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Hoff, A.; Andersen, J.L.; Christensen, Asbjørn; Mosegaard, Henrik

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**A. Hoff, J. L. Andersen, A. Christensen &
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Modelling the economic consequences of Marine Protected Areas using the BEMCOM model

A. Hoff · J. L. Andersen · A. Christensen ·
H. Mosegaard

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Abstract This paper introduces and describes in detail the bioeconomic optimization model BEMCOM (BioEconomic Model to evaluate the COsequences of Marine protected areas) that has been developed to assess the economic effects of introducing Marine Protected Areas (MPA) for fisheries. BEMCOM answers the question ‘what’s best?’, i.e. finds the overall optimal effort allocation, from an economic point of view, between multiple harvesting fleets fishing under a subset of restrictions on catches and effort levels. The BEMCOM model is described and applied to the case of the Danish sandeel fishery in the North Sea. It has several times been suggested to close parts of the sandeel fishery in the North Sea out of concern for other species feeding on sandeel and/or spawning in the sandeel habitats. The economic effects of such closures have been assessed using BEMCOM. The results indicate that the model yields reliable estimates of the effect of MPAs, and can thus be a valuable tool when deciding where to locate MPA.

Keywords Marine Protected Areas · Economic consequences · Optimisation model · Effort allocation · Sandeel fishery

JEL Classification Q22 · C51

A. Hoff (✉) · J. L. Andersen
Institute of Food and Resource Economics, University of Copenhagen, Frederiksberg C, Denmark
e-mail: ah@foi.ku.dk

A. Christensen · H. Mosegaard
National Institute of Aquatic Resources, Technical University of Denmark, Charlottenlund, Denmark

1 Introduction

Marine Protected Areas (MPAs) have become a popular instrument for the management of marine resources (Gerber et al. 2003). 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. MPAs include marine reserves (no-take zone) and areas with partial protection. This paper focuses on the latter situations where MPAs put some restrictions on fishing in the protected areas. A very noticeable example of MPAs is the Natura 2000 network,¹ which was initiated as part of a global effort by the EU to significantly reduce the current rate of biodiversity loss by 2010. However, to date there have been relatively few Natura 2000 sites finally appointed for the offshore marine environment and this represents the most significant gap in the Natura network. Even though the Natura 2000 site designation process should exclusively be based on scientific criteria, its member states are encouraged to ensure good coordination with fishery, authorities and other stakeholders. However, this designation process is slowed firstly by significant lack of scientific knowledge on the distribution/abundance of species in relation to habitat types, and secondly by absence of spatial management instruments to assess biological efficiency and socio-economic effects of alternative MPA scenarios on affected fishing fleets. The techniques for designing MPAs are still under development and therefore the implementation of specific MPAs often rests on schematic principles (Holland 2002; Jones et al. 2007) while, at the end of the day, site selections are often based on expert opinions (Johnson et al. 2008). However, several authors, among others Himes (2007) have discussed the importance of stakeholder involvement in construction and management of MPAs. Whether the main management objective of the MPA is biological, economic, social or political, or a combination of these, it is clear that different groups of stakeholders will be influenced differently by the MPA, and thus differ in their opinions of the utility of the MPA. Biologists may e.g. support MPAs installed to conserve one or more species, while fishermen that worked in this area may oppose the construction of such MPAs as they lose earnings, and may thus try to find ways of non-compliance with the management imposed by the MPA. Thus the successful MPAs should ideally not only be based on expert opinion, but also as far as possible on stakeholder involvement. As such generally spatial explicit marine management poses new challenges on data, modelling and assessment.

This paper introduces and describes in detail the bioeconomic optimization model BEMCOM (BioEconomic Model to evaluate the CONsequences of Marine protected areas) that can assess the economic effects for fisheries of introducing MPAs.

This work was pursued in the EU FP-6 project PROTECT,² of which the primary aim was to provide assessment tools for the biological as well as socio-economic effects of MPAs. BEMCOM was thus developed to assess such economic effects for the fisheries, and thus provides a valuable tool for decision makers, if they intend to use MPAs. BEMCOM is a flexible modelling framework programmed in a generic

¹ <http://ec.europa.eu/environment/nature/natura2000>.

² MPA as a tool for ecosystem conservation and fisheries management, EU-FP6 Contract no. 513670.

way to facilitate its use when investigating different MPA management strategies in various case studies. The flexibility is feasible in the time horizon and number of fishing areas, fleets and species. Fishing area may, for example, be disaggregated down to ICES square, which is often necessary in order to address the questions related to the economic consequences for fishing fleets of MPAs (Holland 2002). BEMCOM answers from an economic point of view the question ‘what’s best?’, i.e. it finds the optimal effort allocation between several harvesting fleets, fishing under a subset of restrictions on catches and effort levels, resulting in the highest total profit among the fleets conducting the fishery. This may not necessarily lead to optimisation of individual fleet or vessel profit, but will give a picture of the highest possible short run gains to the fishing industry from society’s point of view. In connection with the PROTECT project, BEMCOM has been applied to two case studies (PROTECT 2009): the cod fishery in the Baltic Sea and the sandeel fishery in the North Sea, of which the latter is used to illustrate the features of the BEMCOM model in the present context.

