Marine Protected Areas and commercial fisheries: the existing fishery in potential protected areas, and a modelling study of the impact of protected areas on North Sea Plaice

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Voorwoord / Preface

Dit rapport presenteert resultaten van onderzoek, dat in 2005/2006 is uitgevoerd. In het kader van de Europese Vogel en Habitat Richtlijnen dienen lidstaten te beschermen gebieden op zee aan te wijzen, wat mogelijk zou leiden tot beperkingen van visserijactiviteiten in deze gebieden. De vraag was, welke invloed dit zou hebben op de vis en visserij. In dit onderzoek is enerzijds een statische beschrijving opgesteld van de visserijinspanning en de vangsten in de voorgestelde gebieden, en is anderzijds een eerste analyse (simulatie-model) opgezet van het lange-termijn effect op migrerende vis (schol). Dit onderzoek werd eind 2006 afgerond met een concept-rapport.

Door externe omstandigheden is het concept-rapport sindsdien blijven liggen. De gepresenteerde informatie verouderde, de analyse werd ingehaald, en het project kon niet worden afgerond. Begin 2009 was daarmee een situatie ontstaan, waarbij een keuze gemaakt moest worden: ofwel de informatie moest worden bijgewerkt met recente gegevens en het gepresenteerde model in verband gebracht met recentere analyses, danwel de *status quo* moest worden geaccepteerd, en een verouderend rapport worden gepubliceerd.

Inmiddels zijn Natura2000 gebieden op de Noordzee aangemeld, en zijn verdere voorstellen in voorbereiding. De visserij heeft zich verder ontwikkeld, en de inzichten in de biologie van de vis zijn toegenomen. Actualisering van het gepresenteerde onderzoek, gebruikmakend van de meest recente gegevens, zou ongetwijfeld alle uitkomsten in detail kunnen veranderen, maar wij schatten in dat de grote lijnen onveranderd blijven. Daarom is de keuze gemaakt om dit rapport marginaal bij te werken, mede op basis van commentaar van een aantal stakeholders en de opdrachtgever, en nu te publiceren. Waar nodig, zijn misverstanden uitgesloten door expliciet aan te geven op welke jaren de gegevens betrekking hebben.

In het rapport wordt een aantal aanbevelingen gegeven voor verder onderzoek. Ons inziens kan beter daarin worden geïnvesteerd, dan in bijwerking van het huidige rapport met marginaal afwijkende gegevens.

This report presents the results of a research project conducted in 2005/2006. In response to the European Bird and Habitat Directives, Member States had to propose Marine Protected Areas, which could lead to restrictions on fishing activities. The question was raised whether this would influence the fish and fishery.

This research project developed a static description of fishing effort and catches in the proposed areas, and started an analysis (simulation model) of long-term effects of protected areas on migrating species (Plaice). This project resulted in a draft report at the end of 2006.

Due to external circumstances, the draft report has not been finalised. The presented information outdated, newer analyses passed the presented model, and the project could not be closed. Early 2009, a decision had to be made whether to update the information and relate the model to its newer rivals, or to accept the status quo and publish an ageing report.

In the mean time, Marine Protected Areas have been assigned, and new proposals are being developed. Updating the research using most recent data will undoubtedly change all result to some degree, but we expect this to have a minor influence on our conclusions. Therefore, we decided to update the text only marginally, and to publish the report. Where needed, the time frame has been made explicit, and data years have been indicated.

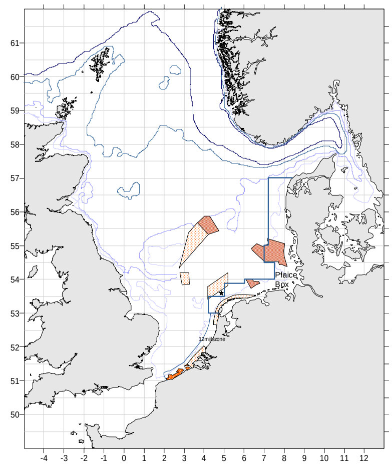
This report presents recommendations for further research. To our opinion, these recommendations should be prioritised over updating this report on the basis of marginally deviating data.

Uitgebreide Samenvatting

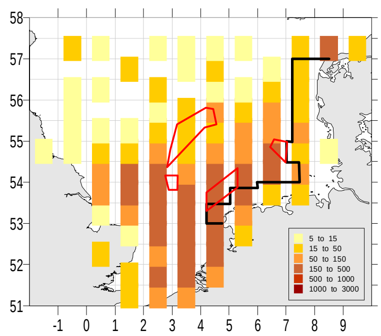
Beschermde Gebieden in Zee (Marine Protected Areas, MPAs) beogen het milieu te beschermen. Beschermde Gebieden zijn daarbij vooral gericht op de bescherming van specifieke organismen (meestal niet vis) en habitats, maar zij hebben ook gevolgen voor de vis en de visserij. De in dit rapport beschreven studie is erop gericht deze gevolgen van Beschermde Gebieden voor de vis en visserij te analyseren. Dit onderzoek is in 2006 afgerond, maar door omstandigheden is publicatie tot 2009 vertraagd.

De Europese wetgeving voorziet momenteel (2006) nog niet in de aanwijzing van Beschermde Gebieden in Zee. De lidstaten hebben voorstellen gedaan voor Beschermde Gebieden onder de Vogel en Habitat Richtlijnen. Nederland heeft hiertoe vijf gebieden geselecteerd (zie Figuur 1 hierboven): twee gebieden in de kustwateren binnen het 12 nm gebied met een diepte < 20 m, twee geïsoleerde gebieden met een zand- resp. steenslag-bodem, en één gebied rond het Friese Front. De keuze van deze gebieden sluit niet helemaal aan bij de bestaande regelgeving voor de visserij in de Schol-box: tussen de te beschermen gebieden en de Schol-box ligt een kleine driehoek, die vrijelijk mag worden bevist. Wij verwachten dat het verkeer van vissersschepen door de Beschermde Gebieden op weg naar deze vrije driehoek grote problemen zal geven voor controle en handhaving.

Analyse van de beschikbare informatie over visserij-inspanning en vangsten (zie Figuur 2 hierboven en Tabel 1 hieronder) wijst erop dat de te beschermen gebieden een beperkte betekenis voor de Nederlandse visserij hebben. Voor de twee belangrijkste takken van de Nederlandse visserij (boomkor en bordentrawl) wordt een gebied van ca. 9% van het totale visgebied gesloten. De te beschermen gebieden liggen niet op de traditionele visgronden, en worden ook niet als kinderkamers of specifieke opgroeigebieden van de beviste soorten gekenmerkt. De uitwisseling tussen de te beschermen gebieden en de omliggende gebieden is groot. Beperking van de visserij in deze gebieden (mocht daartoe besloten worden) zal dan ook niet leiden tot een substantieel verlies van vangsten.



Figuur 1 *De voorgestelde Beschermde Gebieden in de Noordzee.*

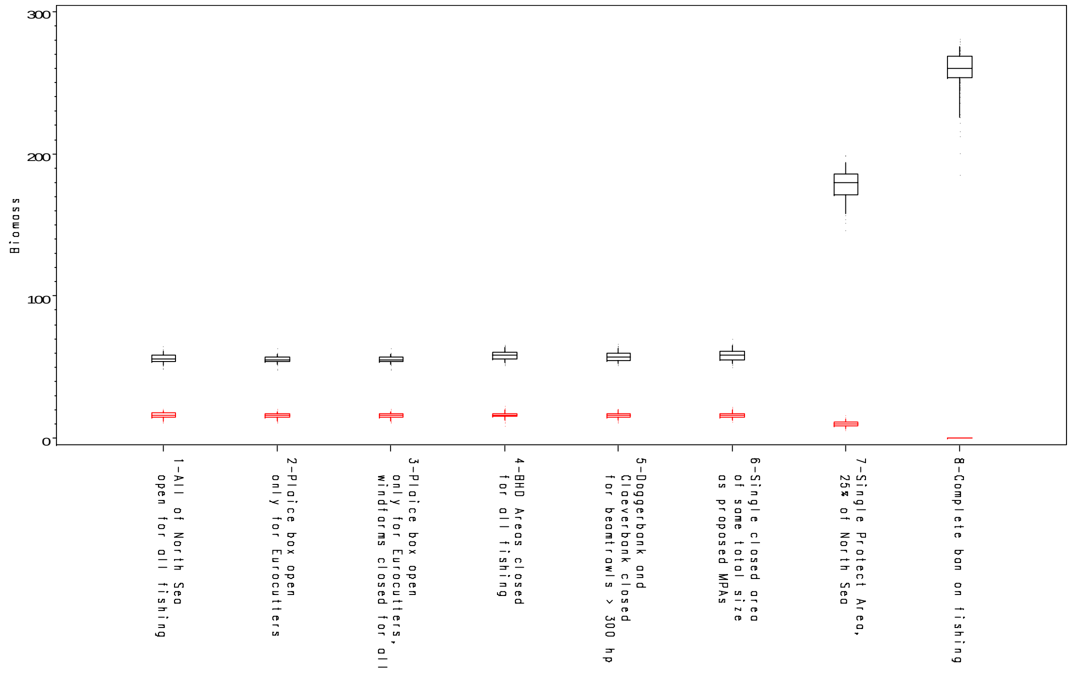


Figuur 2 *De verspreiding van de visserij-inspanning (visuren) van de Nederlandse vloot.*

Tabel 1 *Procentuele verdeling van de huidige visserij-inspanning (links) en vangsten (rechts) in de voorgestelde Beschermde Gebieden.*

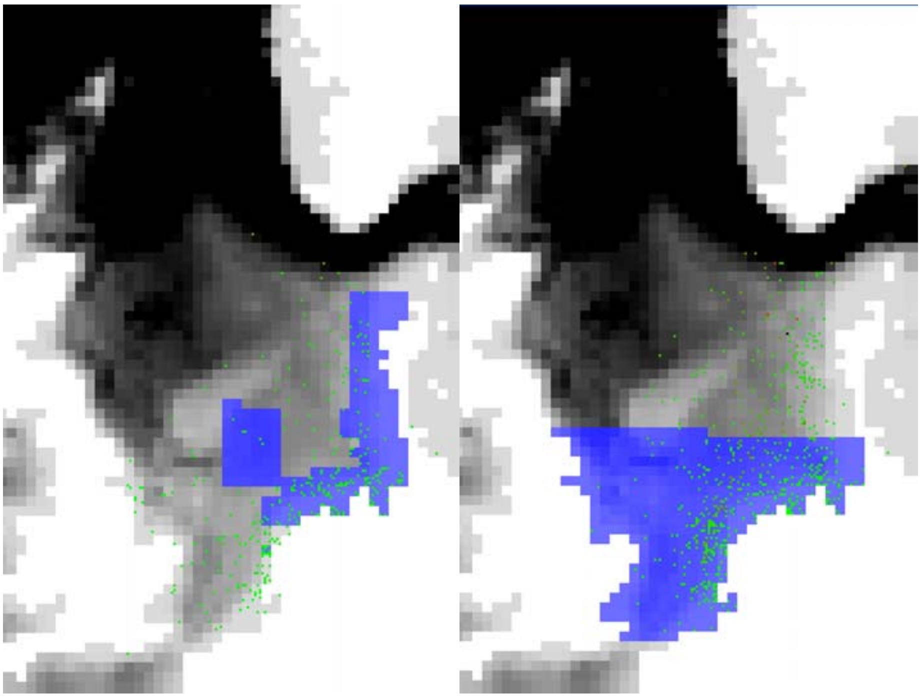
	Visserij-inspanning			**Vangsten**							
	Boomkor <300hp	Boomkor >300hp	Totaal	Schol		Tong		Tarbot & Griet		Schar	
				<27cm	>27cm	<24cm	>24cm	<30cm	>30cm	<24cm	>24cm
Doggerbank	0	1	1	1	2	0	0	0	0	2	1
Claeverbank	1	0	0	1	1	0	0	0	1	0	0
Friese Front	0	7	5	4	3	2	3	1	3	2	2
Sylt Outer Reef	1	1	1	2	5	15	12	6	1	8	7
Borkum Stones	1	0	0	2	0	1	1	2	1	0	0
Totaal	3	9	7	9	12	18	17	9	5	13	12

In dit rapport ontwikkelen we een model voor de analyse van de interactie tussen voorgestelde Beschermde Gebieden en de vis en visserij. Dit model behoort tot de groep van zogenaamde Individueel Gebaseerde Modellen, waarin processen worden beschreven zoals die zich voordoen voor een individuele vis (groei, rijping, sterfte, migratie), waarna de gevolgen voor de gehele vispopulaties afgeleid worden uit de som der individuen. De resultaten geven aan dat de voorgestelde Beschermde Gebieden slechts een heel kleine invloed zullen hebben op migrerende vissen, zoals schol, omdat elke vis die bij toeval het beschermde gebied verlaat, alsnog ten prooi valt aan de visserij. Pas een veel groter beschermd gebied kan tot een zichtbaar effect leiden.



Figuur 3 *Vergelijking van 8 mogelijke scenario's voor gesloten gebieden (van geen, tot een aanzienlijk gebied of zelfs een totale sluiting van de visserij). De verticale as geeft de biomassa weer, van het bestand (zwart, boven) en de vangst (rood, onder), in arbitraire eenheden.*

In dit model wordt geen rekening gehouden met veranderingen in gedrag van de vissers, als gevolg van de gebiedsbescherming en de veranderde verdeling en samenstelling van de vis. Het lijkt waarschijnlijk, dat een mogelijke aanpassing van het gedrag van de vissers het mogelijke effect van Beschermde Gebieden alleen nog maar verder zal verkleinen. Neveneffecten (bijvangsten, discards, bodemberoering) kunnen echter wel sterk veranderen. Daarom bevelen we aan een complexer model, waarin ook het gedrag van de vissers wordt gemodelleerd, op te stellen.
De voorgenomen aanwijzing van Beschermde Gebieden is niet gericht op het beheer van de visserij en de visstand, en de hier gepresenteerde resultaten geven aan dat ook slechts kleine effecten te verwachten zijn. Grotere gesloten gebieden zouden wel betekenis kunnen hebben voor het visserijbeheer, als aanvulling op of vervanging van bestaande beheersinstrumenten, waaronder quota en inspanningsbeperkingen. Als het gebruik van gesloten gebieden wordt overwogen als instrument in het visserijbeheer (en niet alleen ter bescherming van het milieu), dan bevelen wij een verdere analyse aan, waarin de effecten van gesloten gebieden en andere visserijbeheersmaatregelen kwantitatief worden vergeleken



Figuur 4 *De ruimtelijke verdeling van de vis in het model voor de Noordzee schol, bij een beperkt gesloten gebied (links - een gebied zo groot als de huidige voorstellen, maar in dit geval verenigd tot één aaneengesloten gebied), in vergelijking tot de verdeling bij een groot gesloten gebied (rechts als voorbeeld: 25% van de Noordzee gesloten). Het beperkte gebied heeft nauwelijks een dichtere visstand tot gevolg, het grote gebied wel. (Blauw=beschermd gebied, groene stipjes: individuele vissen in het model).*

Bij aanvang van dit onderzoek zijn door de opdrachtgever de volgende vragen gesteld:

- Wat is het belang van de reeds aangewezen gesloten/beschermde gebieden voor de verschillende typen visserij? Hoeveel wordt er ter plekke relatief gezien geoogst van de belangrijkste doelsoorten en kan deze oogst ook elders gerealiseerd worden?

