefore considered to be a minor problem. The Danish catches have, however, been scaled up to the full sandeel catches in order to be able to project the sandeel stocks through the simulation period. Catches of other species have also been included in the model to be able to evaluate total profits of the fleets, but no biological modelling has been made with respect to these.

As said above two scenarios have been considered over an eight year period; a base scenario simulating the status-quo situation where sandeel fishery takes place on all five habitats/banks, and a scenario where the Dogger Bank is closed for sandeel fishery in each of the eight years. In both scenarios, BEMCOM optimises the net present value of profits defined as discounted catch revenue minus variable and fixed costs for the total eight year period. A range of restrictions on catches (quotas) and effort are included in the optimisation to keep the results plausible. However, it is straightforward to relax these assumptions or include other ones, if this is considered relevant.

The model runs show that the net present profits will be 1,055 million DKK in the base scenario, compared to 835 million DKK with closure of Dogger Bank, i.e. corresponding to a reduction of 21%. This is consistent with the observation that the fleets to a high degree reduce their total fishing effort, and only to a minor effect substitute the effort to other fishing areas or species, when Dogger Bank is closed. In some years, it has thus been observed that the effort used to catch sandeel has been reduced by almost 50%, while the effort used to catch other species has not increased. Seeing that Dogger Bank is clearly the most attractive sandeel area in the North Sea with the highest abundance of sandeel, this result indicates that the sandeel fishery on the remaining banks is not as profitable for the Danish industrial fleet.

The closure of Dogger Bank is also reflected in the stock developments on the five habitats. On Dogger Bank the sandeel stock increases with more than 30% in some simulation years when this area is closed, while the stock on the South Eastern Bank and the Central Bank decreases, indicating that the small reallocation of effort is especially focused on these two areas.

Based on these results, it can be concluded that closure of Dogger Bank may improve the stock on this habitat, but will be countered by decrease in stocks on other habitats, and will furthermore be economically bad for the fishermen. The further environmental effects (other stocks breeding on Dogger Bank, sea birds etc.) have not been assessed in the present context, but one effect may be that an improved sandeel stock on Dogger Bank could improve the living conditions on species predating on sandeel. This will, however, also depend on the overall nature of the ecosystem. Furthermore it must be kept in mind that all conclusions drawn above depends on the assumptions and restrictions included in the model.

Finally the results presented in this paper illustrate that high flexibility of the BEMCOM model, that has in the present context been able (i) to model the complex recruitment structure of sandeel, (ii) to model sandeel stock developments on five different habitats (banks) in the North Sea, and (iiii) to model effort reallocation of five different fleets over 74 sub-fishing areas over a period of 8 years subdivided into months.

References

Christensen, A., Jensen, H., Mosegaard, H., St. John, M., and Schrum, C. (2008). Sandeel (*Ammodytes marinus*) larval transport patterns in the North Sea from an individual-based hydrodynamic egg and larval model. Canadian Journal of Fisheries and Aquatic Science, 65: 1498–1511.

Christensen A., Mosegaard H., and Jensen H. (2009) *Spatially resolved fish population analysis for designing of MPAs: influence on inside neighbouring habitats*. ICES Jounal of Marine Science, 66(1), pp 56-63.

Engelhard G. H., van der Kooij J., Bell E. E., Pinnegar J. K., Blanchard J. L., Mackinson S., Righton D. A. (2008). *Fishing mortality versus natural predation on diurnally migration sandeels Ammodytes marinus*. Marine Ecology Progress Series, 369, pp 213-227.

FOI (2007). *Economic Situation of the Danish Fishery 2007*. Institute of Food and Resource Economics, University of Copenhagen.

FOI (2006). *Account Statistics for Fishery 2005.* Institute of Food and Resource Economics, University of Copenhagen.

Greenpeace (2004). *Rescuing the North and Baltic Seas: Marine Reserves – a key tool.* Greenpeace, july 2004.

Hoff A., Frost H. (2008). *Modelling combined harvest and effort regulations: the case of the Dutch beam trawl fishery for plaice and sole in the North Sea*. ICES Journal of Marine Science, 65, pp 822-831.

Sparre, P. (1998). *Introduction to Tropical Fish Stock Assessment – Part 1: Manual*. FAO Fisheries Technical Paper 306/1.

WGNSSK (2007). *Report on the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak – Combined Spring and Autumn (WGNSSK)*.

WWF (2004). *Managing Across Boundaries. The Dogger Bank – a future international marine protected area.* Sebastian Unger, WWF Germany, Frankfurt am Main.