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Designing a Decision Support System for Marine Reserves Management: An Economic Analysis for the Dutch North Sea

Arjan Ruijs[*] Hongyu Ding[†]
Ekko C. van Ierland[‡]

[*]Wageningen University
[†]Fondazione Eni Enrico Mattei and Venice International University
[‡]Wageningen University

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Abstract

In this paper we discuss how a Decision Support System (DSS) for managing the marine environment can be set up. We use the Driving force-Pressure-State-Impact-Respond (DPSIR) framework to analyze which are the major driving forces impacting upon the marine environment in the North Sea. Moreover, a number of potential responses are identified. Furthermore, a preliminary and simplified optimization model has been set up and can be used in a DSS to decide on the best location of marine reserves for the protection of species. The model is based on a bio-economic metapopulation model that can be used to decide which parts of the sea should be opened for fisheries and which should be protected as marine reserve. It accounts for the dispersal of fish and considers both the economic returns from fisheries and the ecological value of marine biodiversity. A number of suggestions are given on how to extend and improve the DSS.

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Hongyu Ding, *Fondazione Eni Enrico Mattei and Venice International University*
Arjan Ruijs and Ekko C. van Ierland, *Environmental Economics and Natural Resource Group, Wageningen University*

Corso Magenta, 63, 20123 Milano (I), web site: www.feem.it, e-mail: working.papers@feem.it

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Keywords: Decision Support System, Marine Biodiversity Conservation, DPSIR Framework, Bioeconomic Modeling, North Sea

JEL Classification: Q2, Q5, Q57, Q58

This paper has been written within the framework of the EU-Network of Excellence Marbef, see www.marbef.org

Address for correspondence:

Arjan Ruijs
Environmental Economics and Natural Resources Group
Wageningen University
P.O. Box 8130
6700 EW Wageningen
The Netherlands
E-mail: Arjan.Ruijs@wur.nl

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Hongyu Ding[1]
Arjan Ruijs[2*]
and
Ekko C. van Ierland[2]

[1] *Fondazione Eni Enrico Mattei and Venice International University, Venice, Italy;*
[2] *Environmental Economics and Natural Resource Group, Wageningen University, the Netherlands*
[*] *Corresponding author: A. Ruijs, Environmental Economics and Natural Resources Group, Wageningen University, P.O. Box 8130, 6700 EW Wageningen, the Netherlands, Arjan.Ruijs@wur.nl.*

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In this paper we discuss how a Decision Support System (DSS) for managing the marine environment can be set up. We use the Driving force-Pressure-State-Impact-Respond (DPSIR) framework to analyze which are the major driving forces impacting upon the marine environment in the North Sea. Moreover, a number of potential responses are identified. Furthermore, a preliminary and simplified optimization model has been set up and can be used in a DSS to decide on the best location of marine reserves for the protection of species. The model is based on a bio-economic metapopulation model that can be used to decide which parts of the sea should be opened for fisheries and which should be protected as marine reserve. It accounts for the dispersal of fish and considers both the economic returns from fisheries and the ecological value of marine biodiversity. A number of suggestions are given on how to extend and improve the DSS.

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1 Introduction

Marine biodiversity and ecosystem functioning are under intense pressure from anthropogenic factors such as fishing, nutrient input, recreational use, navigation and oil and gas industry. Despite of existing policies for regulating human marine activities and protecting the marine environment, there is a growing need for enhancing the efficiency and effectiveness of these policies. For this, an interdisciplinary method (including socio-economic, biological and ecological aspects) is needed, and the effects and causes of change should be integrated and presented comprehensively and systematically to stakeholders and policy and decision makers.

Within the EU funded Network of Excellence MarBEF[1] a start is made with the construction of a decision support system (DSS) in which possible marine policies can be compared and provided in a systematic and transparent way. The aim of the current paper is to make a contribution to the development of such a system, in which interdisciplinary studies on marine biodiversity can be incorporated to assess the effects of EU and national policies on the use and development of the marine environment. Such a DSS should be capable of identifying urgent problems in marine ecosystems, assessing the impacts of ecosystem changes and providing cost-effective policy suggestions for a wide range of stakeholders involved in the problem.

In a desirable DSS, first of all, sufficient information on marine biodiversity and ecosystem functioning should be available. Furthermore, the interrelations between the different stakeholders and their dependence on the ecosystem should be identified. Finally, the DSS enables to analyze the effects of a number of policy scenarios from a number of perspectives, which include the socio-economic, biodiversity and ecological perspective. On the basis of this, policy makers can implement or analyze in more detail those options that they consider most promising. The implemented policies should be closely monitored, in order to be able to improve the DSS and to upgrade it with more and updated information. The process of DSS development and use is presented in Figure 1, where we also display the analytical methods for the DSS.

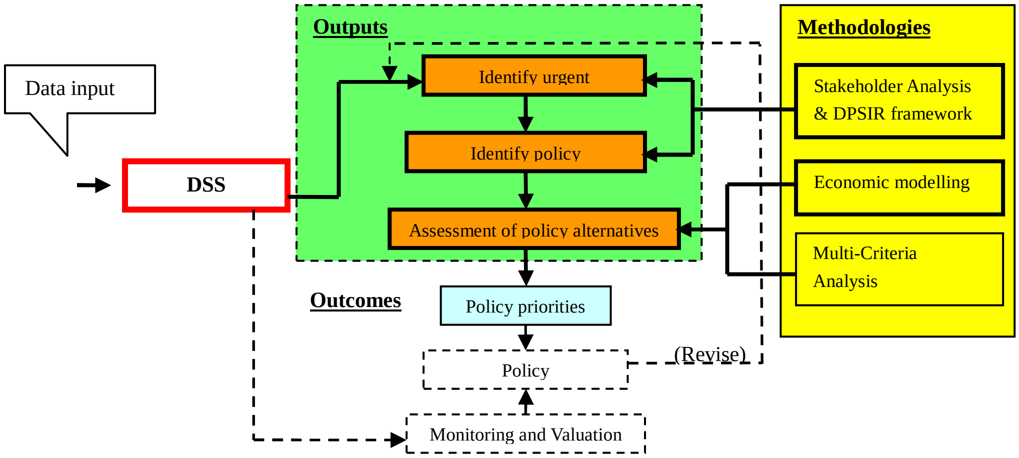

Figure 1: An example of a DSS framework (Ding, 2005)

We use the DPSIR framework to analyze the issues and systems could or should be taken into consideration in a DSS. Moreover, a first, preliminary and simplified optimization model is discussed which can be part of a more elaborate DSS and which focuses especially on the methodology needed for capturing the relationship between fisheries behavior, fish stocks and the policy of setting up marine

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[1] www.marbef.org

protected areas.

The structure of the paper is organized as follows. In Section 2, the issues at stake in the North Sea are discussed in order to identify the necessary elements of a DSS. In Section 3, the methodology used for assessing the policy effects is discussed. This methodology is applied in Section 4 for a case study of the Dutch part of the North Sea. The socio-economic and biological effects of a number of possible policy scenarios are discussed. Finally, in Section 5 we draw conclusions and discuss the limitations of the methods used, and we present suggestions for future research.

2 Methodology

2.1 Stakeholder Analysis

An important element for setting up a useful DSS is to undertake a stakeholder analysis in order to facilitate common understanding, avoid conflicts and establish trust among the involved stakeholders (Soma, 2003). By taking into account different view points and wide rage of interests from the stakeholders, feasibility of suggested policies and cooperation between the stakeholders may be improved. This in turn can enhance the effectiveness of policy implementation.

In the present analysis, stakeholders refer to the groups of individuals making use of the DSS, or having interests in or being affected by marine policies, such as policy makers, marine scientists, NGOs, local communities, and the fishery industry. Despite the large number of stakeholders concerned, the core in a DSS are the policy makers. They play a role as a planner to decide whether or not to adopt a given management strategy, and are responsible for adopting policies affecting overall social welfare in an economy by reallocating the marine resources. Scientists, however, are responsible for the provision of the best information, data and methodology, based on which policy makers can make their decisions. Finally, the effectiveness and social impacts of the implemented policies may be monitored and evaluated by NGOs, with respect to the changes of conditions of the local communities and fisheries industries. Their research results, in turn, can enforce the policy makers to improve the policymaking, and enhance the policy effectiveness.

2.2 Identification of problems in the marine environment: DPSIR framework

2.2.1 The DPSIR framework applied to the North Sea

A widely used methodology for systematically identifying environmental problems is the so-called DPSIR framework, denoted Driving forces-Pressure-State-Impact-Response (See Figure 2). This concept first emerged in an OECD project (OECD, 1999). Later on, its main components had been adjusted gradually and provided an important information function for decision-making.