  De voorgestelde gebieden omvatten max. 9% van de Nederlandse visserij (2001-2005), en hierin worden 5-17% van de vangsten gemaakt, afhankelijk van de soort. Zie Tabel 1.

- Welke uitwerking hebben beschermde gebieden op de totale populatie van de verschillende doelsoorten (o.a. schol, tong, kabeljauw)?

  De voorgestelde gebieden hebben waarschijnlijk een minimale uitwerking op de visbestanden en de vangsten, omdat zij relatief klein zijn t.o.v. de door de individuele vissen gefrequenteerde gebieden. Op grond van de analyse in het gepresenteerde model zijn noemenswaardige effecten op de visstand en visserij te verwachten bij een veel groter beschermd gebied (bijv. 25% van de Noordzee; zie Figuur 4 voor schol).

- Hoe ontwikkelt de visserijdruk als gevolg hiervan?

  Op grond van de analyse in het gepresenteerde model, vallen minimale effecten te verwachten, omdat de voorgestelde beschermde gebieden maar een kleine omvang hebben. Maar het model houdt geen rekening met veranderingen in het gedrag van de vissers. Integratie van ons model, met een ander, reeds bestaand model over het gedrag van vissers, wordt aanbevolen.

- Wat zijn gevolgen op overgebleven gebieden m.b.t. ecosysteem en visstand?

  Gezien de kleine omvang van de voorgestelde beschermde gebieden, valt een minimaal effect te verwachten. Voor migrerende soorten zijn de voorgestelde gebieden te klein; sessiele organismen en vissen met beperkte actieradius zullen zich binnen de beschermde gebieden mogelijk kunnen herstellen, maar zullen in de overgebleven gebieden weer aan oorspronkelijke effecten van visserij bloot staan. Omdat de uitwisseling beperkt is, valt er in de overgebleven gebieden slechts een zeer beperkt effect van het herstel binnen de Beschermde Gebieden te verwachten. Zie echter ook de discussie over het gedrag van vissers, het punt hierboven.

Summary

This report describes the results of a study completed in 2006; due to external circumstances, publication has been delayed until 2009.
Marine Protected Areas (MPAs) are a tool for environmental protection, directed at specific species (not often fish) or habitats, having a side-effect on fish and fishing. The objective of the current study was to analyse the impact of MPAs on fish and fishing.

Marine Protected Areas have not yet been formally established in the North Sea by EU legislation yet. However, member states are under the obligation to propose areas that qualify for protection under the Bird and Habitat directives in 2006. The Dutch government has selected five potential protected areas: two areas within the 20 m depth zone, within the 12 nm limit, two isolated offshore areas (sandbank and gravel) and one offshore frontal zone, representing approx. 20% of the Dutch Exclusive Economic Zone. Surprisingly, the proposed protected areas are not tuned to existing regulations regarding the Plaice Box: between the proposed protected areas and the Plaice Box, a small triangle is left open as a free fishing zone. We expect that fishing vessels crossing the protected areas to fish this free zone will jeopardise the enforcement of the area protection.

For most Dutch fisheries, the proposed protected areas appear to be of relatively little importance. For the two most important fisheries, the large beam trawlers and the otter trawlers, they may cause a loss of up to 9% of the potential fishing area. The overall picture is that the protected areas are not situated in areas of particular interest and are also not favoured by either juvenile or adult flatfish, while the expected exchange between the protected and open areas is large. Therefore, the potential loss of catch possibilities appears to be very limited.

To analyse the interaction between area protection and fisheries, we developed a model for the long term response of fish stocks to MPAs, including the knock-on effect on fishing. The model belongs to the class of Individual Based Models IBMs. Characteristics of individual fish (growth, maturation, migration) were modelled, and emergent properties at the population level were determined by the sum of all individuals. The model indicates, that MPAs will have little effect on migrating species such as North Sea Plaice, since the fish will accidentally leave the protected area during their life and then become vulnerable to fishing. Only MPAs of considerable size (e.g. 25% of the total North Sea) can be expected to have a significant effect.

Our model disregards the response of fishers to area closures and to the altered composition and distribution of the fish. A more complex model, including the effect of fishers to area closures, will show less effects of MPAs on commercial fish stocks and fishing yields, but side effects of by-catches, discards and bottom damage may differ substantially. We therefore recommend to extend the current model, to include potential behavioural changes of fishers.

Currently proposed area protection is not primarily intended to contribute to fisheries management, and our assessment and model indicate that little effect of the currently proposed areas is expected. However, larger area closures may contribute or replace existing fisheries management tools, including quota management and effort regulation. If the installation of MPAs is to be considered within the framework of fisheries management, we recommend further analysis of our model, to compare the quantitative effect of MPAs to that of other fisheries management measures.

(The Summary in Dutch gives a more elaborate account of results, as presented in English in the main report)

1 Introduction

Fisheries have been carried out on the North Sea since time immemorial, and fishers have been the dominant users. In recent decades, the number of other uses of the North Sea is continuously increasing, and an increasing number of these other uses is incompatible with fisheries for various reasons. For example, fisheries are excluded from wind farms and around oil platforms for reasons of safety. In addition, several areas with special ecological features are selected to be designated by European countries as protected areas in accordance with the Birds and/or Habitats Directives. In the Integrated Management Plan for the North Sea 2015 (IMPNS 2015) several areas are selected to be designated by The Netherlands as protected areas. Research within the context of IMPNS 2015 showed that all these areas meet the criteria of both the Birds and/or Habitats Directives and the OSPAR Convention (Lindeboom et al. 2005). Each of those protected areas is selected for different reasons and management plans for each area will differ accordingly and may include a reduction of commercial fishing effort. If the management plan for a protected area includes a local reduction of fishing effort, this may be experienced by the fishery as a threat, even though the effort originally carried out in the protected area can be reallocated elsewhere. Potential negative effects of (partial) area closure to the fishery are dependent on the relative importance of the area to the fishery and on whether other, unprotected areas will compensate for the local reduction in catch.

Protected areas are a tool for environmental protection, directed at specific species or habitats. Area closure may also act as a positive tool for fisheries management by exhibiting some degree of protection to commercial fish stocks that suffer from overexploitation. Although a whole range of potential benefits of protected areas to commercial fish stocks has been identified, e.g., stock recovery and more predictable and higher catches (PROTECT 2006), little empirical evidence exists to demonstrate such effects. A review about the effects of several existing Northern European protected areas (including the Plaice Box and the Cod Box) and one North American protected area in view of fisheries management has been compiled as part of EU-project PROTECT. This review concludes that most of the existing protected areas in the North Sea have had little success in reaching their management objectives. In most cases, it is difficult or impossible to separate effects of management measures from natural variability during the lifespan of the protected areas (PROTECT 2006). However, a variety of groundfish species are recovering in the North American protected area as a result of the large-scale year-round closure of the areas for more than a decade.

Closing an area to fishery undoubtedly has a local effect on fish and other organisms. This effect may quickly reduce to zero when the extra fish produced is harvested when leaving the protected area. Various authors list one or a number of factors that determine the positive effect of protected areas (e.g., Corten 1990, Holland 2000, FSBI 2001, Daan in prep.). The main factors can be grouped into three issues: characteristics of the protected areas (size, location, protection level), of the fish (spatial and temporal dynamics) and of the fishery (spatial and temporal patterns). This means that the smaller or the more fragmented closed areas are, the higher the chance that a fish will cross the boundary, and the less the effect of protection. Also, the more motile a fish, the less it will benefit from a protected area. And the higher the exploitation rate on a target species, especially in a protected area, the larger the protection. In practice, the benefits of closed areas will usually be very difficult to measure in the sea against the large natural variation seen in fish stocks (Horwood et al. 1998).

In this report, we provide an overview of current proposals for Protected Areas in the North Sea, assess what immediate impact protecting these areas will have (immediate, since this does not consider knock-on effects, through restoration of the fish stocks) and present a model study, in which further effect of protected areas is simulated for North Sea Plaice. Developing this model, we address the following questions related to management of protected areas:

1) What is the effect of protected areas on the populations of various target species?
2) What surface area is required to achieve a reasonable protection?
3) Where should the protected areas be located?

It is impossible to judge the combined net effect of fish dynamics, harvesting and size and fragmentation of protected areas without proper quantification. A simulation model enables the exploration of these issues and their consequences for the dynamics of fish populations. Such a model provides reference points against which system dynamics can be gauged.

Our model belongs to the class of individual-based models (IBM), i.e., models that are based on assumptions about key processes driving behaviour (movement) of individual fish, while exploring emerging effects at the population level. This allows us to produce patterns of distribution of fish in both space and time. Superimposing distribution patterns of fishing effort on those of fish determines local fishing mortality F. These two – spatially distributed – factors (numbers of fish occurring somewhere and fishery mortality F) suffice to infer temporal variation in population size and population composition of the modelled species. We add a degree of realism to the model by using as much as possible real areas, real effort and effort distribution, and real behaviour. With such an individual-based model we are able to investigate qualitatively the effects of various management scenarios for protected areas on the modelled fish population and the modelled catch. Key aspects and processes of the model should comprise explicitly the spatial processes of migration and homing relative to the location of spawning, nursery areas and preferred habitats. To this end we need a good insight in the ecology of the selected species, based on field research. We selected Plaice *Pleuronectes platessa* as our model species, because of the extensive research carried out on this species, and because Plaice is one of the most important target species of the Dutch beam trawl fishery. The management scenarios examined cover a control, and realistic and extreme scenarios, ranging from all of the North Sea open to fisheries, through various (partial) closures (including Plaice Box, wind farms and protected areas), to an area that results in substantial positive effects on the target species and the fishery, and finally, a complete closure of all fishing activities

2 Marine Protected Areas in the North Sea

Protected areas have not yet been formally established in the North Sea by EU legislation. However, member states are obliged to propose areas that qualify for protection under the Bird and Habitat directives in 2006 and information on a few proposals is available (Figure 1).

The Dutch government has selected five potential protected areas (Figure 1a): two coastal areas within the 20m depth zone and the 12nm limit that qualify for the Bird directive; two isolated offshore areas representing an offshore sandbank habitat (Doggerbank) and a gravel habitat (Claeverbank) that qualify for the Habitat directive; and one offshore frontal area for which it is not entirely clear under which directive this could be designated. Although the areas are incorporated in the marine Management Policy Plan for 2015, they have not yet been formally proposed to the Commission of the European Communities (CEC). Also, other areas are still being considered.
The Federal Republic of Germany has identified six areas and reported those formally to the CEC (Figure 1b). They encompass three offshore areas under the Habitat directive: Doggerbank (directly adjoining the Dutch proposal), Sylt Outer Reef and Borkum Stones. The proposed special protected area under the Bird directive (Eastern German Bight) partly overlaps with the Sylt outer reef. Furthermore, a large area within territorial waters has been proposed under both directives.

Also for Belgium five areas have been selected, but these are largely situated within territorial waters (Figure 1c). No information is available for other EU countries around the North Sea.

In addition to the protected areas that will be designated under the Bird and Habitat directives, other EU legislation already exists that restricts fishing activities and thus effectively protects areas against impact. For the Dutch beam-trawl fishery, the Plaice Box[1] (Figure 2) is important in this respect and also the 12nm limit, because in these areas, beam trawlers of >300 hp are not allowed to fish since the early 1990s. Furthermore, small fishery exclusion zones of 500m have been established around oil and gas platforms for general safety reasons and newly established wind farms will also be largely closed for fishing activities. Although these areas are generally relatively small they do contribute to the protection of the marine environment and to the restrictions imposed on fishing.

Presently, it is by no means clear to what extent fisheries will be restricted within each of these protected areas, because this will depend on the ultimate management objectives and goals and these have not yet been formulated. In principle, an environmental impact assessment will have to be made for any new human activity planned in these areas, but existing activities may well escape this requirement. Moreover, management plans could allow specific types of fisheries, if they have no negative influence on the ecological values to be protected. However, with regard to protected areas under the Habitat directive, it would seem that fishing activities that disturb the bottom – and thereby the habitat – may be subjected to a critical evaluation. For the Bird directive, the situation is different, because that will depend on the species that need protective action. Fisheries tend to favour the important group of scavenging seabirds by producing an easily accessible food resource in the form of offal and discards, while negative interaction of most types of fisheries employed in the North Sea with many other species of seabirds appears to be limited or may not be resolved at a local scale (e.g. ensuring food availability for diving seabirds).

Eventually, legislation to exclude or restrict fisheries will have to be formulated within the Common Fisheries Policy rather than at the national level, because foreign fisheries can only be controlled at the level of the European Union. Taken overall, it is still highly uncertain to what extent management goals of the protected areas will interfere with the existing fisheries and whether these will be totally or partly prohibited. However, for the present evaluation we will assume that the worst-case scenario applies for the fishing industry: that all fishing will be prohibited

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[1] Plaice Box: EU Regulation 850/98 establishes a protected area in three parts:
a. the 12 nm coastal zone from 51ºN to 53ºN,
b. an area defined by its vertices (see Figure 2 in this report),
c. the 12 nm coastal zone from 57 ºN to Hirtshals lighthouse.
The wording "Plaice Box" does not appear in the Regulation. From the literature, it appears that only the area under b. is indicated by the name "Plaice Box". We adhere to this implicit definition: in our usage, the 12 nm coastal zone is not included in the Plaice Box proper, but treated separately.