Through time the North Sea sandeel fishery has primarily been conducted by Danish fishermen. In 2005, Denmark had 94% of the EU sandeel quota and caught the major part of total EU landings.³ The sandeel fishery is a single species fishery with low bycatches of other species, of which some are taken under by-catch ceilings and some subtracted from their respective quotas, and it is conducted using light, large spanning trawling gears with a small meshed codends (below 16 mm). The highest proportion of North Sea sandeel catches are taken on the Dogger Bank and its boundaries. The Dogger Bank is also believed to be an important spawning ground for many commercial species, e.g. cod, haddock and herring, important feeding ground for several species of seabirds (e.g. Kittiwake) and for the marine mammals harbour porpoise, grey seal and harbour seal. Low sandeel abundances, caused by intensive fishing, may affect the stocks of these species and animals, and may therefore indirectly have further consequences for other fishing fleets. Dogger Bank has therefore been recommended as one possible focus area in connection with the establishment of ecosystem conservation MPAs in the North Sea (WWF 2004) and is further considered to be appointed as a Natura 2000 site by several countries having part of Dogger Bank within their economical zone (see e.g. JNCC 2010).

To illustrate the potential of BEMCOM, the model has thus been used to assess how a closure of Dogger Bank may affect the economic performance of the most important Danish fleets in the sandeel fishery. This is analysed by comparing the present regulation with a situation where the Dogger Bank is closed for sandeel fishery. The indirect economic effects for other fleets, not targeting sandeel, are not accounted for in the present context, as the case study is primarily used to illustrate how BEMCOM works.

The paper first gives a short literature review of other bioeconomic models applied to assess the effects of MPA. Next, a theoretical description of the BEMCOM model is given, including an outline of the dimensions used in the model for the North Sea sandeel fishery. The data used in the model are then described, and subsequently the

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

restrictions used when modelling the fishery. Finally, the results of the model calculations are presented and discussed.

2 Literature review

The plausible effects of MPAs have for many years been analysed from a theoretical as well as a practical point of view. However, whereas a significant number of empirical evaluations of existing MPAs have been made (NRC 2001), the number of spatial management assessment models, including economy as well as biology, are still relatively rare. In 2000, an International Conference of the Economics of Marine Protected Areas was held in Vancouver, Canada, and a number of important contributions were afterwards published in a special issue of *Natural Resource Modelling* (*Natural Resource Modelling*, 2002, Vol 15, issue 3 and 4, introduced by the editors Sumaila and Charles 2002). The special issue gave a broad overview over bioeconomic models for MPA management and assessment existing around the millennium change, many of which are still relevant and inspiring. At that time Holland (2002) also provided a broad review of the literature regarding empirical and theoretical assessment of MPA management.

Today existing bioeconomic models for MPA assessment varies from a logistic model used to investigate the effect of using a MPA to protect one of two sub-populations (Hannesson 2002), to a spatial bioeconometric model used to assess the effects of MPAs on limited entry fisheries (Sanchirico and Wilen 2002). Anderson (2002) compares TAC policies with MPAs applying a model using a Schaefer Growth function. In these studies, the models either simulate the development of the system through time or find equilibrium stocks under given conditions. Smith and Wilen (2003) on the other hand use a spatial choice behavioural model to determine degree of participation and choice of location in the sea urchin fishery in northern California, while Sumaila (2002) applies a computational two-agent bioeconomic model to assess optimal sizes of MPAs in the North East Atlantic cod fishery from an economic perspective. Beattie et al. (2002) likewise uses the model 'Ecopath with Ecosim (EwE)' (Christensen and Walters 2004) to determine optimal placement and size of MPAs in the North Sea through economic optimisation. EwE is also applied to investigate the bioeconomic effects of introducing a three-zone MPA near the Medes Islands by Merino et al. (2009). Herrera (2007) applies a dynamic programming bioeconomic model to evaluate the tradeoffs between temporary or permanent spatial closures as opposed to quota management in certain areas, and show that closures may be preferable to quotas under certain conditions.

As discussed above BEMCOM investigates optimal effort allocation in time and space given introduction of MPAs, i.e. endogenous effort allocation given optimal earnings in the fishery. Smith and Wilen (2003) show that when the fishing effort is assumed endogenous, i.e. responsive to costs and payoffs of fishing in different areas, proposed marine reserves produces less fisheries production than when fishing effort is assumed exogenously uniform and unresponsive to earnings over the entire area. Further, by introducing endogenous fishing port choice in the long run, depending on expected gains and costs of switching port, Smith and Wilen (2004) show that the

more flexible effort choice inherent in possible port switching mitigates some of the costs of closing fishing areas, but also puts more pressure on all open areas. Both of these results indicate that it is important to understand the endogenous behaviour of fishermen and implement this realistically in models assessing MPAs, which is also the aim of BEMCOM.

Finally it should be noticed that all the above mentioned methods, including BEMCOM, discuss the possible effects of introducing MPAs in the future. It must be mentioned that also retrospective analysis of MPAs is an important field, contributing to the overall understanding of the effects of introducing MPAs. [Smith et al. \(2006\)](#) discuss various approaches to retrospective analyses of already introduced MPAs, and introduce a model based on program evaluation techniques, that control for selection effects (effort being moved around because of the introduced MPA), and allows for heterogeneity in fishing production techniques, and in effort distribution in time and space.