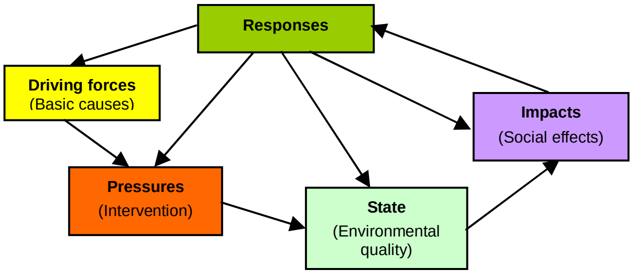

Figure 2: Illustration of DPSIR framework

The main idea of the DPSIR framework is to treat the environmental management process as a feedback loop and provide assessments on environmental problems and assist policymakers with a high-level view of the problem (Peirce, 1998). The analysis begins with identifying the driving forces, which refer to social developments and economic growth elicited from macro level changes in society, such as population growth, income increases, production, consumption and waste disposal. As a consequence, these anthropogenic activities may impose pressures on the environment and therefore lead to changes in the state or environmental conditions that prevail as a result of that pressure (OECD, 1999). Furthermore, the changes in environmental quality will disturb societies and economies which rely on the provision of environmental goods and services (Smeets and Weterings, 1999). Finally, the loop ends up with the responses, which in fact are the possible policy options as a response to the environmental and social changes (Peirce, 1998). .

The DPSIR framework is here used to analyze some of the current issues affecting marine ecosystems. We focus on the issues playing a role in the Dutch part of the North Sea. Within Europe, the North Sea is very important because of its high economic and ecological value. It is one of the world's main productive areas for fish, plankton, seabirds and benthic communities, from which total landings of fish amounted to roughly 2.3 million tons in 1999 (Walday and Kroglund, 2002; Iversen, 2001). In addition, a large number of offshore activities, like fisheries, oil and gas exploration, recreation, shipping, and sand extraction, are essential economic activities in the eight countries[2] surrounding the North Sea. Moreover, the specific physical nature of the North Sea supports approximately 230 species of fish and the coastlines display a large variety of habitats (Walday and Kroglund, 2002).

The major driving forces affecting marine biodiversity and ecosystem functioning in the North Sea include: offshore fisheries, by-catch and discarding, fish processing industries, aquaculture, offshore mining, shipping, coastal constructions and land reclamation, other social and economic forces, and indirect anthropogenic impacts like climate change. As we focus in this paper mainly on the fisheries we will restrict ourselves to describing some of the problems in this domain,

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[2] The eight north-west European countries are the United Kingdom, Norway, Sweden, Denmark, Germany, the Netherlands, Belgium and France.

Offshore fishery

Fishery is seen as one of the human activities with the largest impact on marine ecosystems. During the past 10 years, accompanied by a significantly increased fishing effort, the North Sea stocks of cod, haddock, whiting, saithe, plaice and herring have dropped to or below any previously recorded level (Svelle et al., 1997). This is driven by a number of social and economic developments, like the increased demand for seafood and fish products on the market (Greenpeace, 2004). In addition, the introduction of more efficient fishing techniques resulted in larger impacts on the marine ecosystems. Generally speaking, impacts differ substantially between fishermen using traditional fishing nets and those using bottom trawlers.

- The more traditional fisheries, using nets and gear, have an essential role in the European fishing history. It targets at fish species living near the surface. In the long run, extensive traditional fishing may cause a low recruitment of benthic fauna and reduce genetic diversity. In addition, a by-product of traditional fishing is the problem of by-catch and discarding, which reduces non-target fish stocks in the North Sea[3] and increases the pressures of water pollution. Deteriorated environmental conditions will lead to negative impacts on social welfare as a result of lower revenues for marine-dependent sectors like fisheries and tourism, a decrease in the provision of seafood, and a reduction of the pleasure derived from enjoying healthy marine ecosystems.
- Bottom fishing emerged as a result of technical innovations in fishing fleets and has been developed quickly due to its high fishing efficiency. It is characterized by exploring demersal species with the use of beam or otter trawlers, which particularly results in long-term damages to the benthic habitats. In effect, a significant shift from larger, more long-lived species to smaller, more opportunistic ones can be observed in the North Sea (Greenpeace, 2004). A direct impact to the benthic ecosystem caused by bottom trawling is the increased predation pressure on the benthos (ICES, 1999), which will further lead to the changes of the nutritional dynamics and community structure, and cause damages to the functioning of the benthic ecosystem (OSPAR, 2000). Moreover, an irreversible damage may be due to altering sediment and destroying habitat by the use of trawlers. All these physical changes give rise to similar impacts on the social welfare, as net fishing.

In response to the significant decline and collapse of fish stocks, the emphasis of policymakers has moved from primary pollution management to sustainable development of marine resources dealing with major threats such as habitat damage, biodiversity depletion and population decrease (Roberts, 2005; Roberts, 2003; Watson and Pauly, 2001; Jackson et al., 2001). In the European Union, fishery policy instruments are installed in terms of two major dimensions: human activities control and natural resources conservation, targeting at the sustainable development of both marine resources and fishery revenues.

- Human activities control: The EU's first set of common measures regarding human activities control has been put into force since 1970, in order to regulate the access to fishing grounds and the stable development of fishing markets (European Commission, 2002b). In 1983, the common fishery policy

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[3] Figures showed that over the past decade, total catch from the 25 EU member States has declined by 14%, from an estimated 7,261,000 tonnes to 6,247,000 tonnes. This reflects a decline in landings from demersal stocks, such as cod, haddock and plaice. (Brown, and Tyedmers, 2004: 2)

(CFP) was launched with the purpose of conserving fish stocks, protecting the marine environment, ensuring the economic viability of the European fleets and providing good quality food to consumers (Costello, 1999). Up to date, the CFP has made a contribution to a set of new policy instruments targeting at different management aspects. For instance, 1) the Multi-Annual Guidance programs (MAGPs) and fishing licenses have been introduced to control efforts and capacity of the fishing fleet; 2) Total Allowable Catches (TAC) involve the fixed maximum quantities of fish that can be caught from a specific stock over a given period of time; 3) technical measures are revised to limit the effects of by-catch and discarding (European Commission, 2002a;b). However, the CFP failed to meet its targets as a result of the low level of interaction between fishermen and scientists, the poor enforcement and conflicts caused by a shrinking resource base and fleet over-capacity (Costello, 1999; European Commission, 2002a).

- Natural resource protection: At a European level, a number of Marine Protected Areas (MPAs) have been designed and implemented based on the Bern Convention. These were not representative because of its habitats, biotopes and species (Costello, 1999). In the North Sea, “there are no MPAs in the central part of the North Sea”, “most of the North Sea MPAs are in the south-eastern parts of the area, along the Wadden Sea coasts of Denmark, Germany and the Netherlands” (Walday and Kroglund, 2002a: p. 25). So far, there still is a lot of uncertainty about the ecological and economic impacts of MPAs, but it is clear that more consideration should be given to juvenile and adult dispersal rates as well as its effect on trophic interactions and behavior of fishermen (Beattie et al., 2002: 415).

By-catch and discarding

By-catch and discarding are the by-products of fishing activities. Due to their significant pressures on marine ecosystem, we separately discuss them. By-catch refers to incidentally catching non-target species, whereas discarding fish occurs because the caught fish are not commercial species, they are too small, or they have exceeded allowable quota.

One direct pressure of by-catch and discarding is the reduction of non-target fish, marine mammals, turtles, and invertebrates. By-catch has increased the mortality rate of some precious marine mammals in the North Sea, such as small cetaceans and harbor porpoise, and exerted an extinction threat to them. Discarding causes pressures not only on the non-target fish, but also on those less profitable fish stocks. Moreover, a large number of discarded fish will cause water pollution by depleting oxygen for decomposition and enriching nutrient level in seawater (Greenpeace, 2004).

These pressures affect higher level predators in marine ecosystem in two directions. First, increased mortality rates of jackleg fish can reduce the size of the spawning stock and therefore reduce food for higher level predators. Secondly, discarded fish cause redundant food for scavengers, like seabirds, and may consequently increase the number of these scavenging species in the food web and therefore affect species composition. These effects affect fishermen due to increased fishing costs and instability of fishermen’s long-term income and employment conditions (European Communities, 2002a).

Appropriate responses include strict technical control, by-catch quotas and gear modification. For instance, the mesh size restrictions and square mesh panels can be used to protect young fishes from capture and encourage escape of undersized fishes.