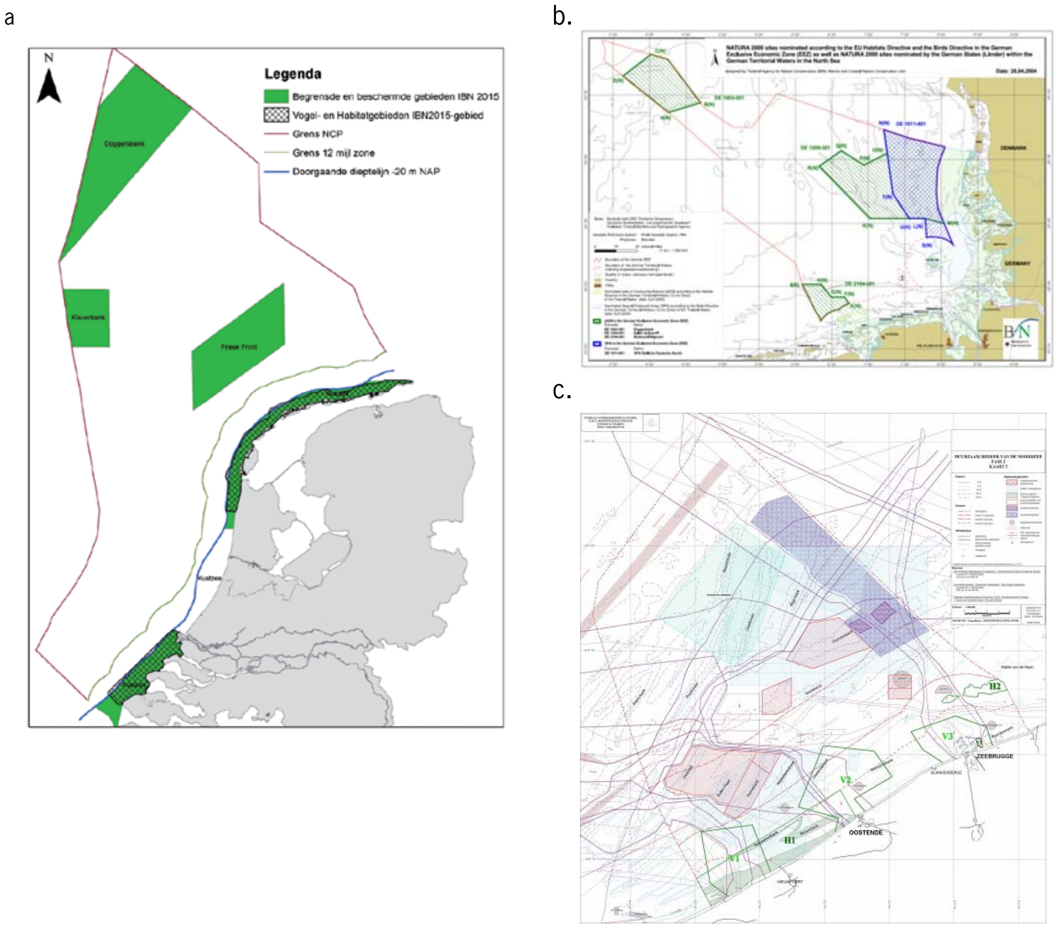

***Figure 1**. Proposed protected areas under the Bird and Habitat directives: a. the Netherlands; b. Federal Republic of Germany; c: Belgium.*

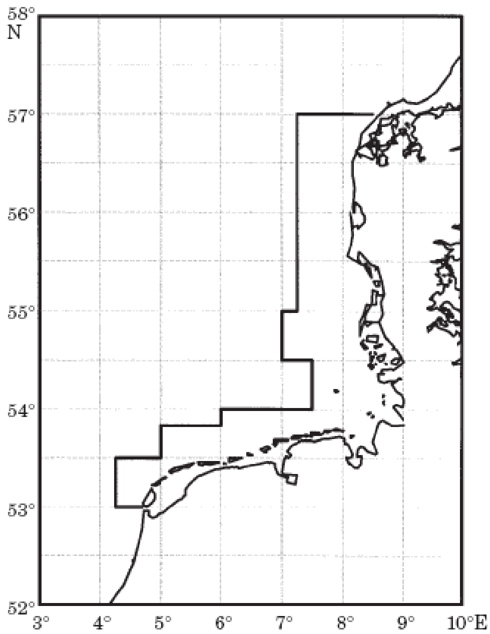

Figure 2. *Location of the Plaice Box*

The offshore protected areas under the Bird and Habitat directives proposed or selected by Germany and the Netherlands are relatively small and lie scattered over their respective Exlusive Economic Zone (EEZ) (Figure 3). For Germany, they encompass about 30% of the EEZ outside territorial waters (12nm), whereas this figure is approximately 20% for the Dutch part. In addition, the larger part of the German area within the 12nm has been assigned the status of protected area within the Bird and Habitat directive. For the Netherlands, this is also the case for the Wadden Sea and parts of the Delta, whereas about 2/3 of the coastal area within the 20m depth contour has now also been selected, comprising of 1/6 of the zone within 12nm. In Belgium, selected protected areas lie virtually exclusively within the 12nm limit, comprising approximately half of the total area.

The selected protected areas within territorial waters as well as the part of the offshore German protected areas overlapping with the Plaice Box are already partly protected, because fishing in these areas with beam trawler >300hp is not allowed. For these fisheries, their establishment is of no consequence.

Surprisingly, in selecting the Friese Front protected area, the Dutch government has not aimed to tune its limits to the existing Common Fisheries Policy regulations regarding the Plaice Box: the southeastern limit cuts the Plaice Box, so that two small triangles overlap, while another triangle is left open as a free fishing zone (Figure 3). Of course, we scientists are not responsible for enforcing cumbersome regulations, but we can assure that this is bound to cause enforcement problems!

Although 20-30% (approximately 5 statistical rectangles) protected area seems considerable, the total surface represents only half of the existing Plaice Box (ca 11 rectangles) while approximately two rectangles overlap. Functionally, this could mean an ‘extension’ of the Plaice Box for the beam trawl fleet >300hp by 25%. Given that evaluations of the existing Plaice Box have not been able to detect any positive effect on the survival of Plaice, or even any difference between the demersal fauna within and outside the box, a marginal increase of 25% is unlikely to show up as an improved survival of Plaice, particularly because the protected areas do not represent a contingent area but rather scattered and isolated plots. In general, large contingent protected areas are more effective for the protection of highly mobile animals like fish than a series of scattered small protected areas with the same total size (Daan 1996).

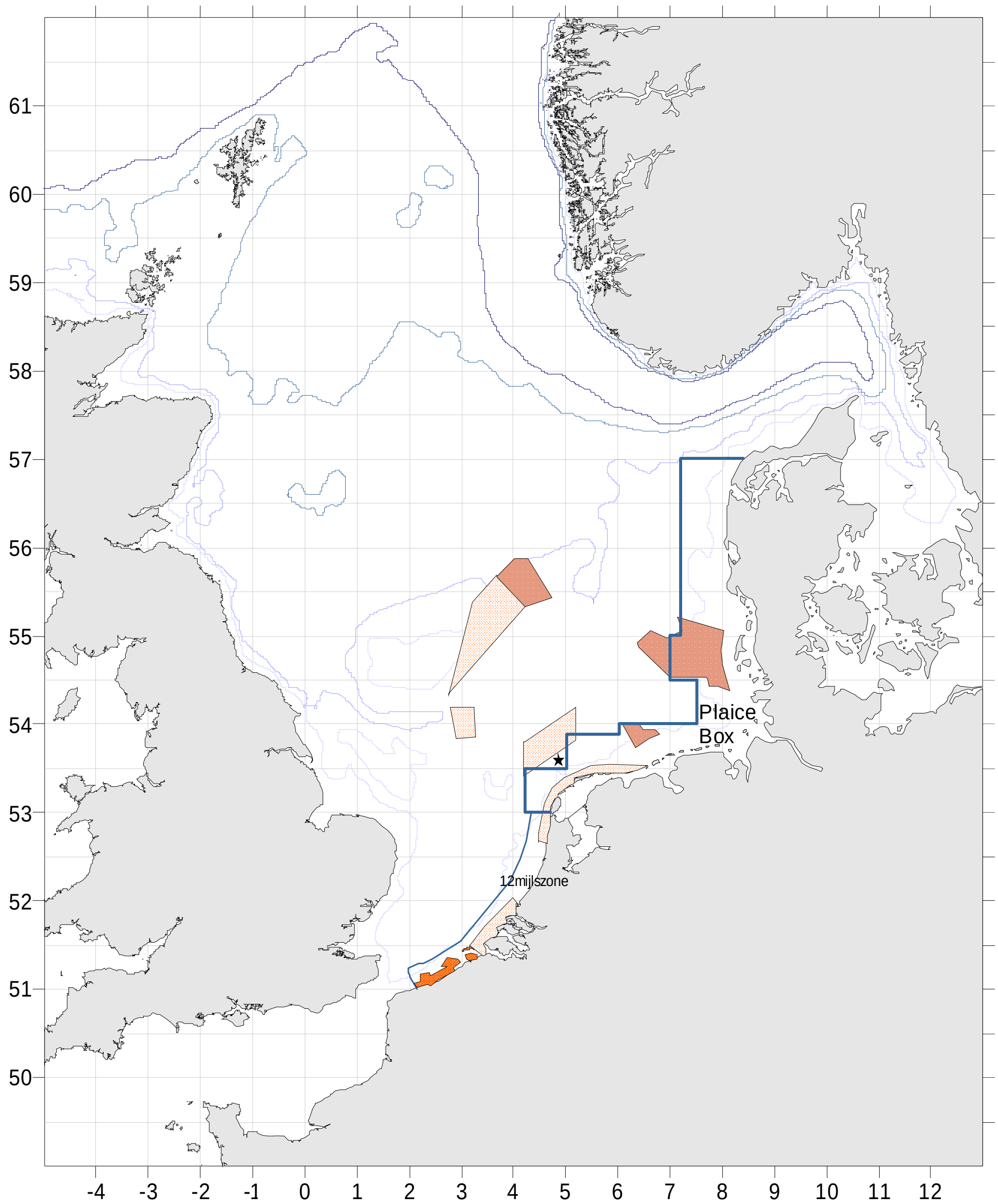

***Figure 3**. Location of all (proposed) protected areas*

3 Current use of protected areas by fisheries

The importance of marine protected areas for fisheries can be interpreted in different ways. Assuming that fisheries in these areas will be eliminated or restricted, they may cause a loss of fishing grounds, thereby having a negative influence on the potential catch. However, if commercial species are also effectively protected in these areas, they might enhance population size, thereby contributing to the goal of sustainable exploitation and increased catch rates in the remaining areas. Whether the net effect on the fisheries is positive or negative depends on several factors:

1. size of protected area relative to the free area;
2. present use of the protected area by the various fisheries;
3. relative densities of target species within and outside protected areas;
4. the rate of exchange of target species between a protected area and the free area.

Consequently, evaluating the importance of the designated protected areas for various types of fisheries is a complicated matter, particularly because all factors contributing to the impact on fisheries may vary from year to year and because protected areas may influence the behaviour of both the fish and the fishers in largely unknown ways.

Information about the spatial distribution of fishing effort is obviously an important factor in evaluating the importance of protected areas, because protection against fishing impact is a trivial matter if these areas are hardly visited by the fleets. Conversely, the loss of important fishing grounds becomes more important, if these areas have been more heavily exploited in the past, whereas also the potential protection offered to the stocks would increase. Spatial information on the recent effort distribution of the various international fleets is limited and therefore we have to restrict this evaluation to the Dutch fishery. This is not to say that they are not important for foreign fleets, but we simply do not know. The available information is derived from two sources: logbook entries of individual skippers (VIRIS) and satellite data recording actual positions of fishing vessels (Vessel Monitoring System – VMS).

The resolution of the VIRIS data is at the ICES statistical rectangle and this does not correspond to the borders of the MPA. However, for the offshore MPA a rough approximation can be made of which rectangles correspond to the MPA. However, the border of the inshore MPA has been drawn according to the 20m depth contour and there is no VIRIS information available that can be sensibly used to assign effort according to this depth contour. The VMS data have a much higher resolution, but good coverage is restricted to the large beam trawlers that are not allowed to fish within the 12 nm limit and all the inshore MPA are within this limit. Therefore, it is impossible to evaluate the importance of the inshore MPA for the Dutch fishery, except that it is of no relevance for the large beam trawl fleet. In the remainder of this chapter the inshore MPA are not being considered.

The assessment of the impact of protecting areas on the fishery in this chapter is based on information relating to the current (2001-2005) fishery. Installation of protected areas will restrict fishing, but may also protect the fish stocks. Increased protection of the currently (2001-2005) overexploited fish stocks may in turn support the fishery, that is: it may reduce the current (2001-2005) too high exploitation rate. In this chapter, the initial effects are described and the potential increase due to restoration of the fish stocks is not considered. In the following chapters, the potential effects of protecting areas in the restoration of the fish stocks will be considered, by means of a simulation study. This chapter has a higher degree of (realistic) detail, but analyses only immediate effects, while the model study is more theoretical, but focuses completely on long-term effects.

3.1 EU logbook

All skippers of EU fishing vessels are under the obligation to complete logbook forms, recording where they fish, the number of fishing hours, and the approximate catches kept on board, on a daily basis. Upon entry in the harbour after each fishing trip, these logbooks are collected by the Fisheries Inspection Service (AID), processed electronically, and entered into the VIRIS data base primarily for control and enforcement purposes. However, after removing the reference to specific vessels, the information is available for scientific analyses as well. Information about the number of days fishing and catches is available by statistical rectangles (1° longitude*0.5° latitude; approximately 30*30 nm) and by gear type. Because the borders of various protected areas do not coincide with degrees longitude or latitude, the information does not provide exact information as to how much effort has been allocated to those areas and only allow a crude comparison.

Figure 4 provides logbook information on the spatial effort distribution of Dutch vessels by gear type with an overlay of the protected areas:

a. Beam trawl: The beam trawl fishery is by far the most important activity of the Dutch fleet, which extends over most of the southern and central North Sea and regularly occurs in all areas identified as potential protected areas. Because extensive and more detailed VMS data exist for this fleet, more accurate information can be obtained from this system and the evaluation is delayed until the next section.
b. Snurrevaad: This gear is rarely used in coastal areas and no records are available from the offshore protected areas.
c. Fykes and pots: Use of fykes and pots is restricted to the Wadden Sea and Delta area.
d. Gill nets (wrecks): Most gill netting on fixed positions (mainly wrecks) is done off the Dutch coast, with some apparent overlap in the Friese Front protected area and none in the other offshore protected areas.
e. Gill nets (unspecified): This gear type includes drift netting and is used mainly in coastal areas in the Southern Bight. Our data contain no records frome protected areas.
f. Hook and line: This is another minor gear type that appears to have been used in the Friese Front protected area.
g. Otter trawl: This gear is still widely used over the southern and most of the central North Sea, including the areas identified as protected areas. However, fishing effort is low in the Doggerbank protected area, while the Friese Front protected area is frequently visited. Twinrigging has been included under this gear type in the past and only from 2006 onwards, specific information will become available.
h. Pelagic trawl: This gear is used in the herring fishery, which is apparently performed outside the protected areas.
i. Pair trawl (demersal): the demersal pair trawl fishery (largely targeted at whiting) covers a wide area, but hardly occurs within the protected areas, with the possible exception of the Claever bank.
j. Pair trawl (pelagic): the pelagic pair trawl fishery is aimed at herring and largely coincides with the pelagic trawl, outside the protected areas.
k. Shrimp trawl: shrimp fishing is largely restricted to the coastal zone, outside the offshore protected areas, but some fishing appears to be exercised on the Doggerbank where no shrimp resources have been reported as far as we know.
l. Trammel nets: This gear appears to be only used off the North Holland coast, outside the offshore protected areas.
m. Other unspecified gears: This mixed bag does not seem to exploit resources within the protected areas.