3 The BEMCOM model

This section presents the theoretical basis of BEMCOM, while the next section presents how the model is quantified in a specific case study.

BEMCOM covers seven dimensions in order to reflect a fishery in a realistic way. These dimensions are:

year	$y = 1, \dots, Y$
month/quarter	$m = 1, \dots, M$
vessel/fleet	$f = 1, \dots, F$
primary fishing ground (area)	$g = 1, \dots, G$
sub-fishing area (squares)	$a = 1, \dots, A$
species	$s = 1, \dots, S$
cohort	$c = 1, \dots, C$

Each dimension can have several alternatives depending on the analysed case study. Notice the distinction between primary fishing grounds and sub-fishing areas. The primary fishing grounds are e.g. the North Sea, Skagerrak etc., while sub-fishing areas are sub-divisions of the primary fishing grounds, i.e. ICES squares. This division is necessary in order to account for the detailed activity of a vessel, but at the same time maintaining focus on the overall fishing grounds considered in a case study. Furthermore, some information may only be available for the overall fishing ground (for example stock information), while other information is often available at a finer scale (for example catch and landings data).

In order to realistically simulate a given fishery, BEMCOM includes biological, economic and production variables that together constitute a detailed description of the analysed case study in question (in the present case the sandeel fishery in the North

sea). The economic variables are all yearly figures measured at the average vessel⁴ level, and include:

profit	$P_{y,f}$
revenue	$R_{y,f}$
total cost	$TOTC_{y,f}$
variable cost	$VC_{y,f}$
fuel and lubricants cost	$FUELC_{y,f}$
provision cost	$PC_{y,f}$
ice cost	$IC_{y,f}$
sales cost	$SC_{y,f}$
crew cost	$CC_{y,f}$
fixed cost	$FC_{y,f}$
maintenance cost	$MAIN_{y,f}$
insurance cost	$INSUR_{y,f}$
other fixed cost	$OTH_{y,f}$
fish price	$p_{y,f,g,s,c}$

The biological variables at the stock level are:

age disaggregated stock numbers	$N_{c>1}$
number of recruits	$N_{c=1}$
landings distribution on cohorts (age) classes	$lf_{f,g,s,c}$
discard fraction of catches	$df_{f,a,s,c}$

where $N_{c>1}$ and $N_{c=1}$ are normally at the yearly level, while the landings distribution and discard fractions are typically constant and thus independent of time.

Finally, the production variables, also at the year and (average) vessel level, are:

catches	$C_{y,f,a,s,c}$
effort	$E_{y,m,f,a}$
fleet size (number of vessels)	$NV_{y,f}$
landings	$L_{y,m,f,a,s,c}$
landings weight	$wt_{s,c}$
discards	$D_{y,f,a,s,c}$

All these variables are determined within the model framework, when the objective function is optimised. The objective function is the present value of total profit ($PVTP$) aggregated over all fleets and over all time periods considered. $PVTP$ is optimised by allocating fishing effort $E_{y,m,f,a}$ over fleets and sub-fishing areas in each time period (month/quarter/year) considered:

⁴ By 'average vessel' is meant that all vessel information is based on average values for the specific fleet segment.

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

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

$$P_{y,f} = R_{y,f} - TOTC_{y,f} \tag{2}$$

where $R_{y,f}$ and $TOTC_{y,f}$ are the total revenue and total cost in year y for an average vessel in fleet f .

The total cost is given by the sum of variable (VC) and fixed (FC) costs:

$$TOTC_{y,f} = VC_{y,f} + FC_{y,f} \tag{3}$$

The variable costs are given by the sum of fuel costs ($FUELC$), provision costs (PC), ice costs (IC), sales costs (SC) and crew costs (CC):

$$VC_{y,f} = FUELC_{y,f} + PC_{y,f} + IC_{y,f} + SC_{y,f} + CC_{y,f} \tag{4}$$

The total 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 ($p_{y,f,g,s,c}$) summarized over months m , fishing grounds a , species s , and age-classes/cohorts c :

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

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 spawning stock biomass (SB), and the landings distribution fraction (lf) on cohort c :

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

$LPUE$ is stock dependent, and thus varies over time with the stock according to the following relationship:

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

This relationship is deduced by assuming that landings are given by the traditional Cobb–Douglas production function, i.e. that landings are given by $L_{y,m,f,a,s,c} = \alpha_{m,f,a,s,c} \cdot E_{y,m,f,a}^{\beta_{m,f,a,s,c}} \cdot SB_{y,s,g}^{\eta_{m,f,a,s,c}}$. By dividing L by E and taking the fraction between the equations for the years y and 0, Eq. 7 can be derived (Hoff and Frost 2008).

⁵ $LPUE$ must be distinguished by the Catch Per Unit Effort ($CPUE$) that may differ from $LPUE$ if discarding takes place. What can be deduced from landings data is $LPUE$.

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

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

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

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

It is thus assumed that discards are a constant fraction of the catches for each fleet, area, species and cohort. The discarded fraction can be estimated from historical catch and discard data. Recorded discard data is often based on a combination of log book registrations by fishers and sample monitoring of actual discards.