Fish processing industry

Fish processing industry refers to the industry that uses fish meat or oil to produce fish-related products for human consumption. In the North Sea, approximately 55% of the landed weight of fish belongs to industrial fishing vessels (OSPAR Commission, 2003). The target-species of industrial fishing are small species, such as sand eels, Norway pout and sprat (Greenpeace, 2004). The harvested stocks will be processed to fresh, frozen or marinated fillets, canned fish, fishmeal, fish oil and fish protein products for direct human consumption (Brown and Tyedmers, 2004).

The environmental quality impacts caused by the processing industry can be subdivided into fishing and processing impacts. In the fishing process, the fish species are harvested from the lower levels of marine food web, which makes ecosystem more vulnerable to damage (Pauly et al., 1999; Greenpeace, 2004). Moreover, the processing process is responsible to a wide range of environmental problems e.g. use of water and energy, and water and air pollution due to litter and oil losses. These effluents normally contain high levels of organic matter, phosphates, and nitrates which are an important source of pollution. Other pollution generated at the processing or packaging process, e.g. solid waste, noise and odor, exert additional pressures to the environment. (Brown and Tyedmers, 2004). Deteriorated environmental quality may directly result in unsustainable fishing in the long run, and thus increase production costs as well as the unemployment rates in the industry. In response, a call for strict regulations on the catches of target species and cleaner production is growing (Brown and Tyedmers, 2004).

Climate change impacts

When talking about anthropogenic impacts on marine ecosystem, we can not neglect the effects of climate change. It is driven by social and economic development, and in turn has significant impacts on the natural environment and human society. A most direct effect of Climate Changes is the increase of the global average surface temperature. Moreover, the sea level is estimated to increase 9 to 88cm by the end of this century (IPCC, 2001) which will also cause a shift of the oceanic distribution of fresh and saline waters. This is particularly harmful to the species sensitive to marine surrounding, e.g. coral reef (IPCC, 2001; Greenpeace, 2004). Another uncertain influence arising from Climate Change may be a structural change of fishing patterns. A first step dealing with the threats of climate change is the Kyoto Protocol (IPCC, 2001).

2.3 Policy suggestions for marine biodiversity management

One of the major purposes of the current marine management policies in the North Sea is to conserve fish stocks, protect the marine environment, ensure the economic viability of the European fleets and provide good food quality to consumers. However, due to poor governance, sovereignty conflicts of coastal management, and a misunderstanding of policy effects, many of the policies have failed to achieve their targets. This demands for new, effective instruments for European marine biodiversity conservation. One of the proposed policy instruments deals with the installment of Marine Protected Areas (MPAs) (See Table 1). In principle, MPAs can vary from multiple-use to strict protection within ‘no-take zones’ (NTZs). However, there are no clear criteria for selecting the protected areas, in particular the NTZs. On the other hand, Marine Spatial Planning (MSP) is a more recent idea concerned with integrated use of a certain geographic area. Joint management of different sectors in the sea becomes more important in MSP, making data sharing, risk assessment, ecological and socio-economic mapping necessary. Therefore, the first obstacle of developing the MSP might be to enhance international cooperation on resource management.

Table 1. Number and area of marine and coastal protected areas in the North Sea (EU Birds and Habitat Directives).

	No of areas (SPA+pSCI)	**Total area (ha)**
Belgium	5	30,700
Denmark	32	342,600
France	58	291,900
Germany	15	103,700
Netherlands	27	773,200
Sweden	30	33,300
UK	129	621,700

NB: SPA= special protected area; pSCI= potential sites for community interest; Source: Walday and Kroglund, 2002:26

After reviewing the major driving forces affecting the North Sea ecosystem and a number of the possible responses, it can be concluded that a large part of the pressures on the North Sea are caused by the fisheries sector. In the EU, this sector is characterized by a large number of policies. However, many of them have failed to achieve their targets. For that reason, in the next section, we concentrate on a bio-economic analysis of fisheries in relation to marine protected areas and analyze some policy scenarios.

3 Modeling the costs and benefits of the alternative policy options

The core of our decision support system is formed by a bio-economic model in order to model the incentives of fishermen, fish movements and the fish stocks at various locations. In addition, to be able to derive the policy instrument yielding the highest social welfare, fisheries revenues are compared with a monetary proxy of the environmental value of marine biodiversity. In this section, we shall develop an integrated bio-economic model to simulate the social welfare effects of alternative policy scenarios. In this approach, the ecological, social and economic effects of a number of policy scenarios are compared.

3.1 Ecological models

3.1.1 Biological growth function

The foundation for the bulk of bio-economic fisheries models are the widely used bio-economic models developed by Gordon (1954) and Schaefer (1957). In their initial work on open-access fishery, they introduced a biological growth function to describe the continuous process of self-recruitment of fish stocks. Others, e.g. Imeson and Van den Bergh (2004), used a discrete version of the Schaefer model to describe this process, which is also used in this paper. The dynamic process of annual biomass change is modeled as follows:

$$X_{t+1} - X_t = g(X_t) - h(E_t, X_t) \tag{1}$$

where, variable X_t is the biomass of fish stocks in year t in a given ecosystem, $g(X_t)$ is the natural growth of biomass and $h(E_t,X_t)$ is the biomass mortality and harvesting. In this case, the mortality rate is simply interpreted as the death rate of fish stocks in harvesting[4].

The term $g(X_t)$ in equation (1) represents the natural growth of fish stocks in year t, which is usually expressed by the logistic growth function (2):

$$g(X_t) = r(1 - X_t / K)X_t \tag{2}$$

with parameters r and K representing the intrinsic growth rate of fish stocks and the carrying capacity of fish stocks of the ecosystem, respectively. Equation(2) shows that biomass grows annually, but up to a maximum of K. Growth function $g(X_t)$ is a quadratic function of the fish stock X_t, which has an inverted U shape with $0 \le X \le K$ (see Figure 3)[5]. Maximum sustainable yield (X_{MSY}) occurs when $\partial g(X_t)/\partial X_t = 0$. For this function, the maximum sustainable yield equals half of the carrying capacity (Perman et al., 1999).

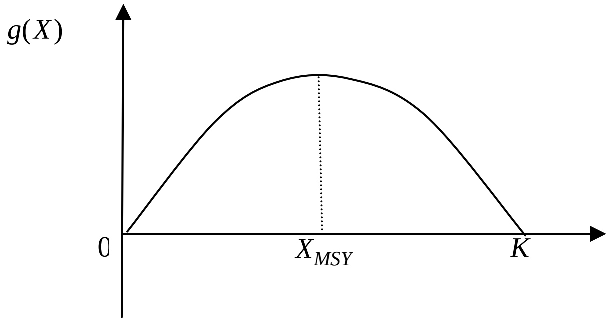

Figure 3: Schematic presentation of the logistic growth function.

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[4] The mortality rates vary between different species or ages. This goes beyond the scope of this paper.

[5] To simplify the problem, we will adopt a simple logistic growth function here, with X in the interval $[0, K]$. For a discussion about the threshold level of biological growth see e.g. Perman et al. (1999).

The term $h(E_t,X_t)$ in equation (1) is the so-called Schaefer production function, which calculates the harvested amount of fish stocks in year t. It is a function of the fishing effort (E_t) and existing biomass (X_t), which is described by equation (3):

$$h(E_t, X_t) = qE_tX_t \tag{3}$$

in which, q denotes the catchability coefficient of per unit of fishing effort. If we substitute equation (2) and (3) into (1), the biomass growth function is as follows.

$$X_{t+1} - X_t = rX_t(1 - X_t / K) - qE_tX_t \tag{4}$$

3.1.2 Metapopulation Model

To deal with the spatial pattern of fish dispersal and fishing efforts, so-called metapopulation models are used. Examples of studies using a two-patch or multiple-patch system include Sanchirico and Wilen (1999, 2001a, 2001b), Leeworthy and Wiley (2000), Sanchirico (2003), Smith and Wilen (2003) and Ruijs and Janmaat (forthcoming). These spatial patterns should be included as they can have large effects on the economic and ecological effects of the reserve creation.

In principle, in metapopulation models it is supposed that the sea in question is divided into a number of patches, which contain or have the potential to contain a certain amount of biomass. All the patches are located a fixed and discrete distance from one to another (Sanchirico and Wilen, 2001a). Moreover, the size of biomass in each patch depends on its own growth processes as well as dispersal from and to other patches (Sanchirico and Wilen, 1999: 131-132). Biomass can migrate between patches and biomass levels can vary between different patches due to differences in carrying capacity, ecological characteristics and harvesting efforts (see Figure 4).