To quantify the approximate proportion of the total effort exercised within each protected area by gear, we have assumed that the rectangle data correspond to the protected areas as follows (weighing factor * ICES rectangle):

Doggerbank:	1.0	* 39F3	+
	0.5	* 38F3	+
	0.25	* 40F4	
Claeverbank:	0.125	* 36F2	+
	0.125	* 36F3	+
	0.125	* 37F2	+
	0.125	* 37F4	
Friese Front:	1.0	* 36F4	
Sylt Outer Reef:	0.5	* 38F6	

The results are shown in table 1. The overall effect of closing the protected areas for all gears would result in an average loss of fishing grounds of 7% compared with the recent performance of the fleets. Doggerbank and Sylt Outer Reef contribute 1% at maximum for individual gears and therefore seem to be of marginal interest to the Dutch fishery. Friese Front accounts for 5% or more for hook and line, beam trawl, otter trawl and pelagic pair trawl, whereas the Claeverbank accounts for up to 3% for the otter trawl and miscellaneous gears. Overall, the otter trawl would suffer most in terms of loss of traditional fishing grounds (9%), followed by beam trawl, hook and line and pelagic pair trawl. Although none of these percentages would suggest major losses for the industry, it should be noted that for the most important component of the Dutch fleet, the beam trawlers >300 hp, this loss has to be added to a much larger loss they already suffered through the establishment of the Plaice Box. Given the uncertainty about the actual distribution of effort within the coastal region, it is not possible to derive any indication of the importance of the protected areas proposed for the inshore waters within the 20m depth contour on the basis of the logbook information. Particularly the fykes and pots, shrimp trawl and trammel nets are concentrated in these areas. If their access to these protected areas will be prohibited, it seems likely that they will not be able to compensate for the losses of fishing grounds, since there are no off-shore areas where these fisheries can go to.

Table 1. *Average effort exercised by the Dutch fleet by gear type in the proposed offshore protected areas as a percentage of the total effort per gear type, based on logbook data, 2001-2005.*

	Doggerbank	Claeverbank	Friese Front	Sylt outer reef	***Total protected areas***
Beam trawl	1%	1%	5%	1%	7%
Danish seine	1%	0%	0%	0%	2%
Fykes and pots	0%	0%	0%	0%	0%
Gillnet (wrecks)	0%	0%	1%	0%	1%
Gillnet (unspecified)	0%	0%	3%	0%	3%
Hook and line	1%	0%	6%	0%	6%
Otter trawl	1%	3%	5%	0%	9%
Pelagic trawl	0%	2%	1%	0%	3%
Pair trawl (demersal)	0%	2%	1%	0%	4%
Pair trawl (pelagic)	0%	0%	5%	0%	5%
Shrimp trawl	1%	0%	0%	0%	1%
Trammel nets	0%	0%	0%	0%	0%
Miscellaneous	0%	3%	0%	0%	3%
Overall	1%	1%	4%	1%	7%

3.2 VMS data

Over the last decade, a large sample of the beam trawl fleet (particularly of vessels >300hp) has been equipped - in a joint project between IMARES and the industry - with 'black boxes', which record the actual position of the vessels at two-hour intervals based on satellite instrumentation. Originally, this programme served only scientific purposes. However, since 2005 these boxes have become obligatory for the entire cutter fleet. The data are primarily used for inspection services and are no longer automatically available for scientific analyses. Extensive data are only available for the beam trawl fleet targeting Sole and Plaice.

Satellite data inform us about the actual location of a vessel, but carry no direct information of their activity (fishing, floating to repair the gear or steaming). However, some indication of their activity can be derived from the speed at which they have moved between two subsequent recordings, because vessels typically fish at speeds of 5-7 Nm, whereas steaming (>8 Nm) or floating (<4 Nm) occurs at typically different speeds. These limits are of course only an indication, because a period of floating and steaming within a 2-hour interval may be interpreted as 'fishing'. Accepting a certain amount of fouling in the interpretation of the data, the maps of the distribution of vessels supposedly fishing provide a reasonable image of the actual fishing effort distribution (Figure 5). The map shows for instance a clear demarcation limit for the beam trawlers >300hp at the 12nm limit and the borders of the Plaice Box, although a few records line up in the direction of harbours. These should not be interpreted as trespassers, but rather for some reason these vessels have reduced their speed while steaming, for instance because of weather conditions. There is no reason to assume that misinterpretation of the data affects different regions differentially and therefore these records of fishing activity may be considered reliable, or at least the best available indication of the relative distribution of beam trawl effort for the two groups (<300hp and >300hp) within and outside the protected areas. Although the resolution allows exact calculations, here we have used the summed/averaged records by 1/9 of a statistical rectangle (20' longitude*10' latitude, *i.e.*, approximately 10*10nm) and used the subrectangles for which at least 50% lies within each protected area.

Table 2 summarizes the average contribution of the different protected areas to the total effort in fishing hours. The overall figures correspond closely with the information derived from the logbook data. However, the large beam trawlers appear to be fishing considerably more in the proposed protected areas than the Eurocutters, particularly so in the Friese Front protected area.

Table 2*. Average effort exercised by the Dutch beam trawl fleet in the proposed offshore protected areas as a percentage of the total effort, based on VMS data, 2001-2005.*

	BT < 300hp	BT > 300hp	***Total***
Doggerbank	0%	1%	1%
Claeverbank	1%	0%	0%
Friese Front	0%	7%	5%
Sylt Outer Reef	1%	1%	1%
Borkum Stones	1%	0%	0%
Total protected areas	3%	9%	7%

3.3 Conclusions on the distribution of fishing effort

For most Dutch fisheries, the proposed protected areas appear to be of relatively little importance. However, for the two most important fisheries, the large beam trawlers and the otter trawlers, they may cause a loss of traditional fishing grounds of up to 9%. This figure is considerably smaller than the percentage area protected within the Dutch (20%) and German EEZ (30%), but may well increase if Denmark and UK follow suit in assigning protected areas.

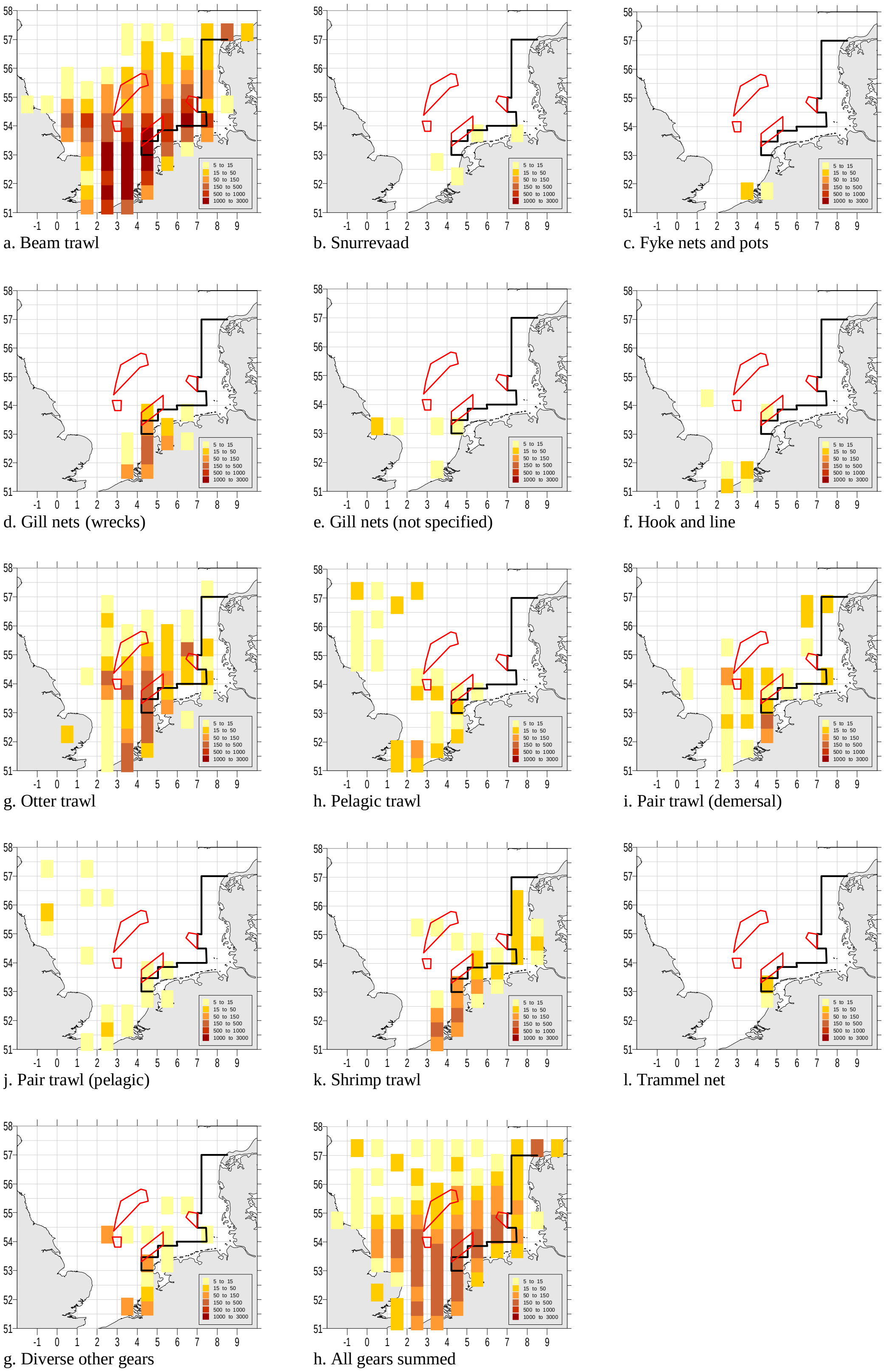

Figure 4*. Average numbers of hours fishing of Dutch vessels by gear type and statistical rectangle*

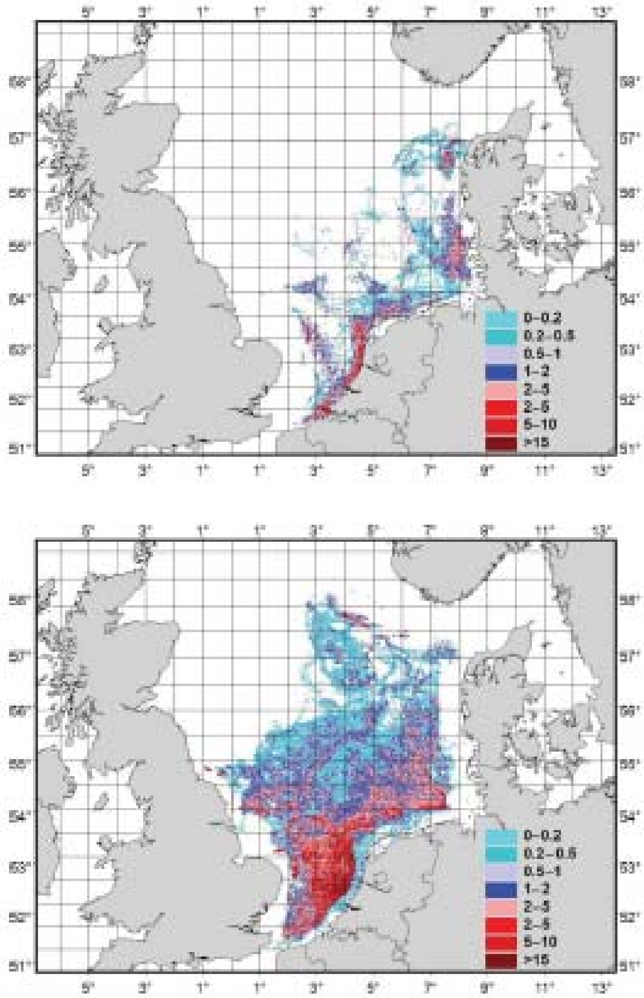

Figure 5. *Relative distribution of fishing effort of the Dutch beam trawl fleet based on VMS data: (top panel) <300hp; (bottom panel) >300hp*

3.4 Relative densities of target species within and outside protected areas

Given the size of the beam trawl fleet and the potential effect of the protected areas on catch rates in this fishery, we here concentrate on the two target species – Sole and Plaice – and some of the main bycatch species – Turbot, Brill and Dab. The logbook data only specify catches that are kept on board and do not include discards. Because the presence of juvenile fish is important for evaluating the protective effects, we have based the evaluation on research vessel data collected during the Beam Trawl Survey (BTS; 1985-2003). These allow the same level of resolution as available for the VMS registrations (10*10nm). For Plaice and Sole we distinguished marketable and unmarketable fish based on the legal minimum landing size (27 and 24 cm, respectively). For Turbot, Brill and Dab no legal minimum landing sizes exist in the Netherlands, but we used those for Belgium (30, 30, and 24 cm, respectively) as a practical approximation.

Figure 5 provides the distribution maps by species in relation to the location of the protected areas. Turbot and Brill have been combined into a single map, because they are relatively scarce and they have similar distributions. Overall, between 9% and 18% of the undersized fish is found within the protected areas, and the percentages for marketable vary from 5% to 17% (Table 3). However, the large majority of both size groups are found in the Sylt Outer Reef, which largely overlaps with the existing Plaice Box, which already provides protection against the beam trawl fleet >300hp. The other protected areas contribute very little to the total abundance of the various target species and their potential effect on stock protection will be negligible.