To project the development in fish stocks (measured in numbers) from year to year, the Pope Approximation (Sparre 1998) is used:

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

where $MORT_{s,g,c}$ is the natural (non-fishing) mortality for cohort c of species s at primary fishing ground g , and C is the catch. Since estimation of interannual variability in natural mortality is associated with high uncertainty, a time-averaged value is used. Recruitment to cohort $c = 1$ can be assessed with various formulas, for example Beverton–Holt or Ricker. The projected stock (Eq. 10) is finally used to evaluate the stock biomass used to scale the $LPUE$ (Eq. 7):

$$SB_{y,s,g} = \sum_c N_{y,s,g,c} \cdot wt_{s,c} \quad (11)$$

The theoretical framework presented above has in the present context been implemented in the software optimisation program GAMS. Below the model is applied to the North Sea sandeel fishery, to illustrate what results can be produced by using the model as an assessment tool.

4 Dimensions for the North Sea sandeel fishery case

The Danish fishery for sandeel is primarily conducted by trawlers above 18 m. In the present context, vessels for which sandeel constitutes more than 25% of their total landings measured in weight are considered. This leads to the inclusion of vessels

from five fleets in the analysis; (i) Trawlers 18–24 m, (ii) Industrial trawlers⁶ 24–40 m, (iii) Mixed trawlers 24–40 m, (iv) Industrial trawlers >40 m, and (v) Mixed trawlers >40 m.

The primary fishing grounds covered by these fleets are five sandeel habitat regions in the North Sea; the Central Banks (C), Dogger Bank (D), North Eastern Banks (NE), South Eastern Banks (SE) and Western Banks (W). Individual sandeel stocks are considered for each of these regions, and each region is divided into ICES squares as sub-fishing areas; in total the five regions covers 72 sub-fishing areas in form of ICES squares. Furthermore, the remaining part of the North Sea (4ABCOTH) as well as other areas (OTH) is included as primary fishing grounds where other industrial and consumption species are caught by the sandeel fleets, but these are not divided into sub-fishing areas.

The species caught on these primary fishing grounds are sandeel (SAN), other industrial species besides sandeel (IND) and different consumption species (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 five age classes, $c = 0, \dots, 4$.

The recruitment of sandeel is represented by number of juveniles settling on primary fishing ground g around March in year y , which is given by (Christensen et al. 2009):

$$R_{y,g} = \sum_{g',c} (T_{g,g'} \cdot S_{y,g,g'} \cdot Q_{c,g'}) \cdot N_{y,c,g'} \quad (12)$$

Here $T_{g,g'}$ is the larval transport matrix from primary fishing ground g' to primary fishing ground g , which includes all relevant physical processes (hydrography, swimming and timing) contributing to larval dispersal (Christensen et al. 2009), $Q_{g',c}$ is the fecundity (eggs per sandeel) at age c at primary fishing ground g' , and $S_{y,g,g'}$ is the larval survival fraction under transport from primary fishing ground g' to habitat g for year y . For the sandeel stocks, recruitment time series unambiguously show that S is strongly dependent on stock density (Arnott and Ruxton 2002), reflecting ecosystem resource competition and cannibalism, so that S decreases with increasing stock density. This effect is included in the present model.

The underlying biological model for the sandeel stock is formulated as a single species model, with average predation pressure levels (from other species) estimated from the operational multispecies stock assessment model SMS (Lewy and Vinther 2004) routinely applied in ICES work. Surely other species preying on sandeel stocks (like cod, sea birds and marine mammals) will respond a change in the abundance of sandeel, which could in principle be addressed by a multispecies simulation model. However there are very large uncertainties and disadvantages associated with applying current multispecies simulation models (which is different from a data driven multispecies stock assessment model) in this context: (i) species interaction parameters are rather uncertain, (ii) the spatial distribution of predating species are rather

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

uncertain, and (iii) multispecies simulation models display natural fluctuations in stocks with long time scales (unless artificially damped). The latter means that the timing of establishment of the MPA also becomes a variable due to the timing with stock fluctuation cycles. Therefore, in short, it is expected that model uncertainties in relation to multispecies effects will overshadow the uncertainties in the intrinsic response of the sandeel+fishery sub system, which is the focus of the present paper, and consequently it is out of scope of this contribution to disentangle multispecies effects in relation to potential MPA impact on sandeel fishery, but this is surely an interesting topic for future research.

The analysis is run over eight years (2006–2013). 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 April to August. 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.

5 The North Sea sandeel fishery model

Stock numbers for each of the five sandeel stocks used to initialise the model in 2006, together with weight at age data, has been taken from [WGNSSK \(2007\)](#). Larval transport matrix $T_{g,g'}$ together with data related to recruitment (Eq. 12) have been taken from [Christensen et al. \(2008, 2009\)](#).

Landings distribution factors lf , used to distribute landings on age classes (Eq. 6) have been evaluated based on historical landings data from 2005 and 2006 ([WGNSSK 2007](#)). Individual catch at age data for the five North Sea banks is not available, so the catch at age distribution on each bank is set equal to the overall catch at age distribution in the North Sea.