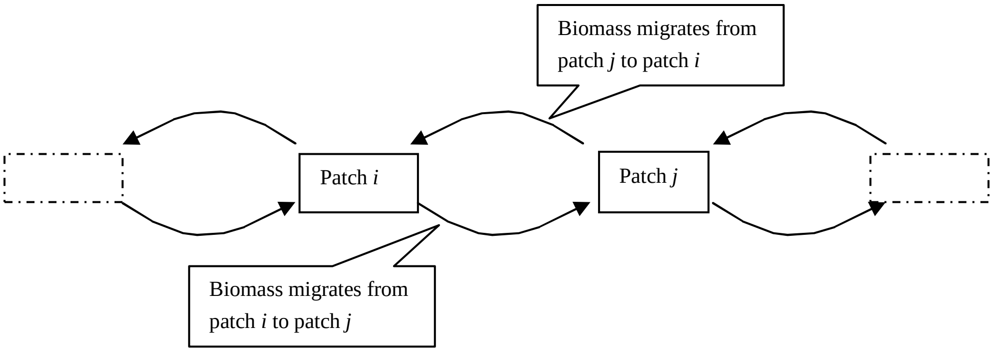


Figure 4: Chart of possible biomass migration patterns between patches (Ding, 2005).

Sanchirico and Wilen (1999) defined a 'metapopulation' as 'a group of linked subpopulations distributed across a set of spatially discrete habitats or patches'. The use of metapopulation models become more and more interesting as patchy heterogeneous environments and linkages between the patches are important in understanding effects of anthropogenic pressures on marine ecosystems and because ignoring the spatial dimension might result in the loss of a considerable amount of interesting information such as spatial patterns of vessel and biomass movement (Sanchirico and Wilen, 2001a).

Equation (1) can easily be changed into a metapopulation model by simply adding an additional term, $(d_{ii}X_{it} + \sum_{j\in I, j\neq i} d_{ji}X_{jt})$ which describes the migration of biomass between patches. Equation (1) can be rewritten as follows,

$$X_{i(t+1)} - X_{it} = g(X_{it}) + (d_{ii}X_{it} + \sum_{\substack{j\in I \\ j\neq i}} d_{ji}X_{jt}) - h(E_{it}, X_{it}) \tag{5}$$

with $i, j \in I = \{1,2,...,n\}$

where I is the set of patches, i and j are elements of set I. Parameter $d_{ii} \leq 0$ denotes the emigration rate of biomass in patch i. Multiplied by the amount of biomass in patch i, X_i, $d_{ii}X_{it}$ equals the total amount of biomass that moves from patch i to other neighboring patches. Parameter $d_{ji} \geq 0$ is the immigration rate of biomass leaving from patch j to patch i. d_{ji} multiplied by the amount of biomass in patch j, X_j, it expresses the amount of biomass moving from alternative patch j into patch i. Therefore, $\sum_{j\in I, j\neq i} d_{ji}X_{jt}$ calculates the total immigration of biomass into patch i. The term $d_{ii}X_{it} + \sum_{j\in I} d_{ji}X_{jt}$ measures the net inflow of biomass in patch i. Note that $\sum_{i\in I} d_{ij} = 0$. From this it follows that net dispersal depends upon biomass in all patches and the direction of dispersal is endogenous to the model, depending on density differences between the patches.

3.2 A bioeconomic model of fisheries behavior

3.2.1 Dynamic optimization model

The bioeconomic model set up in this paper considers, among other things, the policy question whether to open or close parts of the sea for fisheries. Assume that the North Sea area can be divided into a number of discrete patches I. Fish can freely move between patches. Introduce the binary variable, θ_i^F, indicating whether a patch i will be open for fisheries (θ_i^F=1) or whether it will be protected as a marine reserve or marine protected area (MPA) (θ_i^F=0). Metapopulation equation (5) changes into

$$X_{i(t+1)} - X_{it} = g(X_{it}) + (d_{ii}X_{it} + \sum_{\substack{j\in I \\ j\neq i}} d_{ji}X_{jt}) - \theta_i^F h(E_{it}, X_{it}) \tag{6}$$

The question which distribution of MPAs and fishing grounds gives the optimal economic returns for society can be formulated as a constrained dynamic optimization model that can be solved using optimal control theory. In this model, we introduce an objective function existing of two terms: net fishing rents and ecological value of MPAs. The bio-economic fisheries model can be written as follows.

$$\underset{X_{it}, i\in I, t\in T}{Max} \sum_{t=0}^{T}\sum_{i=1}^{n}\Big[R_{it}^{F}(X_{it},E_{it})\theta_i^{F} + EV_{it}^{M}(X_{it})\theta_i^{M}\Big]\left(\frac{1}{1+\rho}\right)^{t-1} \tag{7}$$

$$X_{i(t+1)} - X_{it} = g(X_{it}) + (d_{ii}X_{it} + \sum_{\substack{i\neq j\\ j\in I}} d_{ji}X_{jt}) - \theta_i^{F} h(E_{it}, X_{it})$$

$$X_{iT} \geq X_{i0} \tag{8}$$

With $\theta_i^F + \theta_i^M = 1$, θ_i^F, θ_i^M binary variables, $i, j \in I; I = \{1,2,3.......n\}$

with ρ the discount rate. Equation (8) gives the transversality condition, preventing fishermen behavior that would lead to species extinction. In the results, a patch *i* will be open for fishing if the net present value of fishing rents of that patch exceed the net present ecological. In that case, $\theta_i^F = 1$ and $\theta_i^M = 0$. Else, the patch will be turned into an MPA, with $\theta_i^M = 1$ and $\theta_i^F = 0$.

3.2.2 Net fishing rents

In equation (7), fishery revenues $R_{it}^F(E_{it}, X_{it})$ are a function of gross benefits of selling the harvests $HB_{it}(E_{it}, X_{it})$ and total harvesting costs $HC_{it}(E_{it})$,

$$R_{it}^{F}(E_{it}, X_{it}) = HB_{it}(E_{it}, X_{it}) - HC_{it}(E_{it}) \tag{7}$$

It depends on the fishing efforts as well as biomass in patch *i*.

$$HB_{it}^{F}(E_{it}, X_{it}) = p_{it}^{F} h_{it}^{F}(E_{it}, X_{it}) = p_{it}^{F} qE_{it}X_{it} \tag{8}$$

in which parameter $p_{i\tau}^{F}$ is assumed to be the exogenous market price of harvested fish stocks. In this case, we assume that fishermen are price takers. The amount of fish harvested from patch *i* is given by $h_{it}^{F}(E_{it}, X_{it})$ which has already been discussed in equation (3).

Harvesting costs $HC_{it}(E_{it})$ depend on fishing efforts in patch *i* and transport costs, which depend on the distance between the patch and the harbor.

$$HC_{it}(E_{it}) = \omega E_{it} + TC_{it}(E_{it}) \tag{9}$$

With ω harvesting costs per unit of effort and $TC_{it}(E_{it})$ transport costs.

$$TC_{it}(E_{it}) = \phi E_{it} D_i \tag{10}$$

in which, Φ represents the marginal transport costs per unit of effort per kilometer and parameter D_i distance in kilometers from patch *i* to the port. Distance affects harvesting costs considerably as fuel costs can make up a large part of variable costs. This has also been found by Smith and Wilen (2003) in their case study of the Northern California red sea urchin fishery, which showed that "fishing effort fans out in a manner that declines geometrically with distance from the port."(Smith and Wilen, 2003:189).

It has to be noted that the objective function chosen, refers to a situation in which a social planner, e.g. the government, can manage fisheries in such a way that the optimal effort level is not exceeded, e.g. by introducing fisheries rights or Individual Transferable Quota's (ITQs). This not necessarily reflects the real-life situation in which individual fishermen working on an open fisheries market choose their optimal effort individually, given what other fishermen and the government are doing.

3.2.3 Ecological value of MPAs

In this paper, we investigate from a social planner's perspective, which areas should remain open for fishing and which should be closed as MPA. In the MPAs, fishing activity is not allowed (θ_i^F=0 in equation (6)) and therefore no direct economic benefits will be obtained from it. The effect will be that in the closed areas stocks of biomass can grow without the risk of being harvested, which, through dispersal, will also positively affect stocks in the fishing areas. Next to this positive externality effect of closing areas, the expected positive effect of patch closure on marine biodiversity has an intrinsic value which can be covered by estimating the ecological value of the area. The ecological value is defined as

$$EV_{it}^{M}(X_{it}) = PB_{it}(X_{it}) - PC_{it}(X_{it}) \tag{11}$$

in which $PB_{it}(X_{it})$ are the total benefits of marine conservation in patch *i* at time *t*, which reflects the ecological value. Ecological value is assumed to depend directly on biomass densities. A very restrictive assumption we make is that there is a linear relationship between ecological value and biomass density. More research is needed on the relation between ecosystem functioning, marine biodiversity and fish biomass levels. This, however, goes beyond the scope of this paper. We define

$$PB_{i\tau} = p_{i\tau}^{M} \cdot X_{i\tau} \tag{12}$$

with $p_{i\tau}^M$ the shadow price of fish biomass in the protected patches reflecting the ecological, non-market value of biomass in monetary terms. To simplify the problem, we assume a fixed $p_{i\tau}^M$. The effect of $p_{i\tau}^M$ on optimal closure strategies will be analyzed using a sensitivity analysis. Its value will have large impacts on the allocation of fishing efforts and corresponding management strategies.