***Table 3**. Percentage of (un-)marketable fish by species (group) and protected area according to the BTS surveys in August, 1985-2003*

	Plaice		Sole		Turbot & Brill		***Dab***	
	<27	>27	<24	>24	<30	>30	<24	>24cm
Doggerbank	1%	2%	0%	0%	0%	0%	2%	1%
Claeverbank	1%	1%	0%	0%	0%	1%	0%	0%
Friese Front	4%	3%	2%	3%	1%	3%	2%	2%
Sylt Outer Reef	2%	5%	15%	12%	6%	1%	8%	7%
Borkum Stones	2%	0%	1%	1%	2%	1%	0%	0%
Total protected areas	9%	12%	18%	17%	9%	5%	13%	12%

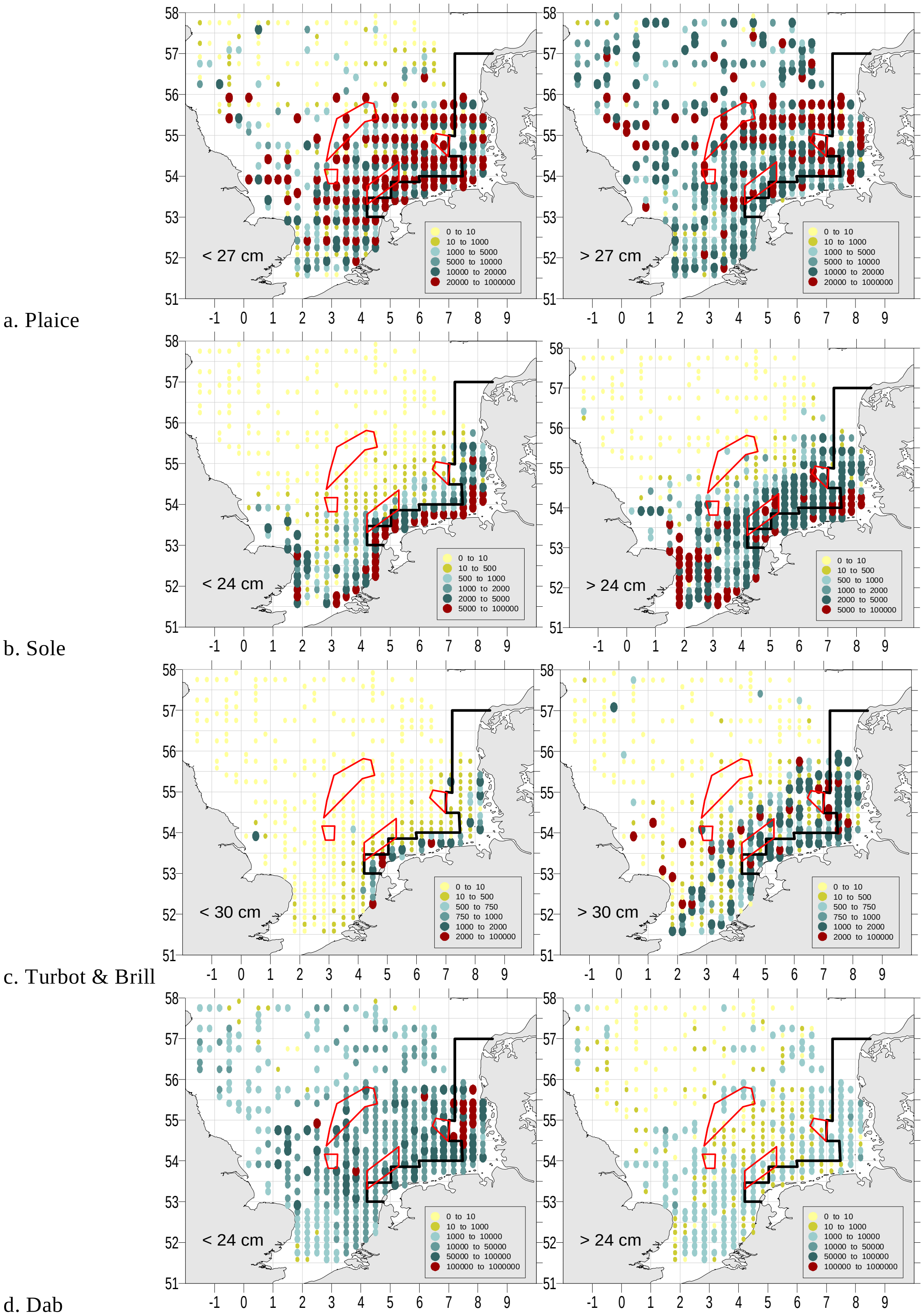

Figure 5*. Average catch rates of flatfish by species (group) according to BTS (1985-2003).*

3.5 Conclusions on the present use of protected areas

The overall picture emerging is that the protected areas are not situated in areas that are of particular interest to the various fleets and, with the exception of the Sylt Outer Reef, are also not favoured by either juvenile or adult flatfish, while the expected exchange between protected and open areas is large. Therefore, the potential loss of catch possibilities appears to be very limited. Likewise, the protective potential for commercial species is equally limited for exactly the same reasons. The only conclusion based on an expert judgement can be that the importance of these protected areas for the management of the Dutch fisheries is marginal. The two sides of the coin are thus that the protected areas may do little good for the stocks, but also do little harm to the fisheries.

The major uncertainty is how the fisheries will respond to closures. They obviously have to concentrate in the open areas, unless the closure is associated with a simultaneous effort reduction. If there is a small protective effect, the fishers may nullify this effect by concentrating along the borders of protected areas because of some continuous overflow. Such an effect is apparent from the effort distribution of the large beam trawl fleet along the Plaice Box. However, skippers may also decide to exploit other regions more intensively than they have done so far, thereby affecting other biota that may be in need of protection. This has been the case after the large-scale closure of Cod spawning grounds in 2001, when beam trawlers moved to the western North Sea where they caught much more rays than usual. Because of unpredictable human behaviour, some surprises may be expected.

A final point is enforcement. The extent and form of the protected areas as selected may complicate the enforcement, because trespassing may be difficult to detect. Even the VMS registrations can easily be fouled, because the two hour intervals would not guarantee that vessels have not been fishing through the protected areas. Particularly the definition of the Friese Front without taking into account the existing Plaice Box appears to represent a missed chance, because it leaves a small triangle open for large beam trawlers.

4 A model for migration of North Sea Plaice

4.1 The model

In this section, the general outline of the simulation model will be described, in non-technical language. Appendix 1 provides a full description of the model.

Conceptually, the model consists of three layers: a physical and a biological one, and the fishery on top. The physical layer represents the North Sea (including the Wadden Sea) as a rectangular grid. Each grid cell has relevant physical characteristics, such as mean depth, position, size and temperature. The biological layer contains Plaice, reacting to their physical environment. These Plaice spawn in designated areas (the spawning areas), that is: new animals are introduced at the start of each year in these grid cells, whereas the adults have to return to these areas during the spawning season. In their first year of life, young Plaice migrate towards nursery grounds (mainly the Wadden Sea). At the end of the first year, and in subsequent years, the Plaice migrate through the sea, while they grow in size, get older, undergo natural mortality, and are being fished. The migratory behaviour depends on depth preferences (that is: on depth of the grid cell where the fish resides, and on depth of the adjacent cells), the age of the fish, and a generalized migration pattern with a stochastic variation on swimming direction. Finally, the fishery, which is considered to be static too. Based on the actual fishing efforts (hours fishing per ICES square, as derived from VMS registrations) and an average fishing mortality as derived from ICES assessments, the partial fishing mortality for each square has been calculated. Apart from area closures (and proportional redistribution of fishing effort over the remaining area), the partial fishing mortality is kept fixed. Our implementation is based on discrete time steps of one week.

The model is individual based, that is: the characteristics of the individual fish are modelled. The emergent properties of the population are determined by the sum of all individuals, not by imposing trends on abundance and distribution on the collection of all individuals. Our implementation of the model is minimalistic, in the sense that we modelled the absolute minimum number of processes for an individual fish that may show potential effects of area protection on survival, distribution and fishing yield. In particular, dependence on food sources and mutual interactions between individuals have not been included, which contrasts with conventional Individual Based Models (Railsback and Grimm 2006). Since our objective is rather focused (analysis of effects of protected areas), we preferred a traceable and tractable minimalist model.

4.2 Management scenarios

In the initial phase, this model is used to simulate the natural distribution of Plaice under the current (2001-2005) fishing regime. Parameter values were derived from literature and the resulting distribution pattern compared to the actual distribution. Subsequently, a range of scenarios for protected areas was imposed, in which fishing was reduced or set to zero in protected areas and the corresponding fishing effort was redistributed over the remaining areas.

Control scenarios:

1. All of the North Sea open to all fisheries
2. Plaice Box only open to Eurocutters (18,200 nm^2)
3. Plaice Box only open to Eurocutters (18,200 nm^2) and Windfarms (2) closed to all fisheries (100 nm^2). This scenario most closely resembles the actual situation, before the establishment of protected areas under the Bird and Habitat Directive.

Experimental scenarios, additive to control scenario 3:

4. Protected areas (n=5) of Birds and Habitats Directives closed to all fisheries (5,000 nm^2)
5. Of these 5, only Doggerbank and Claeverbank closed for large beam trawls (2,600 nm^2)
6. One area of the same size as all protected areas together, closed to all fisheries (5,000 nm^2)
7. One area of a size of 25% of the North Sea closed to all fisheries (38,400 nm^2)
8. The whole North Sea closed to all fisheries (153,600 nm^2)

Each of the model scenarios was initiated at t=0 with a small number of Plaice reproducing at the spawning sites. Obviously, a small number of reproducing Plaice in an otherwise empty sea is not a realistic starting condition. Following this initiation, the model quickly converges to a stable annual fluctuation after some 600 time steps (weeks), characterising each scenario. Results will be presented for the full series starting at t=0, with the initial 600 weeks shaded.

A comparison of scenario results is presented below, in a Box-Whisker plot of the long-term averages (and variation) in abundance, fishing yield, and individual weight. Separate 'time series' describing the evolution in abundance, fishing yield, and individual weight for each of the scenarios is presented in Appendix 2, as well as a map of the spatial distribution

5 Model Results

Full details of the results for the scenarios (see section 4.2 above) are described in Appendix 2. Here, the comparison amongst scenarios is presented.

The first two scenarios (the whole North Sea open to fisheries respectively the Plaice Box closed for beam trawlers > 300 hp) effectively set the standard for the current conditions. The results obtained characterise the model assumptions, with parameters tuned to realistic values. The third scenario (Plaice Box only open to Eurocutters and Windfarms closed to all fisheries) adds another 100 nm^2 of closed area. Results closely resemble those of the first two scenarios (Figure 6), that is: closing the wind farm areas has a negligible effect on the simulation runs. The fourth scenario encompasses all proposed protected areas, with a total surface area of 5,000 nm^2. As for scenario 3, the effects on fish stock and fishery appear to be minimal, although a slight increase (3%) in total catch weight is found. Protecting an even smaller area, only Doggerbank and Cleaverbank (2,600 nm^2), thus has a negligible effect too, and results in a smaller (2.5%) increase in total catch weight. Replacing the proposed protected areas by a single continuous area of the same size (scenario 6) does not alter the results, indicating that the small size, and not the fragmentation of the protected areas determines the overall lack of response. In contrast to the previous two, this scenario does not show an increase in total catch weight; that is: the positive effects on the stock are counterbalanced by less efficiency in the fishing, which is due to the large protected area. Closing a substantial part of the North Sea (25%, scenario 7) does indeed have a considerable effect. Stock abundance increases by 50%, mean individual weight increases by 100%, and stock biomass increases by 200%. Since we situated this 25% closed area in the southern North Sea, where the Plaice fisheries are concentrated, the catch in numbers is reduced by 60%. The increased survival, however, results in a higher average weight, and total catch weight is only reduced by 40%. The final scenario, closing the whole North Sea for all fishing, obviously results in a recovery of the stock, abundance nearly doubling, and biomass increasing nearly five-fold, but no catch remains.

Overall, all scenarios show nearly identical results, except for the last two, based on protected areas of much larger size then the current proposals.

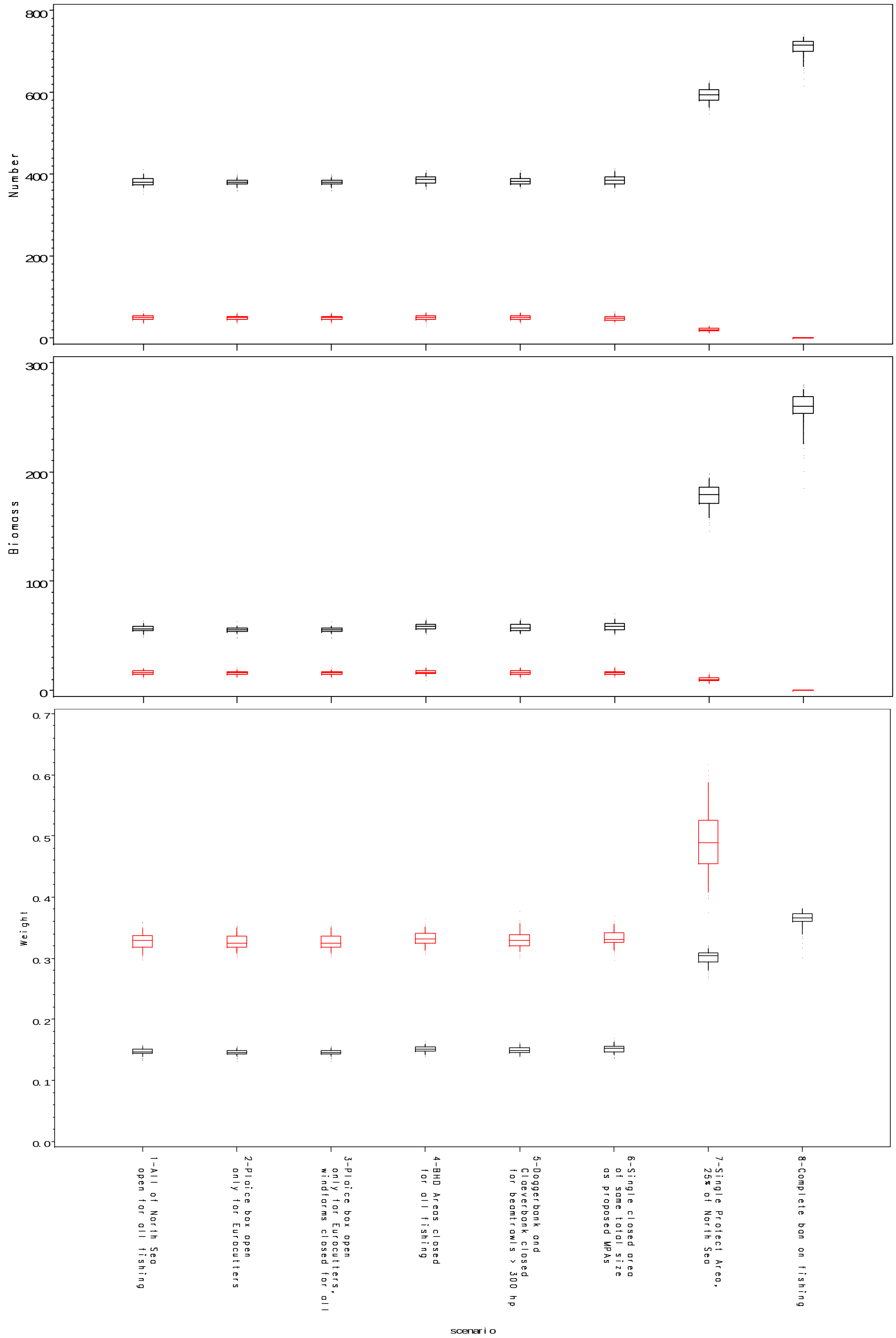

Figure 6 *Comparison of model output for stock (black boxes) and catch (red boxes) in terms of numbers (top panel), weights (middle panel) and weight of individual fish (bottom panel) for the 8 scenarios described in section 4.2 . Note that in scenario 8 all fishing is prohibited (catch is zero), and no average weight in the catch can be calculated. All vertical axes are on an arbitrary scale.*

6 Conclusions, discussion and recommendations

Marine Protected Areas (MPAs) are a tool for environmental protection, directed at specific species (not often fish) or habitats, having a side-effect on fish and fishing. The objective of the current study was to analyse the impact of MPAs on fish and fishing. To this end, we first analysed actual fishing effort and catches in currently foreseen MPAs in the Dutch part of the North Sea, disregarding the long-term response of the fish stock and fisheries to area closures. This led to the conclusion, that the currently proposed MPAs might have a small effect on total fishing effort and total yield. Additionally, we developed a model for the long term response of fish stocks to MPAs, including the knock-on effect on fishing, but disregarding the response of the fishers to area closures and to the altered composition and distribution of the fish. This led to the conclusion, that MPAs will have little effect on migrating species such as North Sea Plaice, since the fish will accidentally leave the protected area during their life and then become vulnerable to fishing. Only MPAs of considerable size (in the order of 25% of the total North Sea) can be expected to have a significant effect. Poos et al (in prep.) developed a model for the response of fishers to the spatial distribution of fish and the spatially varying costs of fishing, disregarding the response of fish stocks. In this approach, a protected area would conform to an area without fish or an area with extreme costs of fishing. They conclude that the spatial distribution of the fishery is clearly linked to the spatial distribution of the fish, though most of their analysis is focused on the effect of quota: fishers move away from areas with high abundance of species for which quota are limiting.