In the present context, it is assumed that the Landing per Unit Effort (*LPUE*) is equal to the Catch per Unit Effort (*CPUE*), given that the North Sea sandeel fishery targets all active age classes and does not discard catches ($df = 0$ in Eq. 9). As seen in Eq. 7, the *LPUE* is assumed to change in accordance with 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, implying a proportional relationship. Contrary to this, the *LPUE* of other industrial and consumption species are considered independent of the sandeel *LPUE* and thus assumed constant over time. This is a reasonable assumption, because the sandeel is caught in a closely monitored single-species fishery with only very limited catch of other species. All initial *LPUE* values are estimated by taking the fraction between catch and effort data from 2005 for each of the included sub-fishing areas (ICES squares). These data are obtained from the Danish Directorate of Fisheries based on logbook data.

For the included fleets, data related to vessel characteristics, activity and catches are obtained from the vessel and sales slip register hosted by the Danish Directorate of Fisheries. Fish prices have been calculated from historical catch weight and value data for the fleets. Prices are assumed constant for the North Sea and surrounding areas,

Table 1 Fish prices in 2005 (DKK/kilo)

	Sandeel	CON	IND
TR. 18–24 m	0.74	12.53	0.85
IND.TR. 24–40 m	0.70	3.26	0.80
MIX.TR. 24–40 m	0.76	2.70	0.84
IND.TR. >40 m	0.69	2.21	0.81
MIX.TR. >40 m	0.70	2.96	0.82

CON consumption species, IND other industrial species, TR. trawl, IND.TR. industrial trawl, MIX.TR. mixed trawl

Table 2 Cost data for the fleets fishing sandeel in the North Sea

	Variable costs					Fixed costs		
	Fuel ^a	Ice ^a	Main ^a	Sales ^b	Crew ^b	Rent ^a	Ins ^a	Misc ^a
TR. 18–24 m	2.59	218	1.372	0.10	0.28	5.7	135	114
IND.TR. 24–40 m	5.58	1, 18	2.143	0.11	0.26	9.0	250	172
MIX.TR. 24–40 m	4.87	334	2.486	0.10	0.29	9.2	225	174
IND.TR. >40 m	12.48	3, 27	6.312	0.12	0.27	27.3	389	310
MIX.TR. >40 m	7.87	598	4.969	0.04	0.22	46.4	324	690

Source FOI (2006)

Fuel fuel costs, Ice ice and provisions costs, Main maintenance costs, Sales sales costs, Crew crew costs, Rent rent of plant and equipment, Ins insurance costs, Misc miscellaneous costs, TR. trawl, IND.TR. industrial trawl, MIX.TR. mixed trawl

^a Fuel, Ice, Main, Ins, Misc measured in 1,000 DKK/year

^b Sales, Crew measured in % of catch revenue

and also assumed constant over the simulation period (thus assuming that α equals zero in Eq. 8), and equal to the 2005 prices which are shown in Table 1.

The assumption of constant prices through time can be discussed seeing that the prices on industrial species have changed considerably during the years preceding 2005. However, sandeel prices are determined on the global market, and price development for sandeel is strongly influenced by catches of other industrial species and the production of soya beans. Thus determining plausible price developments must not only include the development in sandeel stocks. Thus for simplicity, the price is assumed constant.

Cost information (used in Eqs. 2–4) for the included vessels is based on data from the Danish fisheries account Statistics (FOI 2006). 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. Costs are not assumed to change because of inflation, rising fuel prices etc. Foreseeing these future developments are outside the scope of this analysis. All costs are calculated as average costs for a vessel within each of the included fleets, and are presented in Table 2.

Finally, the discount rate used to evaluate the PVTP (Eq. 1) is set to 5%., which is the figure suggested by the Danish Ministry of Finance, when making cost-benefit analysis of public investments.

6 Technological assumptions and restrictions

BEMCOM is a linear optimisation model, seeking the most profitable solution for society. In order to exclude corner-solutions reflecting unrealistic/unlikely outcomes, such as stop an entire fleet fishing, or allow one (the most profitable) fleet to take all sandeel catches, it is generally required to include several constraints in the model.

It is assumed that the sandeel fishery, as well as the fishery of other industrial and consumption species, is limited by quotas. Without these restrictions, the model may propose solutions with unrealistic catch and landings levels. This could lead to very low stocks of one or more species, which would not be allowed in reality. Another solution would be to specify final stock levels in the last year of the optimisation period. But as the aim of the model is to assess how the stocks develop, given that the fleet optimises its profit over the period considered, it seems more appropriate to limit the yearly catches while the stock is allowed to vary according to this.

For sandeel, the quotas are specified on a habitat region level (5 banks) and scaled each year, relative to the 2005-level, according to the estimated sandeel biomass, i.e. increasing with increasing biomass and vice versa. With regard to the other industrial and consumption quotas, these are given on a fleet level and assumed constant throughout the simulation period at the 2005-level. Thus, reallocation between fleets of these quotas is assumed not to be possible.

The sandeel fishery is conducted with almost no bycatches as mentioned previously. Effort measured as days at sea per vessel per month 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 in each region by the maximum number of days at sea per month in the region observed in 2005. This is done to prevent the fleets from unrealistically concentrating all effort in a single region with high sandeel concentration.

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 monthly efforts 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 the model ending up with some fleets 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 fleets with the highest profit.