Closing areas for protection also brings monitoring costs, which is denoted by $PC_{i\tau}$ and are assumed to depend on the size of the biomass to be maintained.

$$PC_{i\tau} = c_X X_{i\tau} \tag{13}$$

with c_x the average maintenance costs of labor and capital per unit of biomass. By substituting equations (6), (12) and (13) into (11), we get equation (14) to depict the ecological value of MPAs.

$$EV_{i\tau}^{M} = PB_{i\tau} - PC_{i\tau} = \left(p_{i\tau}^{M} - c_X\right) X_{i\tau} \tag{14}$$

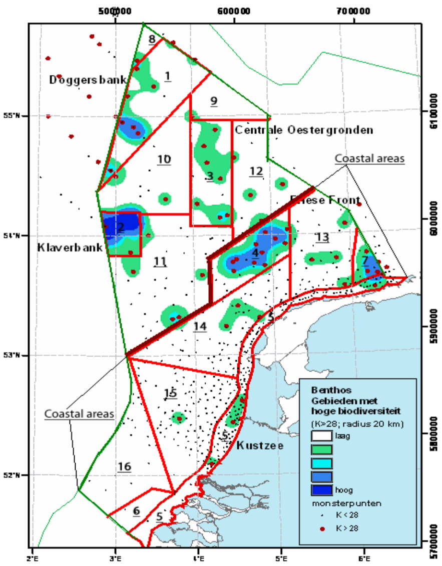
Summarizing, the objective function, (7), is to maximize the sum of the ecological value of the protected areas plus the net fishing rent obtained from the fishing grounds over a period as a function of metapopulation model (6). The optimal solution contains the optimal patch management scheme (which patches are open or closed), the optimal fishing effort in each patch and the resulting optimal biomass.

4 A case study in the Dutch North Sea

4.1 Background

The model discussed in Section 3, will be used to analyze management issues at stake in the Dutch North Sea. The current version of the model is only able to model open-closure decisions and the optimal corresponding fisheries effort. Other activities, like navigation, oil and gas exploration, windmill parks, aquaculture, etc. can be added to the model by changing the objective function and maybe adding extra constraints. Moreover, in order to include also non-monetary objectives in the decision making, the model may have to be incorporated in a multi-criteria analysis which includes criteria like biodiversity measures and other criteria of which it is difficult or controversial to estimate a monetary value.

The Dutch part of the North Sea is selected for two reasons. First of all, the portion of the North Sea belonging to the Netherlands has a large shallow area along the coastline and several important marine protected areas distributed in the sea, which provides an ideal system for the spatial study on marine biodiversity conservation and fishery management. Secondly, in the Dutch marine policies, the biological hot spots of the North sea have been delineated and currently policies are made with regard to which areas to close for fisheries. Figure 5 shows a map of the 16 patches we consider in our study, which contains the important hot spots of the North Sea as well as the biologically less important areas.



*Patches 1-7 in Figure 5 are in under the Dutch National Spatial Strategy called

- Patch 1: the Dogger Bank;
- Patch 2: the Cleaverbbank;
- Patch 3: Central Oyster Grounds;
- Patch 4: the Frisian front;
- Patch 5: the Coastal Sea;
- Patch 6: the zeeuwse banken;
- Patch 7: the borkumse stenen.

Figure 5: Location of patch distinguished in the model in the Dutch North Sea[6]

In RIKZ (2005), seven important areas with high biodiversity values have been selected. In our metapopulation model, we consider 16 patches: the seven hotspot areas jointly with 9 alternative patches with a lower biodiversity value. Dispersal rates of biomass between the different patches are given in Table 2. These dispersal rates indicate the flow of biomass between interconnected patches. The negative numbers reflect the rate of biomass emigration from a patch and the positive numbers reflect the rate of biomass immigration from one patch to another. Zeros mean that there is not dispersal between unlinked patches.

Table 2. Biomass dispersal rates for the 16-patch system, d_{ij}

d_{ij}		To															
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
From	P1	-0.4	0	0	0	0	0	0	0.25	0.05	0.1	0	0	0	0	0	0
	P2	0	-0.4	0.15	0	0	0	0	0	0.1	0.05	0.1	0	0	0	0	0
	P3	0	0	-0.4	0	0	0	0	0	0.1	0.05	0.05	0.15	0	0	0	0
	P4	0	0	0	-0.4	0	0	0	0	0	0	0.1	0.1	0.05	0.15	0	0
	P5	0	0	0	0	-0.4	0.1	0.1	0	0	0	0	0	0.05	0.1	0.05	0
	P6	0	0	0	0	0.1	-0.4	0	0	0	0	0	0	0	0	0.1	0.2
	P7	0	0	0	0	0.1	0	-0.4	0	0	0	0	0.1	0.2	0	0	0
	P8	0.25	0.1	0	0	0	0	0	-0.4	0.05	0	0	0	0	0	0	0
	P9	0.05	0	0.1	0	0	0	0	0.05	-0.4	0.15	0	0.05	0	0	0	0
	P10	0.1	0.05	0.05	0	0	0	0	0	0.15	-0.4	0.05	0	0	0	0	0
	P11	0	0.1	0.05	0.1	0	0	0	0	0	0.05	-0.4	0.05	0	0.05	0	0
	P12	0	0	0.05	0.1	0	0	0.1	0	0.05	0	0.05	-0.4	0.05	0	0	0
	P13	0	0	0	0.05	0.05	0	0.2	0	0	0	0	0.05	-0.4	0.05	0	0
	P14	0	0	0	0.15	0.1	0	0	0	0	0	0.05	0	0.05	-0.4	0.05	0
	P15	0	0	0	0	0.05	0.1	0	0	0	0	0	0	0	0.05	-0.4	0.2
	P16	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0.2	-0.4

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[6] The patches are divided according to the report on “Areas of special ecological values of the Dutch Continental Shelf.”. See RIKZ 2005 for more details.

We assume that initial biomass levels X_0 and carrying capacity K only depend upon the size of the patches and that the intrinsic growth rates are higher in the hotspots than in the other patches. Initial biomass level and carrying capacity per patch are, of course, related to the size of each patch (See Table 3 for the parameter's value).

In Figure 5, Patch 8 is the smallest patch. Its size is assumed to be equal to 1 unit. The sizes of the other patches are given relative to the size of Patch number 8. The initial biomass level is assumed to be equal to 0.2 million ton and the carrying capacity to 0.5 million ton in patch 8. Initial biomass levels and carrying capacities for the other 15 patches are calculated by multiplying the relative size with the initial biomass and carrying capacity of Patch 8. With respect to the biomass growth rates (r_i), values have been distracted from in Bjørndal and Lindroos (2004) (see also Hakoyama and Iwasa (2000) and Smith and Wilen (2003)).

In addition, distances between patches and the harbor are considered as an important element for the spatial study and are expected to affect fishermen behavior. We assume that a port is located at the middle point of the coast line. On the basis of that, distances from the center of each patch to the port are estimated.

Table 3. Patch specific parameter values

Parameters	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
Distance$^{1)}$	267	169.75	184.3	106.7	14.55	145.5	145.5	315.25	247.35	194	121.25	189.15	140.65	58.2	67.9	130.95
Biomass growth rate, r(i)	0.43	0.42	0.46	0.4	0.53	0.45	0.49	0.21	0.2	0.2	0.19	0.19	0.28	0.27	0.27	0.23
Relative patch size(i))$^{2)}$	10	2	8	7	9	1.5	1.5	1	4	9	13	9	9	10	10	9
Initial biomass level, $X_0(i)^{3)}$	2	0.4	1.6	1.4	1.8	0.3	0.3	0.2	0.8	1.8	2.6	1.8	1.8	2	2	1.8
Carrying capacity, K(i)	5	1	4	3.5	4.5	0.75	0.75	0.5	2	4.5	6.5	4.5	4.5	5	5	4.5
Number of linkages with other patches	3	4	5	4	5	3	3	3	5	5	6	6	5	5	4	2

Notes: 1) Distance to harbour in km; 2) in units; the smallest patch, i.e. patch 8, is supposed to be of size 1; 3) in million tons; 4) in million tons

For the fisheries related parameters, we adopted figures from the Norwegian North Sea, such as the catchability parameter q, discount rate ρ and market price of herring p, which have been employed by Bjørndal and Lindroos (2004) (See Table 4). Finally, we take a 10 year planning period. So, in objective function (7), $T = 10$. The model will be solved using GAMS (see the Appendix for the GAMS code).