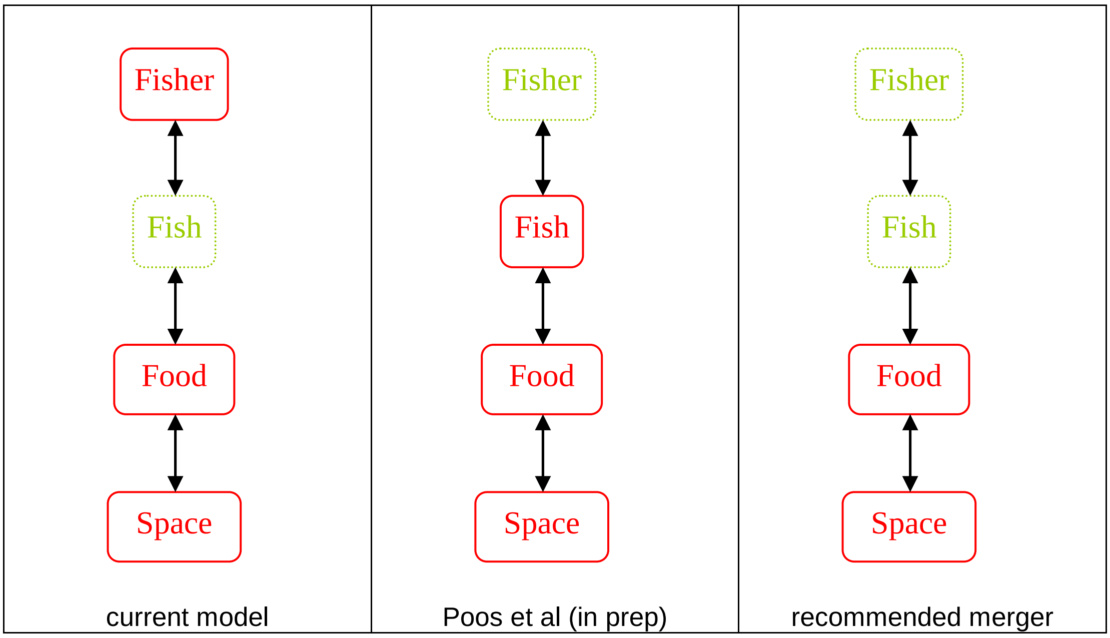

Figure 7 *Comparison of the model structure of the current model, the model of Poos et al (in prep) and the recommended merger of the two models. Static objects in red, dynamic options in green.*

Overall, each model study so far covered only the reaction of one of the agents (fish, fishers) to an MPA, be it the fish (current study) or the fisher (Poos et al. in prep.). Combining the two models (Figure 7), to extend to a two-layered model, seems recommendable. However, the inclusion of an additional dynamic layer of fishers into the current model can be expected to water down the effect of MPAs in comparison to the model presented here. That means: a two-layered, more complex model will show even less effects of MPAs on commercial fish stocks and fishing yields than the model presented in this report did. The conclusion that MPAs of as little size as currently proposed, will have little effect on fishing effort and yield, will not change.

Side-effects of fishing on by-catch, discards or damage to bottom fauna will strongly depend on the exact distribution of fishing effort, which in turn depends on the distribution of the fish. Both single-layered models have static layers (the habitat, including MPAs; for the fish-model: the fishing intensity; for the fisher-model, the fish) and one dynamic layer (either the fish or the fishers). Although both models are implemented as an Individual Based Model IBM, the fact that only one layer exhibits dynamic behaviour makes the results rather predictable, and single-layered models are generally not considered to be genuine IBMs (Grimm and Railsback 2006). In two-layered models, fish and fisher will respond to each other: fishers operate where the fish is, matching their spatial distribution to the fish, but fishers exploit the fish, and where fishers are, fish stocks decrease, breaking the spatial match between fish and fisher. As a consequence, the model is much less predictable and outcomes may be surprising, even for the informed expert. Indeed, the large-scale closure of the Cod spawning grounds in 2001 had a significant and unforeseen effect on the distribution of fishing effort, resulting in unwanted by-catches in other areas, which could have been predicted by more complex models. We therefore recommend to develop a two-layered model of the interaction between fish and fisher under the influence of MPAs. Extending this line of thought, inclusion of a dynamic layer for the bottom fauna, the fish-food, would complete the analysis. However, the dynamics of the food-level is much more complex, and a three-layered model much more unpredictable, to warrant a three-layered set-up immediately. We therefore recommend to develop a step-wise approach, via a two-layered towards a three-layered model.

The aim of the MPAs proposed in relation to the Bird and Habitat Directives is primarily the protection of resident organisms, such as bottom fauna and locally foraging birds. Our model study indicates that these MPAs will have an insignificant effect on migratory species such as Plaice. Our implementation of the migratory behaviour (specific spawning grounds, nursery areas, depth preferences, and annual migration cycles) is quite specific for the North Sea Plaice. Other exploited fish stocks, such as Cod and Sole, differ in the characteristics of their migration processes. Although there is no doubt, that the proposed MPAs will have insignificant effect for these other species too, it will require little extra effort to adapt our model to these species, and compare the effect of MPAs under different migratory strategies.

In addition to the variety of migration strategies over the species, there is a wide variation in migration tactics within a single species, between individuals. Tagging studies (Rijnsdorp en Pastoors 1995) indicate that individual fish differ in distances, directions and routes, though individuals seem to repeat their personal annual route throughout most of their life. Individual migratory characteristics were not implemented in our model: each migration step was a random event, not related to past experiences of the individual fish. Individual variation in migration characteristics may interfere at two levels: a short-term and a long-term effect. In the short term, individual variation in migration may reduce the effect of MPAs on fish stocks. The more motile individuals will show a higher susceptibility to fisheries. Once they have been removed from the stock in their first years of life, the remaining fish stock is more homogeneous, dominated by the more sluggish animals, that are not as susceptible to fishing anymore. Consequently, MPA protection of these sluggish fish will be more effective than predicted by our current model. Inclusion of inter-individual variation in the migration parameters of our model will be straightforward; the question is whether there is independent evidence from tagging studies in the field to document the natural range of variation in migration characteristics. This will require extensive statistical analysis of available tagging data. In the long term, however, MPA protection of predominantly 'sluggish' fish might alter the genetic basis for the migratory behaviour, comparable to the selection of smaller and earlier reproducing fish in overexploited fish stocks (Jørgensen et al 2007). The implementation of MPAs, however, will mitigate potential effects of the current (2001-2005) fishery. Noting the parallel to the smaller and earlier reproduction case, it is expected that any potential genetic effect of the current (2001-2005) excessive fishing pressure on migratory behaviour will restore very slowly, in an order of many generations. Consequently, the short-term effects will dominate the long-term effects for many many years.

The current proposals for MPAs in the Dutch parts of the North Sea respond to the Bird and Habitat Directives; these are not primarily focused at their effects on fish and fisheries. Area closures, however, may also act as a positive tool for fisheries management, by exhibiting some degree of protection to commercial fish stocks that suffer from overexploitation. In our current analyses, we took the status quo (2001-2005) as our starting point, in which most stocks are overexploited, and showed that the currently proposed MPAs will have little effect on fish and fishery. The implementation of MPAs within the framework of the Bird and Habitat Directives will now have little effect on fisheries management. Implementation of much larger MPAs, however, covering an order of 25% of the North Sea, will affect fish and fishery considerably, and will thus affect fisheries management. The implementation of large MPAs can be an effective tool in fisheries management, supplementing or replacing quota or effort management measures. Since our aim was to study the effects of the currently proposed MPAs only, we did not quantify to what extend larger MPAs can contribute to, or replace other tools in fisheries management. If the installation of MPAs is to be considered within the framework of fisheries management, we recommend further analysis of our model, to compare the quantitative effect of MPAs to that of other fisheries management measures. In any case, our current figure of 25% of the North Sea should not be interpreted as a final advice, since it was only intended to indicate an order of magnitude.

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Justification

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The scientific quality of this report has been peer reviewed by a colleague scientist and the head of the department of Wageningen IMARES.

Approved:	Dr. Tobias van Kooten Colleague scientist
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Date:	01-07-2009

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Signature:	
Date:	01-07-2009

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Appendix 1. Detailed model description

General description

Conceptually, the model consists of three layers: a physical and a biological one, and the fishery on top. The physical layer represents the North Sea (including the Wadden Sea) as a rectangular grid. Each grid cell has relevant physical characteristics, such as mean depth, position, size and temperature. The physical layer is static, ie characteristics do not change in response to any event in the model. The biological layer contains the Plaice, reacting to their physical environment. These Plaice spawn in designated areas (the spawning areas), that is: new animals are introduced at the start of each year in these grid cells, while the adults return to these areas during the spawning season. In their first year of life, young Plaice migrate towards nursery grounds (mainly the Wadden Sea). At the end of the first year, and in subsequent years, the Plaice migrate through the sea, while they grow in size, get older, undergo natural mortality, and are being fished. The migratory behaviour depends on depth and temperature preferences (that is: individual fish compare the depth and temperature of the grid cell where they resides, to those of the neighbouring cells, and determine their route accordingly), the age of the fish, and a generalized migration pattern with a stochastic variation on swimming direction. Finally, the fishery, which is considered to be static too. Based on the actual fishing efforts (hours fishing per ICES square, as derived from VMS registrations) and an average fishing mortality as derived from ICES assessments, the partial fishing mortality for each square has been calculated. Apart from area closures (and proportional redistribution of fishing effort over the remaining area), the partial fishing mortality is kept fixed.
Our implementation is based on discrete time steps of one week. Stochastic variation is included in several processes, without inter-individual or serial correlation.

The model is individual based, that is: the characteristics of the individual fish are modelled. The emergent properties of the population are determined by the sum of all individuals, not by imposing trends on abundance and distribution on the collection of all individuals. Our implementation of the model is minimalistic, in the sense that we modelled the absolute minimum number of processes for the individual fish, that could show potential effects of area protection on survival, distribution and fishing yield. In particular, dependence on food sources, and mutual interactions between individuals have not been included, which contrasts with conventional Individual Based Models (Grimm and Railsback 2006). Since our objective is quite focused (analysis of effects of protected areas), we preferred a traceable and tractable minimalist model.

In the initial phase, this model is used to simulate the natural distribution of Plaice, under the current (2001-2005) fishing regime. Parameter values were derived from literature, and the resulting distribution pattern compared to the actual distribution. Subsequently, a range of scenarios for protected areas was imposed, that is: fishing was set to zero in protected areas (and the corresponding fishing effort was, or was not, redistributed over the remaining areas). This results in two types of output:

-a map of the average distribution of Plaice, for each of the scenarios, and

-a ‘time series’ describing the evolution in abundance, in fishing yield, in individual weight, etc.

Each of the model scenarios was initiated at t=0 with a small number of Plaice reproducing at the spawning place. Obviously, a small number of reproducing Plaice in an otherwise empty sea is not a realistic starting condition. Following this initiation, the model quickly converges to a stable annual fluctuation after some 600 time steps (weeks), characterising each scenario. By initiating an extreme state, we could easily discriminate the final state from initial conditions. The outputs listed below present the full ‘time series’, with the initial 600 weeks shaded.

Modelling environment

The model was implemented in SWARM 2.2 (anon. 2004), an open-source simulation environment for individual based modelling (IBM). SWARM offers many pre-programmed routines for input-output, graphical presentation modules and so on. Only the relevant process routines have to be written by the user. SWARM runs under Knoppix (a Linux/Unix version) on a MS-Windows based machine. SWARM is written in Objective-C.

Model specifications

Physical model, closed areas and fishery effort.

The model environment is a rectangular grid divided in small cells of about 10 by 10 nautical miles. The upper left cell has coordinates (0,0). The x-coordinates increase from left to right (West to East) and the y-coordinates increase from the top to the bottom (North to South). To increase the computational efficiency the direction zero is to the positive x-direction, turning counter clockwise.

Each cell of the environment has the following attributes:

- Depth: computed by taking the average depth from all real observations within the cell.
- The fishing mortality computed by multiplying a factor with the average number of fishing hours per year within the cell during the period 2001-2005; the factor is 8×10^{-6} (week^{-1} (fishing hour per year)$^{-1}$) for fishing vessels with >300hp and 2×10^{-6} (week^{-1} (fishing hour per year)$^{-1}$) for the other ones.
- Direction to a deeper area (deeper area is located at 75N 1.5E);
- Direction to a shallower area (shallower areas are located at 54N 8E and 54N 5E);
- The fraction of the cell that is closed for the fisheries.
- The latitude in decimal degrees (negative = South);
- The longitude in decimal degrees (negative = West);

Each cell is divided into a number of smaller sub cells. Each sub cell can only hold one fish at the time. Each box has a flag that tells the model that the box is open or closed to fishery.