The number of vessels in each fleet is considered constant throughout the simulation period and equal to the number of vessels observed in 2005. These are: 10 vessels for Trawlers 18–24 m, 32 vessels for Industrial trawlers 24–40 m, 7 vessels for Mixed trawlers 24–40 m, 15 vessels for Industrial trawlers >40 m, and 13 vessels for Mixed trawlers >40 m.

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 yearly sandeel catches, which is done by scaling 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 according to data presented by ICES Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK 2007).

It must be emphasized that BEMCOM does not validate its results against historical values. This is because the model optimises, i.e. proposes potential optimal fishing situations given various input data based on historical values. Moreover, the transport matrix and the biological parameters are based on average values, making a year-to-year validation irrelevant. As such, it is not possible to validate the model as the potential optimal situation has not been reached yet. This is opposed to simulation models, which should be validated against historical data before being used for forecasts.

7 Scenarios and results

Two scenarios have been analysed to illustrate how BEMCOM may be used to assess the effect of MPAs. The first scenario is the base scenario, illustrating the status-quo situation where no changes from the management scheme in 2005 are made. This scenario thus allows sandeel fishery on all banks in the North Sea. Given the quota and effort restrictions listed above, the model assesses the economical optimal distribution of catches between sandeel and other species, and thus the optimal allocation of effort from an economic viewpoint, disaggregated down to ICES square, for the Danish fleets conducting the sandeel fishery. 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. To model the Dogger Bank closure, the LPUE has 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 Eqs. 6 and 7). Except for this added restriction of zero effort on 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 choose to redistribute their effort for sandeel to the remaining banks in the North Sea or substitute the sandeel effort with effort used to catch other species, as the fishery for sandeel is performed independently from the fishery on other species.

When simulating the development in the five regions of the sandeel spawning biomass (SB) during the optimisation period in the base scenario it has been shown that the biomasses oscillates around average values that are highest in the Dogger Bank region (~800,000 tonnes) and lowest on the South Eastern region (~100,000 tonnes). Thus the sandeel populations in the five regions are not threatened with the fishing pressure applied in the base scenario, i.e. the fishing pressure observed in 2005 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 shows the spawning biomasses with Dogger Bank region closed relative to the biomasses in the base scenario. It is observed that the sandeel stock on Dogger Bank increases relative to the base scenario as would also be expected. It is further seen that the stocks in the Western and North Eastern regions are not much influenced by the closure of Dogger bank, while the stocks in the Central and South Eastern

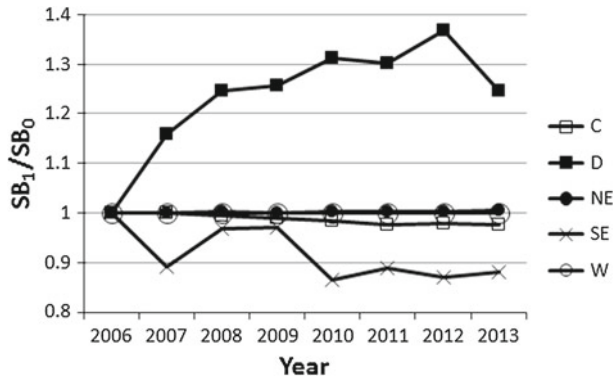


Fig. 1 Sandeel spawning biomass (SB_1) when Dogger Bank is closed relative to base scenario (SB_0)

regions decrease compared with the base scenario. These effects are primarily caused by the fishing pressure being moved towards the remaining areas, when Dogger Bank is closed. The larval transport from the Dogger bank towards the other areas is also increased by the increased stock on the Dogger bank, but this effect is counteracted by the increased fishing pressure on the banks.

The simulations show that in the base scenario the economic optimal total effort for the sandeel fishery in the North Sea lies between 1,500 and 2,500 sea days per year for the Danish fleet. Contrary to this, the optimal number of days at sea used to catch sandeel decreases to below 1,000, except in the last year in the scenario with Dogger Bank closed. The reason for this sharp decline in effort between the two scenarios is that the number of days at sea used on Dogger Bank in the base scenario is only to a small degree reallocated to the other banks when Dogger Bank is closed. The simulations show a slight increase in effort in the South Eastern and Central Regions, corresponding to the decreasing stocks in these regions, cf. Fig. 1.

The reduction in effort to catch sandeel in the closure scenario is not reallocated to catch other species, as the number of days at sea used to catch other species is more or less the same for the two scenarios; $\sim 7,000$ days are used in total each year to catch other species in the North sea by the included fleets in both scenarios, while ~ 900 days are used to catch other species in other areas. Thus the simulations suggest that it is thus not profitable to increase the effort towards fishing other species for the fleets included in the study. The reasons for this is believed to be firstly the relatively low LPUE values for these species, and secondly that the quotas of these species are kept constant throughout the optimisation period.