Table 4. Fisheries parameters values

Parameters	Parameter definition	Parameter value
q^*	catchability	0.06152
ρ^*	Discount rate	0.05
p^*	Market price of single species	€ 246.3 per ton of biomass
p_1^{**}	Existing biological value	€ 90 per ton of biomass
c_x^{**}	Costs of marine conservation	€ 12.2 per ton of biomass
ω^*	Costs of fishery operation	€ 144 per unit of effort
φ^{**}	Costs of transportation of fleets	€ 20.5 per km

Notes: * based on from Bjørndal and Lindroos (2004); ** based on own estimation

4.2 Defining policy scenarios

Biomass levels vary between patches and directly influence the fishermen's spatial behavior, such as the harvesting efforts per patch. The more productive patches may be fished more intensively, which may lead to more serious impacts to the marine ecosystem. In the next section, model results will be discussed for a number of policy scenarios which reflect different policy constraints on the basis of which patches are allowed to be closed. First, the benchmark solution is discussed in which all patches may be opened or closed. The optimal pattern of closed and opened patches is derived by the model. In a 16-patch system, there are $2^{16} = 65536$ possible combinations. Moreover, four scenarios are considered, in which the ecological importance of hotspots is considered to be more important. It is compared how these scenarios score on overall net benefits, biomass and effort. The following scenarios are considered:

1. The nine alternative patches are kept open and only the hotspots may be closed. The model derives which of the hotspots should be closed. This reflects a situation in which emphasis is given to the economic rents that can be obtained from fisheries. Only the hotspots might be considered to be closed, but only if their ecological value is higher than the economic rents from fishing them.
2. The seven hotspots are closed for fishing and the alternative patches may be opened or closed. The model derives which of these alternative patches should be opened. This scenario puts high emphasis on the ecological importance of the hotspots. In fact, this represents a situation in which the ecological value of these hotspots is considered to be higher than that of the alternative patches that are closed and they are also assumed to be higher than the fisheries revenues that could be obtained for them were they opened for fisheries.
3. Hotspots near or along the coastal areas are closed as they serve as important spawning grounds which may restock the other patches. The remaining hotspots situated in the pelagic areas of the North Sea, which for fishermen are also interesting fishing grounds, are opened in order to compensate fishermen from the loss of the productive coastal areas. The model derives which of the alternative patches should be opened or closed to optimize net rents. This scenario puts an emphasis on the importance of protecting spawning grounds for the survival of species. However, by keeping the pelagic hotspots open, the effects of closing areas on the fisheries sector are reduced.
4. The pelagic hotspots are closed but fishing is allowed in the coastal hotspot areas. This scenario is comparable to Scenario 3, but by opening the coastal hotspots, more emphasis is put on the costs fishermen have to make to reach the more remote fishing grounds and less emphasis is put on the importance of protecting the coastal spawning grounds.

In the model, we take a planning period of 10 years from 2005 until 2014. In the next section, the results of the different scenarios are compared for a situation in which the ecological value of a tonne of biomass is assumed to be $p_{i\tau}^{M}$ = € 50,-. In Ding (2005) a sensitivity analysis is executed in order to analyse the effect of the ecological value on the model results.

4.3 Model outputs with respect to the five scenarios

In this section, the results for the benchmark scenario and the four policy scenarios are discussed. In the Benchmark Scenario, there are no policy guidelines with respect to which patches are (not) allowed to be opened or closed. The model derives the optimal spatial pattern of closed and opened patches, taking into account the potential fisheries revenues and ecological value of each patch. Table 5 show that in order to obtain optimal net revenues, all hot spots except the biggest one (Patch 1) are to be closed as marine protected areas. Moreover, also six of the alternative patches are to be closed whereas three of the largest patches are kept open. Spatial pattern of opened patches is such that all of them are surrounded by closed patches. Most of the hot spots are closed due to their relatively high growth rate. Through the dispersal, they may restock the bordering opened patches. Patch 1 is kept open for two reasons. First, it is a productive area for fisheries due to its large size as well as high growth rate. Even though harvesting in this remote patch encompasses high travel cost, benefits are also high due to the high harvests. Secondly, it is surrounded by three closed alternative patches, that despite of their relatively low growth rates, may restock the patch if biomass levels are lower than in the alternative patches. This restocking of opened patches is important. The benefits obtained from closing areas is not only reflected by the direct ecological value of the increased biomass in that area, but also by the indirect revenues obtained from the increase of biomass in the surrounding patches. There is a clear trade-off between which of the two features result in highest returns. For the remote patches 1, 8, 9 and 10, the revenues from fishing Patch 1 and closing Patch 8, 9 and 10 (what gives direct ecological returns and indirect restocking returns in Patch 1) are apparently higher than the ecological value of closing the hotspot Patch 1 and fishing (partly) the Patches 8, 9 and 10. For the other hotspots, the balance is the other way around.

Table 5. Model results for the four scenario for p_{it}^M = € 50 per ton.

Scenario	Hotspots[2]		Alternative patches[2]		Total net benefits[3]	Fishing rents[3]	Ecological value[3]	Total biomass	Fishing effort
	closed	opened	closed	opened					
BM[1]	2,3,4,5,6,7 (29)	1 (10)	8,9,10,12,14,16 (42)	11,13,15 (32)	28,511	16,238	12,273	551	701
1	all (39)	0 (0)	0 (0)	all (74)	24,835	17,774	7,061	484	705
2	all (39)	0 (0)	8,9,12,14,16 (33)	10,11,13,15 (41)	27,860	15,214	12,646	557	842
3	4,5,6,7 (19)	1,2,3 (20)	8,9,10,12,14,16 (42)	11,13,15 (32)	27,999	17,832	10,167	525	746
4	1,2,3 (20)	4,5,6,7 (19)	8,9,12,14,15,16 (43)	10,11,13 (31)	26,391	15,317	11,073	569	680

Notes: 1) Benchmark; 2) numbers in between brackets indicate the size of the opened or closed areas, relative to the size of Patch 8; 3) in €1000,-.

For policy reasons, it might be infeasible or unacceptable to have no policy constraints. For that reason, we consider the results of four policy scenarios in which other characteristics, such as environmental or economic concerns, are considered as well. In **Scenario 1**, in which the nine alternative patches are kept open and only some of the hotspots may be closed, emphasis is put on economic rents. Fishermen get as little rules and regulations on where to fish as possible, but due to environmental concern, some of the hotspots may be closed if that turns out preferable from a social welfare perspective, i.e. if it makes net fisheries plus ecological revenues higher. For this scenario, it is most efficient from a social planner's point of view to close all hotspots. The restocking effects plus ecological value produced by closing these patches exceeds net rents from fishing them. Compared to the benchmark scenario, total net benefits are 13% lower. Fishing revenues, however, are 9% higher but the sum of ecological values of the closed patches decrease by 42%, especially because less patches are closed, and also total biomass levels decrease by 12%. In this scenario the percentage of the area closed decreases from 63% in the benchmark scenario to 35% (see Table 5).

In **Scenario 2**, more emphasis is given to ecological conservation. The seven hotspot areas are closed from fishing and it is determined which of the alternative patches should be opened and closed. From an ecological point of view this scenario is optimal, but from a fisheries point of view it is the worst. Table 5 shows that in this case net revenues are optimal if the large patches 10, 11, 13 and 15 are opened. Opening rules are comparable to the Benchmark results. Closure rules are such that again the open patches are surrounded by closed patches. The only difference with the Benchmark is that now Patch 1 has to be closed for its ecological value; instead the neighboring Patch 10 is kept open (see Figure 5). Percentages of areas opened or closed are almost the same as in the benchmark scenario. Therefore, also total net revenues are not very much different (-2%). As hotspot Patch 1 is now closed, biomass levels and ecological value of the closed patches slightly increase and fishery revenues decrease. However, to prevent an even larger reduction of these revenues, fishing efforts have to increase substantially. Apparently, fishing in Patch 1, as is done in the Benchmark Scenario, results in higher returns with lower effort levels than fishing in Patch 10. The parameter estimates used in this study are such that apparently, the restocking impacts of the hotspots are so large that keeping them open for fisheries would be worse for biomass. It is noted that this is not concluded from all studies (see e.g. Ruijs and Janmaat (forthcoming)). It depends on the growth rates of the ecologically important areas compared to those of the alternative patches whether opening the hotspots and closing the alternative patches would result in more or less or more biomass than closing the hotspots.