In the Integrated Management Plan for the North Sea 2015 (IMPNS 2015) four areas with special ecological features are selected to be designated by The Netherlands as protected areas. Research within the context of IMPNS 2015 showed that all these areas meet the criteria of both the Birds and/or Habitats Directives and the OSPAR Convention (Lindeboom et al. 2005).The four new areas are expected to be formally designated as Special Areas of Conservation (SACs, Birds Directive and/or Habitats Directive) around 2008 under the 1998 Nature Conservation Act. These areas are also due to be registered as Marine Protected Areas (MPAs) within the OSPAR framework. Each of those four protected areas is selected for different reasons and thus, management plans for each area will differ accordingly.

Apart from the protected areas, the Plaice Box and wind mill farm areas are closed to fishery. The latter presently concern relatively small areas. Other areas are closed sometimes, like those for military use. Roughly 7% of the Dutch Continental Shelf, for example, is used for military purposes in parts of a year, but when not, the areas are open to fisheries. Areas around oil platforms are not taken into account, since it concerns single areas of less than 1 nm^2 that do not add significantly to the 100 square nautical miles boxes.

Plaice behaviour

Each fish in the model has knowledge about

- its age,
- its migration speed,
- the time of the year,
- its location in the sea,
- the depth at this location,
- the depth it prefers,
- the direction to deeper water,
- the area where originally hatched.

The fishery effort per box is known and from this the amount of fish caught is computed and stored.

Spawning

Each year, a fixed number of fish hatch at the spawning area. Spawning is divided over three area's with centres in in the southern North Sea between Harwich and Hoek van Holland (58 %), in the Eastern part 60' North of Ameland (19 %) and in the Western part off the coast of Flamborough Hd. (13 %). (Wimpenny, 1953). When fish is already present in a sub-cell, a nearby sub-cell is chosen instead.

Mortality

We assume that natural mortality M for each fish is constant and known. The fishing mortality F is fixed for all fish within a cell. We then have the probability that a fish dies during some period is given by:

$$P\left(z_{[0,1)}\right) = e^{-(M+F)\Delta t} \quad \text{............................ [1]}$$

Where $z_{[0,1)}$ is a random number from a uniform distribution over the interval [0,1)

The next thing we want to know is whether a fish died in a natural way or was caught. The probability that a fish that died, was caught is given by:

$$P\left(z_{[0,1)}\right) = \frac{F}{M+F} \quad \text{............................ [2]}$$

A closed area can be simply introduced into the model by setting F to 0.0 for the cells involved. This is also used to prevent fish younger than 3 years from being caught.
Let E_a be the fishing effort in some area a, we then have

$$F_a = \beta E_a \quad \text{.................................. [3]}$$

where F_a is the partial fishing mortality in this area. β depends on the effectiveness of the fishery. The model covers two types of fisheries: beam trawling with engine power > 300 HP and beam trawling with engine power ≤ 300 HP.
The model ensures that the average of all F_a 's is equal to some reasonable fishing mortality F :

$$F_a = \frac{E_a}{\tilde{E}} F \quad \text{................................ [4]}$$

where $\tilde{E}$ is the mean effort per area over all area's where fishing occurs

Migration and dispersion

Information on exchange of fish between adjoining areas is limited and best information is available from the extensive tagging experiments carried out in the 1950s and 1960s. De Veen (1970) and Rijnsdorp & Pastoors (1995) estimated that Plaice dispersed at a rate of approximately 30 nm^2 per day from the location of release, which means that after one day, 60% of the fish resides within a circle of radius 5-6 nm. However, superimposed on this dispersion is a directional migration component of approximately 100nm per 6 months. Based on these directional migration rates and dispersion rates, Plaice Is expected to stay less than two weeks within any of the protected areas proposed (Claeverbank has size 15*15 nm, while Doggerbank has size 30*60 nm).

For a species like Cod, dispersion rates are higher (60 nm^2 per day; ICES, 1971). For other commercial species, no information is available, but there is no reason to assume that migration and dispersion rates would be much smaller. Consequently, the results for Plaice provide a reasonable estimate of expected effects of protected areas on commercial species in general.

It is possible that the estimated dispersion rates are affected by disturbance by fisheries and it might be hypothesized that dispersion might be reduced in an area with no fishing. However, migration is an inherited feature and should remain similar and therefore cause the fish to leave the protected area anyway.

In our model, every fish has a preferred imprinted starting direction φ_0 and an age dependent migration speed (table 1). Migration has a directional component of about 100 nautical miles (nm) over half a year. However large plaice is known to migrate from the south of the North Sea to the Northern part and back again which sums up to more than 500 nm. On the other hand, larvae reach the Wadden Sea from their spawning grounds in half a year which covers a distance of about 100 miles.

The migration pattern is based on a counter clockwise pattern. To mimic this, the migration direction turns counter clockwise within each year, starting at φ_0. Each year this direction changes over a total angle of 2π. Furthermore it is known that larger Plaice migrates to deeper water (Wimpenny, 1953). If some fish is located in an area where the depth is outside the preferred range, it will move into a deeper or shallower area. Special measures are taken to let the larvae migrate into the Wadden Sea area.
Rijnsdorp & Pastoors (1995) also describe a dispersion component during migration in the order of 1000 nm^2 per annum, that is: 60% of the animals stay within a circle of 30 nm.

Table *Depth preferences and migration speeds for fish of different ages*

Age	Minimum preferred depth	Maximum preferred depth	Mean migration speed (nm / a)	Mean dispersion speed (nm / a)	Weight at age (kg)
0	1	10	200	230	0.0010
1	5	20	200	280	0.0692
2	10	40	200	330	0.1238
3	15	50	200	380	0.2098
4	20	60	200	430	0.2650
5	20	80	200	480	0.3394
6	25	100	300	530	0.4096
7	25	100	400	580	0.5028
8	25	100	500	630	0.6228
9	25	100	600	680	0.7332
10+	25	100	700	730	0.8172

Migration step

The migration distance $D(a,\Delta t)$ for a fish of age a during a simulation step Δt is dependent on the mean migration speed of the fish (see table 1). The fish moves from position $(x(t-\Delta t), y(t-\Delta t))$ to $(x(t), y(t))$ according to:

$$\theta = \frac{\varphi(t)\alpha_{x,y} + \varphi(t) + \varphi_0}{\varphi(t)+1}$$
$$x(t) = x(t-\Delta t) + D(a,\Delta t)\cos(\theta) \quad \text{................ [5]}$$
$$y(t) = y(t-\Delta t) - D(a,\Delta t)\sin(\theta)$$

where $\phi(t) = 2\pi \times t$ (t in units of years) and $\alpha_{x,y}$ is the direction to a deep area. By using the weight $\varphi(t)$ for the computation of the migration direction θ, the intention to move to a deeper area becomes stronger during the year.

Homing

Homing behaviour is achieved as follows. For fish of age > 2, a new position is computed as the weighted mean of the position computed as shown in [5] and the position (x_0, y_0) of the spawning place:

$$x'(t) = \frac{w(t)x_0 + x(t)}{w+1}$$
$$y'(t) = \frac{w(t)y_0 + y(t)}{w+1} \quad [6]$$

The weight function increases during the year and becomes zero directly after the spawning process:

$$\varphi(t) < \pi : w(t) = 0$$
$$\varphi(t) >= \pi : w(t) = f\left(1 - \sqrt{1 - \left(\frac{\varphi(t) - \pi}{\pi}\right)^2}\right) \quad [7]$$

where f is a scaling factor. Figure 8 shows the values for this weight function.

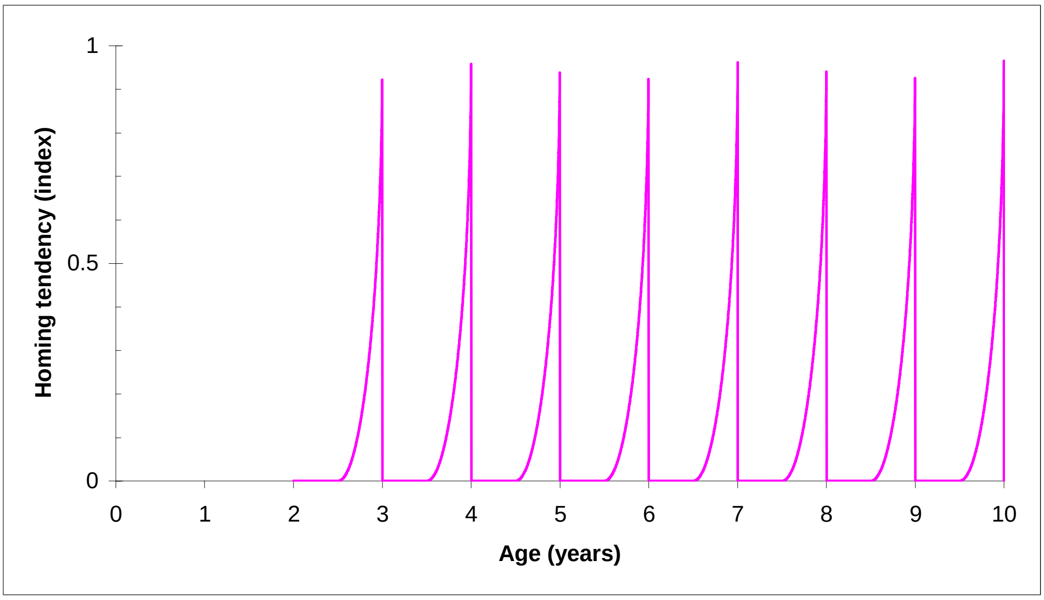

Figure 8. *– Homing tendency as a function of the age of the fish. Each time step, the new position of a fish is calculated as the average of the current position and its spawning place, weighting the home position by a weighting factor, as depicted in this graph (see text).*

Dispersion

Next a dispersion is implemented around the new positions computed by [6]:

$$x_d(t) = x(t) + d(a, \Delta t)\cos(\phi)$$
$$y_d(t) = y(t) - d(a, \Delta t)\sin(\phi) \quad [8]$$

Here ϕ is a random direction and $d(a, \Delta t)$ is the mean dispersion distance during the time step for a particular age a.

Preferred depth

The model tries to keep fish at some preferred depth which is dependent on its age (see table 1). For this purpose the following algorithm is used [9]:

- if the new position as computed by [8] is within the limits, it is accepted.
- else: if the position has a similar or better depth than the starting position it is accepted,
- else: a position halfway the staring position and the new position is chosen as a new position and the algorithm is repeated.

Cell constraint

Each cell can hold only one fish at the time. So when a new position has been computed by [10] and there is already some other fish at that location, a new free location in the neighbourhood is selected instead.

Sometimes it may happen that there is no free cell available. In this case the fish doesn't move, but during the next step the mean migration speed is incremented by 25%, so the fish is able to catch up.

Appendix 2. Detailed model results

Table *Summary of model results: population and catch statistics, averaged over time. The initial 600 time steps, in which the models have to converge, have been left out.*

Scenario	Population number	Population biomass	Individual weight in the sea	Catch number	Catch biomass	Individual weight in catch
1	381	56	147	49	16	328
2	380	56	146	48	16	327
3	380	56	146	48	16	327
4	386	58	151	49	16	332
5	383	57	149	49	16	330
6	385	59	152	48	16	333
7	593	179	301	21	10	490
8	710	259	364	0	0	-

SCENARIO 1, ALL OF THE NORTH SEA OPEN FOR ALL FISHING

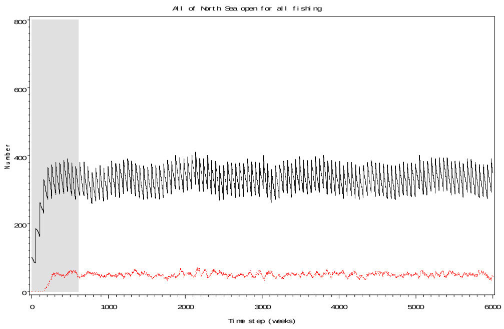

Figure 9. *'Time series' of the numbers in the population and the catch, for scenario 1 (All of North Sea open for all fishing), as derived from the simulation model. Solid black line indicates the population number; dotted red line the number in the catch.*

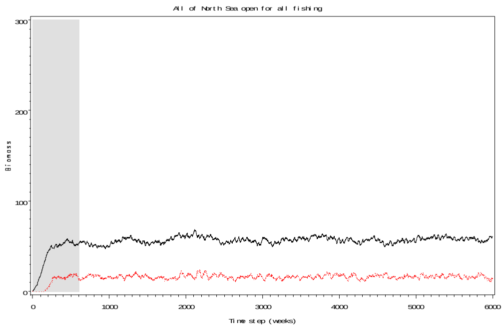

Figure 10. *'Time series' of the biomass in the population and the catch, for scenario 1 (All of North Sea open for all fishing), as derived from the simulation model. Solid black line indicates the population biomass; dotted red line the biomass of the catch.*

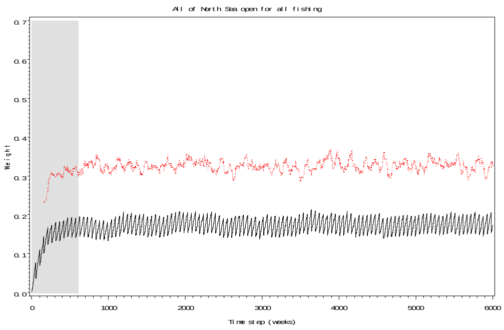

Figure 11. *'Time series' of the average individual weight in the population and the catch and the catch, for scenario 1 (All of North Sea open for all fishing), as derived from the simulation model. Solid black line indicates the average weight in the sea; dotted red line the average weight in the catch.*

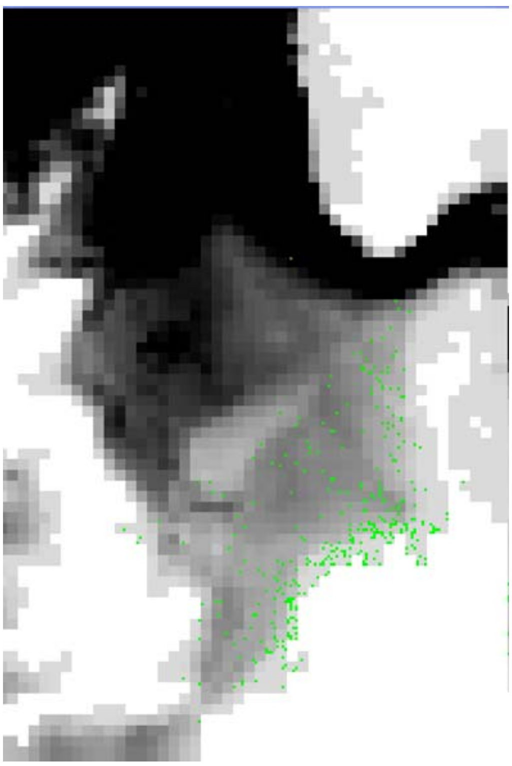

Figure 12. *Spatial distribution of the population, for scenario 1 (All of North Sea open for all fishing), as derived from the simulation model (snapshot of the distribution at t=6000).*