The optimal *PVTP* is defined as the sum over the optimisation period of catch revenue minus variable and fixed costs, all discounted to 2006 values. Summarising over the analysed period and all fleets, *PVTB* is 1,055 million DKK in the base scenario and 835 million DKK with Dogger Bank closed, i.e. a reduction of 21%. Thus even though the closure of Dogger Bank increases the stock in this region, with expected spill-over effects into the Central and South Eastern regions, this is not reflected in an increased *PVPT*. The reason is believed to be that the fleets cannot benefit from the increasing stock on Dogger Bank, and that the expected stock increase in the Central

and South Eastern regions are not enough to compensate for this. Further, as discussed above, the effort previously devoted to the Dogger Bank is being reallocated to the remaining fishing grounds, thus making the fishery less profitable in these areas.

8 Sensitivity analysis

As discussed in the data section above the biological and economic parameters used in the models are averages over a number of years or single year estimates based on the data available. In both situations, these can be subject to stochastic variation and other sources of uncertainty. The results discussed above are thus just point estimates of possible trends, and the natural question is then how these estimates react to variations in the input parameters.

To analyse this, central input parameters have thus individually been varied with $\pm 20\%$ in both scenarios. The following economic parameters have been varied: (1) discount rate (ρ), (2) fuel costs (*FUELC*), (3) ice costs (*IC*), (4) maintenance costs (*MAIN*), (5) sales costs (*SC*), (6) crew costs (*CC*), and (7) fish prices (p). Furthermore, the following biological parameters have been varied: (1) sandeel fecundity (Q), (2) sandeel larval transport (T), (3) initial sandeel stock (N), (4) sandeel weight at age (wt) and (5) sandeel natural mortality (*MORT*).

Only the influence on the *PVTP* will be discussed in relation to the sensitivity analysis. Figure 2 illustrates how the *PVTP* varies, relative to its original value when the economic and biological parameters are varied in each of the two scenarios.

Figure 2 firstly shows that the effect of varying the economic parameters on the *PVTP* generally is higher than the influence of varying the biological parameters in both scenarios. The highest influence on the *PVTP* occurs when varying the fish prices, which leads to an almost 50% change in *PVTP* in both scenarios. It is furthermore seen that the *PVTP* increases when all variable costs (fuel, crew, sales, maintenance and ice costs) decrease and vice versa, as expected, with crew costs having the highest impact. It is further seen that the *PVTP* changes with 5% when the discount rate is changed.

Secondly, Fig. 2 shows that the influence of varying the prices, the sales cost and the discount factor is approximately of the same magnitude in the two scenarios. Contrary to this, the effect on the *PVTP* of varying the fuel and the ice costs is more pronounced, when Dogger Bank is closed, while the effect on the *PVTP* of varying the crew and maintenance costs is most pronounced in the base scenario.

With regard to the biological parameters, Fig. 2 shows that all the biological parameters have a larger influence on the *PVTP* in the base scenario compared to a closure of Dogger Bank. The reason is that less sandeel is caught, when Dogger Bank is closed, thus making the biologic sandeel parameters less influential on the economic performance in this scenario. However, the *PVTP* varies by less than $\pm 10\%$ in both scenarios, when the biological parameters are varied with $\pm 20\%$. Thus it must be concluded that the economic results are less sensitive to variations in the biological parameters compared to variations in the economical parameters.

Figure 2 further shows that when the sandeel natural mortality, weight at age and initial stock size increases the *PVTP* decreases and vice versa. The largest effect is

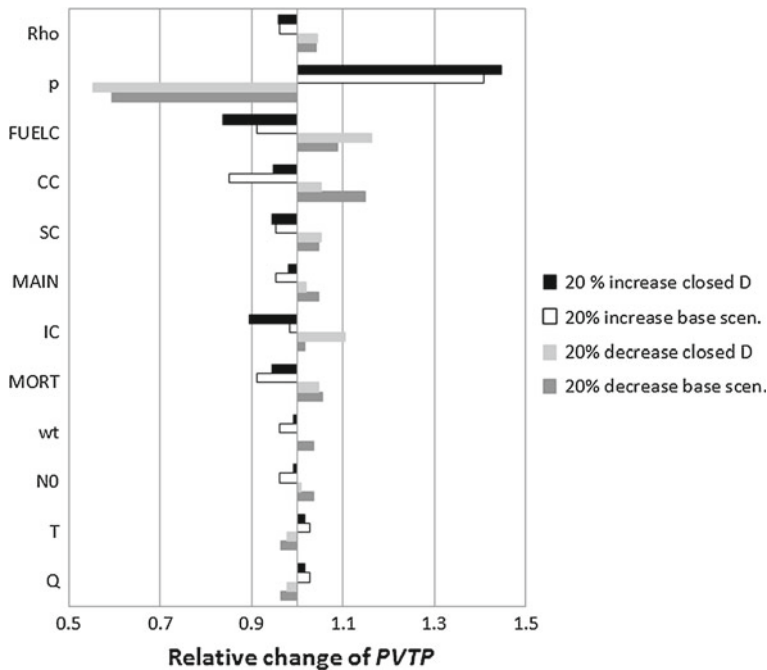


Fig. 2 Change, relative to original value in PVTP before and after variation in economic and biological parameters

observed, when varying the natural mortality. It seems intuitively reasonable that the total earnings of the fishery decreases with increasing natural mortality, as less fish are available. Furthermore the response to natural mortality changes displays strongest nonlinearity (difference in response to increase/decrease), which reflects the strong nonlinearity of the biological model. The nonlinearity of the biological model is also revealed in the different responses to parameter variations between base and Dogger Bank closure scenarios. However, it is initially surprising that the *PVTP* decreases when the initial stock sizes and weight at age increase, as this should offer more fish for the fishery, but remembering that the *PVTP* is a non-linear function of the stock and thus weight at age, this makes the influence of these two parameters less predictable than the other parameters. Finally, Fig. 2 shows that increasing the larval transport between the five regions and the sandeel fecundity (eggs per sandeel), results in increasing *PVTP* in both scenarios, and vice versa. Thus increased sandeel mobility and reproduction potential implies increased possibilities for the sandeel fishery to obtain high total earnings.