Scenario 3 considers a situation in which the coastal hotspot patches are closed due to their importance as spawning ground. As compensation to the fishermen, the more remote hotspots are opened. It is derived which alternative patches should be opened or closed. In this scenario, the patches 11, 13 and 15 are kept open, just like in Benchmark scenario. As a result, 46% of the sea is opened for fishing. Even though in the Scenario 1 65% was opened, fisheries revenues in Scenario 3 are slightly higher mainly because much higher growth rates in the spawning ground can give rise to a faster biomass recruitment in the neighboring fishing patches. Even though four of the hotspots are opened, total biomass levels are 9% higher than in Scenario 1 in which all hotspots were closed. It thus brings higher total fishing rents as well as a higher ecological value. The alternative patches closed now restock the other patches. The spatial pattern is again in such a way that, as much as possible, opened patches have closed patches as neighbor. However, we should also notice that the closure of more coastal hotspots will lead to a significant increase in the fishing efforts for harvesting in the pelagic sea.

Finally, in **Scenario 4**, the remote, pelagic hotspots are closed and the coastal hotspots are opened. This scenario is assumed to consider more the effect of patch closures on fishermen income than the previous scenario, but this turns out not to work. In order to ensure sustainable recruitment of biomass it is now the coastal alternative patches that are closed and the more remote ones that are opened. Results show that now only patch 10, 11 and 13 are closed. In total 44% of the sea is open for fishing. From a fishermen point of view this is one of the least interesting policies. From a biomass point of view it is interesting as total biomass levels are highest in this case. Ecological value of the closed areas, however, is not extraordinary compared to that of the other scenarios especially because a large part of the patches that are interesting from an ecological value point of view are opened.

The effect of the ecological value, $p_{i\tau}^{M}$, is clear. The lower the value, the less patches will be closed and vice-versa. For all patches, there is a switching point for the ecological value of biomass after which protecting a patch gives higher ecological returns than the fisheries returns that could be earned if the patches were not protected. If the policy constraints allow for it, especially the smaller hotspot areas will be closed already at lower ecological values than the larger ones as fisheries revenues in the larger hotspots are substantial. The alternative patches closed already at low ecological values are the smaller and more remote patches and those not directly connected to a hotspot. This again demonstrates the importance of travel costs and the restocking effect of closed patches on the bordering patches. Especially closing patches bordering closed hotspots would result in a large potential loss of fisheries revenues. In this report, a description of the temporal effects of the different policies, i.e. the path of biomass and fisheries developments, as well as a sensitivity analysis to analyze the effect of parameter changes has not been described. For that we refer to Ding (2005).

5 Conclusions

In this paper, we have made a first step to design the decision support system (DSS) for marine biodiversity management in Europe. In our proposal, the DSS is constituted of environmental problem identification, stakeholder analysis and economic analysis procedures in order to take into account multidisciplinary regarding marine study and identify the optimal policy recommendations to the current maritime management and resources conservation strategies.

Within the framework of our DSS, we discussed the driving forces causing pressures on the North Sea and analyzed the respective impacts on both marine environment and human well-being by means of the DPSIR framework. Our analysis showed that the severest anthropogenic interventions on the marine ecosystem were from the various types and scales of fishery industries. Against this background, a bio-economic metapopulation model was setup to look for the trade-offs between the allocation of fishing stocks for sustaining marine ecosystem and the for the fishery economic activities, aiming at the maximization of the social welfare. This model worked as a fundamental component of the decision support system in order to provide relatively efficient policy measures regarding optimal spatial allocation of the marine resources, which we referred to fish stocks in the present paper. To simplify the problem, we proposed a simplified situation, within which two alternative marine activities (fisheries and marine conservation) would be selectively determined by DSS as policy recommendations. However, given possible policy constraints or objectives in a number of scenarios, it had been derived which parts of the North Sea should be opened or closed regarding their natural distributions of the fish stocks in order to reach optimal social welfare.

Even though the bio-economic metapopulation model presented in this paper is still very simplistic and only considers some of the activities taking place in the North Sea and the considerations taken into account in political decision making processes, it gives interesting results and shows how it can support in the decision making procedures. Against this background, it clearly shows the advantages and disadvantages in terms of a set of criteria for a number of policy alternatives. Moreover, it allows for the selection of cost-effective policy alternatives.

In practice, the results of the present study show that first, and not surprisingly, the four policy scenarios derived from the economic model results considered in analysis give lower net revenues than the global optimal solution. This indicates that the optimal economic strategy not necessarily reflects a feasible policy strategy. Political constraints or alternative considerations like giving more emphasis to the effects on either fishermen income or biodiversity conservation influence the choice of optimal strategy from a social welfare point of view. Second, by taking into account the ecological functions of an ecosystem into the model, such as the restocking function, we can that when closing partially some patches of the marine environment this policy option can have positive impacts in terms of both economic and ecological values. In all scenarios analyzed, spatial patterns are such that as much as possible closed patches neighbor an open patch. This would suggest that it is from an economic and ecological point of view better to have a number of small marine reserves instead of one large. In Ruijs and Janmaat (forthcoming) it has been discussed that the optimal size depends on the growth and dispersal rates within each patch. The third conclusion is that, for the parameter values chosen, biomass is best served by closing the hotspot areas but only if not all alternative patches are opened. Closing the rest would result in a large loss of biomass. The results show that there is a clear trade-off between ecology and economy, and that due to the dependence of the results on the values of the dispersal and growth rates, location of protected areas should be chosen wisely. More analysis is needed to really understand the impact of ecosystem differences on the effects of closing one area on biomass levels in the surrounding areas.

We need, however, to acknowledge that this study constitutes a first step of designing a decision support system for marine resource management policies, and the respective modeling is simplified. Nevertheless, the present road map can benefit from additional improvements, which can be part of follow-up research, and this way improve the reliability and operationalibility of the propose decision support system. We refer to, the enlargement of the proposed model specification. At the present analysis, it only focuses on one sector of the economy, models marine biodiversity and marine ecosystem functioning in a very simplified manner, and does not account for all activities taking place in the North Sea. Furthermore, a richer biological model with more species, the dependence of growth and dispersal on ecological characteristics and the interactions between the different species will result in more realistic results. Next, also the behavior of the fisheries sector can be studied in more detail. A social planner is considered who intends to maximize social welfare. However, the question is whether the social planner, i.e. the government, can force or stimulate fishermen to act according to this social optimum. For that reason, it would be good to pay more attention to modeling real fishermen behavior and the interaction between behavior of policy makers and fishermen (see e.g. Beattie et al., 2002).

In addition, experience with solving the current model shows that solving the spatial, dynamic optimization model becomes more difficult the more choices, periods or patches are to be considered. Already with 16 patches, 2 choice alternatives and 10 periods, solving the benchmark model on a normal desktop computer took about a day. Therefore, it is recommended that future extended versions of the model are not solved using GAMS but maybe using other software like MATLAB, C++, Fortran or other mathematical or programming languages. These programmes can handle larger scale models and may therefore be faster. Also for many of the parameters, the lack of data forced us to make very rough estimates or use data from other regions or situations. More precise estimates have to be made of especially the biological parameters like dispersal and growth rates but also of the ecological value of marine biodiversity and costs of harvesting and transport. Finally, if all costs, benefits and impacts of choices made can be monetarized, optimizing a social welfare function produces the socially optimal strategy. However, as monetarizing all relevant criteria may be difficult and as some of the valuation methods are controversial, especially in a policy making debate, a multi-criteria analysis or multi-objective programming exercise may be considered. In such types of analysis more criteria can be considered, which are weighed against each other to come to the most preferable marine policy. Criteria not only include economic, biological and ecological criteria but may also include cultural, sociological and political criteria. Such methods require intensive participation of decision makers and the consultation of many stakeholders in order to know which criteria are important and how to weigh them.