The sensitivity analysis thus illustrates that the economic results of the BEMCOM optimisations are most sensitive to fluctuations in the economic input parameters. In the present context official Danish logbook and account data have been used to set the economic parameters and Catch Per Unit Effort data for each fleet, while all biological input parameters are taken from the ICES (International Council for the Exploration of the Seas) working groups and databases. All data are thus considered reliable.

Generally care should always be taken in judging the reliability of the input parameters to any simulation and optimisation model.

9 Summary and conclusion

The present paper explores the potentials of the bioeconomic optimisation model BEMCOM for assessing biological and economic effects of introducing MPAs to management of fish stocks and marine environments. The model identifies optimal fishing patterns over time and space by asking 'what's best' measured in economic terms. Effort is thus reallocated towards the most profitable outcome in a situation with or without MPAs, taking into account various biological and economic constraints. BEMCOM is moreover able to include several fleets exploiting several species, and the model is thus highly flexible. As such, the model is considered to meet the needs of managers, who wish to assess economic and biological consequences of MPAs over time. As discussed in the introduction, the need for spatial management assessment models is growing because MPAs are becoming a popular management instrument alongside quota and effort management, most notably through the Natura 2000 network.

To illustrate how BEMCOM works, it was applied to the case of the Danish sandeel fishery in the North Sea. Sandeel is one of the most important species, measured in economic value for the Danish industrial fishery. On Dogger Bank, which is the largest habitat for sandeel in the North Sea, a number of important human consumption species feed upon sandeel. Harvesting sandeel may therefore affect the feeding conditions of these predatory species, which may have economic consequences for the European fishing fleet. Closing Dogger Bank has thus been discussed by different stakeholders for many years. However before implementing such a management regime, it is important to assess possible effects. The BEMCOM model has been developed to facilitate this by comparing status quo management with a possible closure of Dogger Bank.

These two scenarios have been considered by modelling a period of eight years. In both scenarios, BEMCOM optimises the *PVTP* aggregated over all fleets and over all time periods. The model runs show that the *PVTP* will be 1,055 million DKK in the base scenario, compared to 835 million DKK with closure of Dogger Bank, i.e. a reduction of 21%. This is consistent with the observation that the fleets to a high degree reduce their total fishing effort, and only partly reallocate effort to other fishing areas or species when Dogger Bank is closed. This indicates that the sandeel fishery in the other regions and fishery for other species are not nearly as profitable for the Danish fleet as fishing sandeel on Dogger Bank.

BEMCOM also illustrates how the closure of Dogger Bank affects the stock developments in the five sandeel bank regions in the North Sea. On Dogger Bank, the sandeel stock increases with more than 30% in some years, when this area is closed. The stock in the South Eastern Region and the Central Region decreases, indicating that effort is mainly reallocated to these two regions. The increased fishing pressure counteracts the expected increase in the sandeel stock in the regions, following increased larvae transport from Dogger Bank.

The results of the case study illustrate that high flexibility of the BEMCOM model that in the present context has been able (i) to model the complex recruitment structure of sandeel, (ii) to model sandeel stock developments in five different habitat regions (banks) in the North Sea, and (iii) to model effort reallocation of five different fishing fleets over 74 sub-fishing areas over a period of 8 years subdivided into months.

The results of the case study furthermore inform policy makers that a possible closure of Dogger Bank may lead to conflicting results seen from a biological and economic point of view. As the sandeel stock on Dogger Bank is expected to increase, a closure of this area will be beneficial for species dependent on sandeel in the ecosystem. On the other hand the BEMCOM analysis suggests that the fishing fleets depending on sandeel, especially from Dogger Bank, will lose earnings if the area is closed for fishing, because it is not profitable for these fleet segments to shift to fishing other species in the months where they usually target sandeel. As such a closure of Dogger bank will be beneficial for improving biodiversity and ecosystem health, but may affect economic benefits in the short term. It should thus be considered how to compensate fleets dependent on fishing sandeel on Dogger Bank, to e.g. not have a problem of non compliance. One possibility could be to introduce secure long term access rights to the fleets involved, when the stocks have recovered, and/or offer the fleets alternative industry species quota rights during the closure. The latter will have distributional effects and thus becomes a political discussion about distribution of losses and gains resulting introducing MPAs.

In all BEMCOM, when used to assess the bioeconomic effect of proposed MPAs, aid in the policy process of optimal management settings connected with the MPA. It can be concluded that the flexibility of the BEMCOM model demonstrates that cross-disciplinary decision supporting tools, addressing both biological and economic impacts of alternative MPA scenarios, are within reach in the near future.

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