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Appendix: GAMS model code of the bioeconomic metapopulation model (global optimal)

```
Sets

 i   patches (based on the division of the DCS   /p1*p16/
 tau time periods   /2005*2015/
 tau1(tau) time periods   /2005*2014/
 Act types of activity   /F, M/
 run combination of prossible values for theta(i) /r1*r65536/;

Alias(i,j);
alias(i,j1,j2,j3,j4,j5,j6,j7);
alias(run,zz);


Scalars
 K       carrying capacity in million tones per unit of patch in patch i /1/
 x0      Initial biomass in million tones per unit of patch in patch i  /0.4/
 Rho     Discount rate of existent value at year Tau  /0.05/
 p       Market price of fish per tonne in Euros  /246.3/
 p1      Shadow price per tone biomass in Euros in the closure  /50/
 cX      Maintenance cost pertonne biomass per day in euros  /12.2/
 Omega   Harvesting costs per unit of effort in 1000 Euros /0.144/
 Phi     Marginal transportation costs of each effort moving every km from coastal line to patch
         i in 1000 Euros /0.00205/;

Parameter

$ontext
Fishery might disturb the composition of adult fish stocks and also the spwaning fish.
Therefore the catchability might be changed as one of the scenario analysis.
This might happen due to the improved technologies in fishery or some other directly control on
fleets.
$offtext ;

r(i)       Intrinsic growth rate in patch i
           /P1=0.43,P2=0.42,p3=0.46,p4=0.40,p5=0.53,p6=0.45,p7=0.49,p8=0.21,p9=0.20,p10=0.20,
           p11=0.19,p12=0.19,p13=0.28,p14=0.27,p15=0.27,p16=0.23/
q(Act)     Catchability
           /F = 0.06152 , M = 0/
DIS(i)     Distances of patches from the coastline in kilometres
           /p1=200,p2=120,p3=130,p4=95,p5=80,p6=110,p7=110,p8=240,p9=185,p10=180,p11=120,p12=120,
           p13=90,p14=90,p15=90,p16=100/
size(i)    size of the patch in units
           /p1=10, p2=2, p3=8, p4=7, p5=9, p6=1.5, p7=1.5, p8=1, p9=4, p10=9, p11=13,
           p12=9, p13=9, p14=10, p15=10, p16=9/
theta(i)
res(*);



table d(i,j)   dispersal rate of fish from patch i to patch j

     p1    p2    p3    p4    p5    p6    p7   p8    p9    p10   p11   p12   p13   p14   p15   p16
p1  -0.4   0     0     0     0     0     0    0.25  0.05  0.1   0     0     0     0     0     0
p2   0    -0.4   0.15  0     0     0     0    0.1   0     0.05  0.1   0     0     0     0     0
p3   0     0.15 -0.4   0     0     0     0    0     0.1   0.05  0.05  0.05  0     0     0     0
p4   0     0     0    -0.4   0     0     0    0     0     0     0.1   0.1   0.05  0.15  0     0
p5   0     0     0     0    -0.4   0.1   0.1  0     0     0     0     0     0.05  0.1   0.05  0
p6   0     0     0     0     0.1  -0.4   0    0     0     0     0     0     0     0     0.1   0.2
p7   0     0     0     0     0.1   0    -0.4  0     0     0     0     0.1   0.2   0     0     0
p8   0.25  0.1   0     0     0     0     0   -0.4   0.05  0     0     0     0     0     0     0
p9   0.05  0     0.1   0     0     0     0    0.05 -0.4   0.15  0     0.05  0     0     0     0
p10  0.1   0.05  0.05  0     0     0     0    0     0.15 -0.4   0.05  0     0     0     0     0
p11  0     0.1   0.05  0.1   0     0     0    0     0     0.05 -0.4   0.05  0     0.05  0     0
p12  0     0     0.05  0.1   0     0     0.1  0     0.05  0     0.05 -0.4   0.05  0     0     0
p13  0     0     0     0.05  0.05  0     0.2  0     0     0     0     0.05 -0.4   0.05  0     0
p14  0     0     0     0.15  0.1   0     0    0     0     0     0.05  0     0.05 -0.4   0.05  0
p15  0     0     0     0     0     0.05  0.1  0     0     0     0     0     0     0.05 -0.4   0.2
p16  0     0     0     0     0     0     0.2  0     0     0     0     0     0     0     0.2  -0.4


$ontext
*make the table with possible theta values
PARAMETERS
table_theta(*,*);
table_theta("1",I) = 0;
file scherm /'con'/;
```

```
LOOP (run,
Loop (zz,
     table_theta(run,I)$(ord(run) le round((ord(zz)*2**(ord(I)-1)),0)) = 1 - table_theta(run,i);
     );
     putclose scherm 'table row ', ord(run) /;
     );
$offtext

variables

 Obj                  Objective value
 E(i,tau)             Total fishing effort in patch i
 X(i,tau)             The existed size of Biomass in patch i
 FRev(i,tau1)         Fishery revenues
 MPB(i,tau1)          Marine protection benefits ;

Positive variables

 E(i,tau), X(i,tau)  ;

Equations

EQ_J1                Equation to calculate total revenues of fishery and eco-vale of MPAs
EQ_X(i,tau)          Equation to calculate existent biomass in patch i
EQ_XT(i,tau)         Equation to calculate biomass of fish stocks in the year 2005
EQ_FRev(i,tau1)      Equation to calculate Fishery revenues
Eq_MPB(i,tau1)       Equation to calculate Marine protection benefits  ;

EQ_J1..              Obj =E= sum((i,tau1),((p*q('F')*E(i,tau1)*X(i,tau1)*size(i)- omega*E(i,tau1)
                     – phi*E(i,tau1)*DIS(i))*theta(i) + (p1*X(i,tau1)
                     – cX*X(i,tau1))*size(i)*(1-theta(i)))/((1+Rho)**(ord(tau1)-1)));
EQ_FRev(i,tau1)..    FREV(i,tau1) =E= p*q('F')*E(i,tau1)*X(i,tau1)*size(i)- omega*E(i,tau1) –
                     phi*E(i,tau1)*DIS(i);
EQ_MPB(i,tau1)..     MPB(i,tau1) =E= (p1*X(i,tau1) - cX*X(i,tau1))*size(i);
EQ_X(i,tau)$tau1(tau)..
                     X(i,tau+1)-X(i,tau) =E= r(i)*(1-X(i,tau)/K)*X(i,tau) + sum(j,d(j,i)*X(j,tau))
                     - q('F')*E(i,tau)*X(i,tau);
EQ_XT(i,tau)$(ord(tau) eq card(tau))..     X(i,tau) =G= X0;

Model  Marine /All/;

X.fx(i,'2005')= X0;
E.l(i,tau) = 0;
x.l(i,tau+1) =  x.l(i,tau) + r(i)*(1-X.l(i,tau)/K)*X.l(i,tau) + sum(j,d(j,i)*X.l(j,tau));
x.up(i,tau) = K;


parameter
objOpt,  xOpt(i,tau),  thetaOpt(i),  eOpt(i,tau),FRevOpt(i,tau1),MPBOpt(i,tau1),  modstatus(run),
solstatus(run), runopt;
objOpt=0;


$offlisting
$offsymxref
option solprint=off;
option limrow=0;
option limcol=0;

file scherm /'con'/;

$include 'table_theta.inc';

loop(run,
     theta(i) = table_theta(run,i);
     X.fx(i,'2005')= X0;
     E.l(i,tau) = 0;
     x.l(i,tau+1) =  x.l(i,tau) + r(i)*(1-X.l(i,tau)/K)*X.l(i,tau) + sum(j,d(j,i)*X.l(j,tau));

     putclose scherm 'The current run is ', ord(run):8:0, '.'/;
     Solve  marine Using NLP maximizing Obj;

     if(marine.modelstat ne 2,
        res(run) = 1e+16*theta('p1') + 1e+15*theta('p2') + 1e+14*theta('p3') + 1e+13*theta('p4')
                + 1e+12*theta('p5') + 1e+11*theta('p6') + 1e+10*theta('p7') + 1e+9*theta('p8')
                + 1e+8*theta('p9') + 1e+7*theta('p10') + 1e+6*theta('p11') + 1e+5*theta('p12')
                + 1e+4*theta('p13') + 1e+3*theta('p14') + 1e+2*theta('p15') + 1e+1*theta('p16') ;
        );
     if((obj.l ge objOpt) AND (marine.modelstat eq 2),
                 runopt = ord(run);
                 objOpt = obj.l;
```

```
                 xOpt(i,tau) = x.l(i,tau);
                 eOpt(i,tau) = e.l(i,tau);
                 thetaOpt(i) = theta(i);
                 FRevOpt(i,tau1) = FRev.l(i,tau1);
                 MPBOpt(i,tau1) = MPB.l(i,tau1);
          );
);
putclose scherm 'Finished!'/;
display xOpt, eOpt, thetaOpt, objOpt, runopt, frevopt, mpbopt ,res;
```

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