Scenario 2, Plaice Box open only for Eurocutters

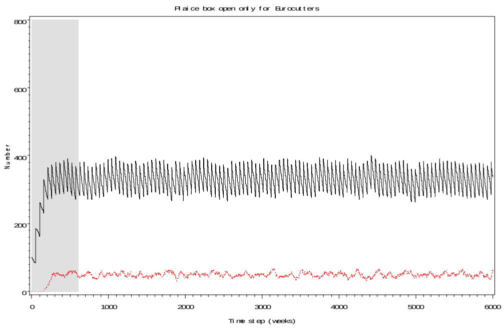

Figure 13. *'Time series' of the* *<u>numbers</u>* *in the population and the catch, for* *<u>scenario 2</u>* *(Plaice Box open only for Eurocutters), as derived from the simulation model. Solid black line indicates the population number; dotted red line the number in the catch.*

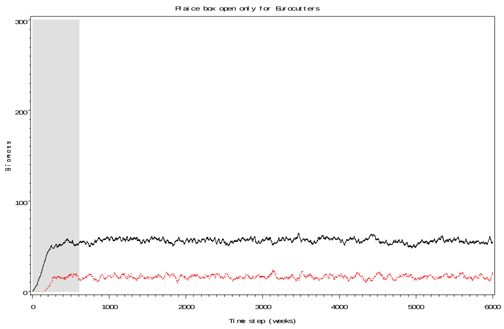

Figure 14. *'Time series' of the* *<u>biomass</u>* *in the population and the catch, for* *<u>scenario 2</u>* *(Plaice Box open only for Eurocutters), as derived from the simulation model. Solid black line indicates the population biomass; dotted red line the biomass of the catch.*

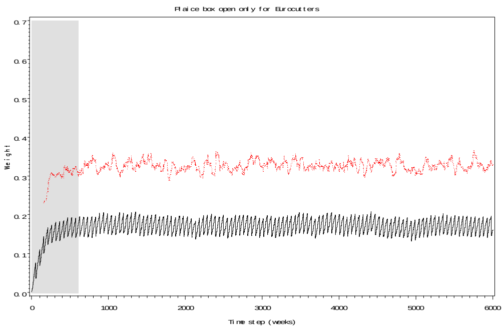

Figure 15. *'Time series' of the average* *<u>individual weight</u>* *in the population and the catch, for* *<u>scenario 2</u>* *(Plaice Box open only for Eurocutters), as derived from the simulation model. Solid black line indicates the average weight in the sea; dotted red line the average weight in the catch.*

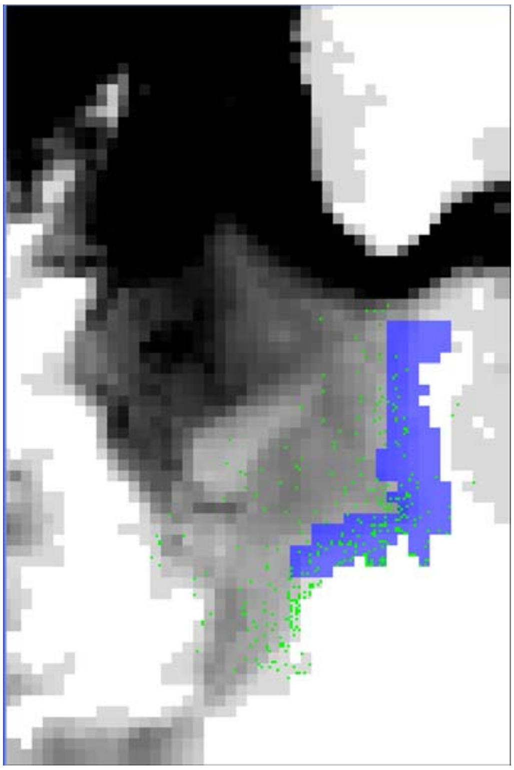

Figure 16. *<u>Spatial distribution</u>* *of the population, for* *<u>scenario 2</u>* *(Plaice Box open only for Eurocutters), as derived from the simulation model (snapshot of the distribution at t=6000).*

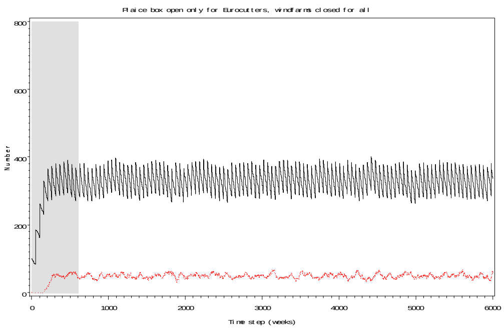

Figure 17. *'Time series' of the <u>numbers</u> in the population and the catch, for <u>scenario 3</u> (Plaice Box open only for Eurocutters, windfarms closed for all), as derived from the simulation model. Solid black line indicates the population number; dotted red line the number in the catch.*

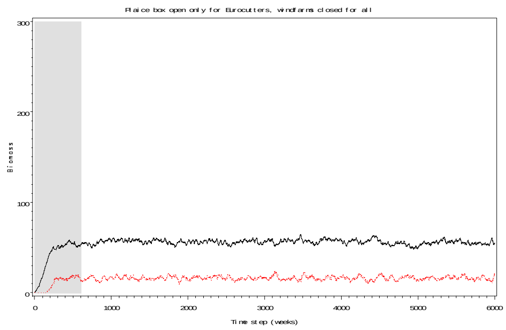

Figure 18. *'Time series' of the <u>biomass</u> in the population and the catch, for <u>scenario 3</u> (Plaice Box open only for Eurocutters, windfarms closed for all), as derived from the simulation model. Solid black line indicates the population biomass; dotted red line the biomass of the catch.*

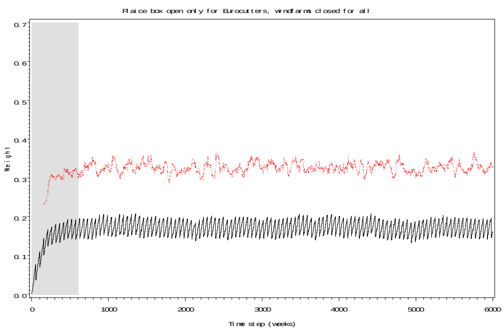

Figure 19. *'Time series' of the average <u>individual weight</u> in the population and the catch, for <u>scenario 3</u> (Plaice Box open only for Eurocutters, windfarms closed for all), as derived from the simulation model. Solid black line indicates the average weight in the sea; dotted red line the average weight in the catch.*

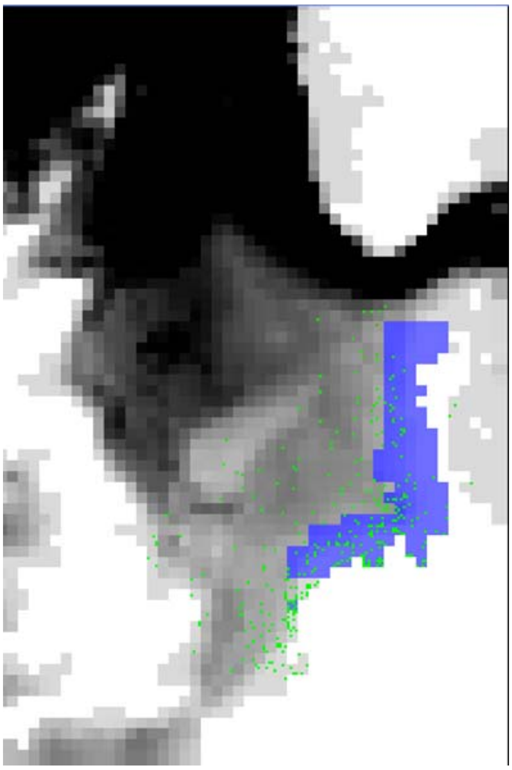

Figure 20. *<u>Spatial distribution</u> of the population, for <u>scenario 3</u> (Plaice Box open only for Eurocutters, windfarms closed for all), as derived from the simulation model (snapshot of the distribution at t=6000).*

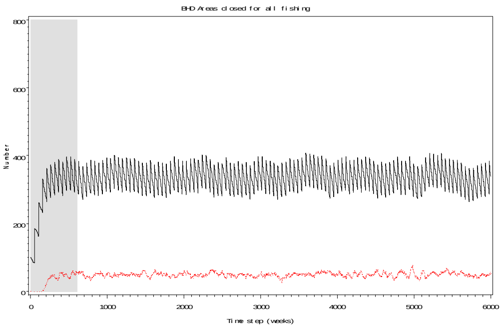

Figure 21. *'Time series' of the* *<u>numbers</u>* *in the population and the catch, for* *<u>scenario 4</u>* *(BHD Areas closed for all fishing), as derived from the simulation model. Solid black line indicates the population number; dotted red line the number in the catch.*

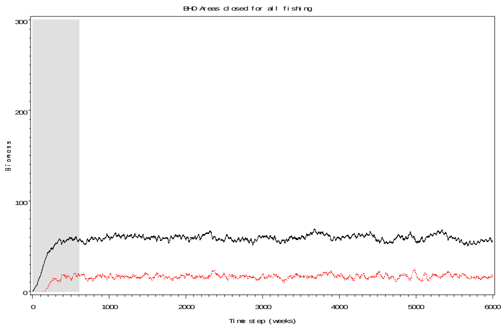

Figure 22. *'Time series' of the* *<u>biomass</u>* *in the population and the catch, for* *<u>scenario 4</u>* *(BHD Areas closed for all fishing), as derived from the simulation model. Solid black line indicates the population biomass; dotted red line the biomass of the catch.*

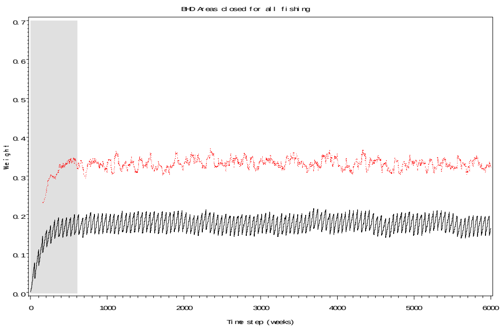

Figure 23. *'Time series' of the average* *<u>individual weight</u>* *in the population and the catch, for* *<u>scenario 4</u>* *(BHD Areas closed for all fishing), as derived from the simulation model. Solid black line indicates the average weight in the sea; dotted red line the average weight in the catch.*

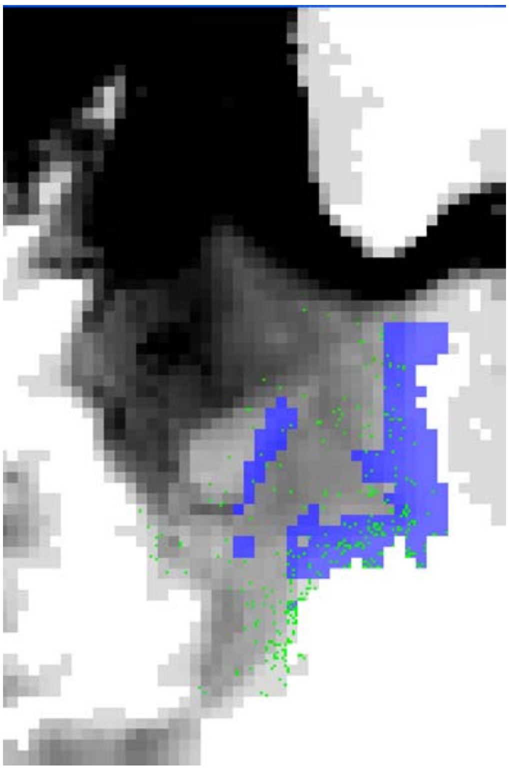

Figure 24. *<u>Spatial distribution</u>* *of the population, for* *<u>scenario 4</u>* *(BHD Areas closed for all fishing), as derived from the simulation model (snapshot of the distribution at t=6000).*

SCENARIO 5, DOGGERBANK AND CLAEVERBANK CLOSED FOR BEAMTRAWLS > 300 HP

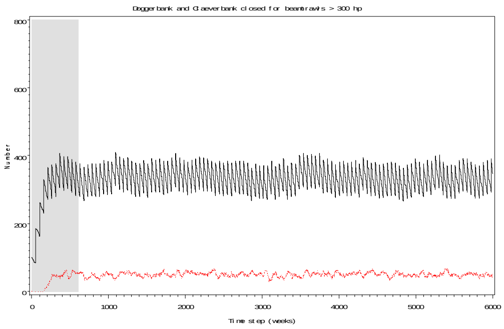

Figure 25. *'Time series' of the <u>numbers</u> in the population and the catch, for <u>scenario 5</u> (Doggerbank and Claeverbank closed for beamtrawls > 300 hp), as derived from the simulation model. Solid black line indicates the population number; dotted red line the number in the catch.*

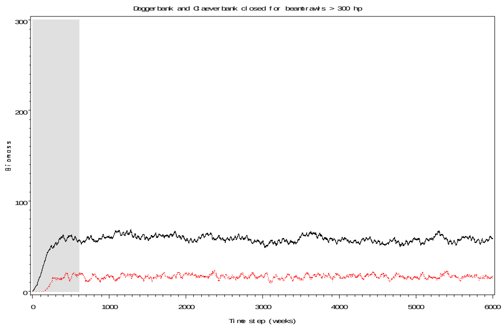

Figure 26. *'Time series' of the <u>biomass</u> in the population and the catch, for <u>scenario 5</u> (Doggerbank and Claeverbank closed for beamtrawls > 300 hp), as derived from the simulation model. Solid black line indicates the population biomass; dotted red line the biomass of the catch.*

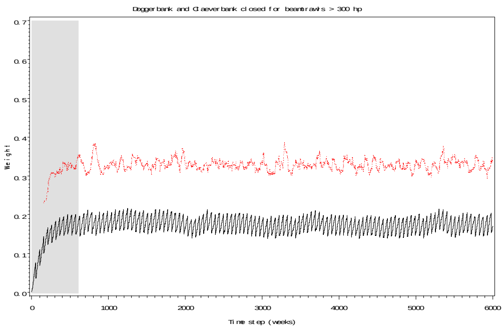

Figure 27. *'Time series' of the average <u>individual weight</u> in the population and the catch, for <u>scenario 5</u> (Doggerbank and Claeverbank closed for beamtrawls > 300 hp), as derived from the simulation model. Solid black line indicates the average weight in the sea; dotted red line the average weight in the catch.*

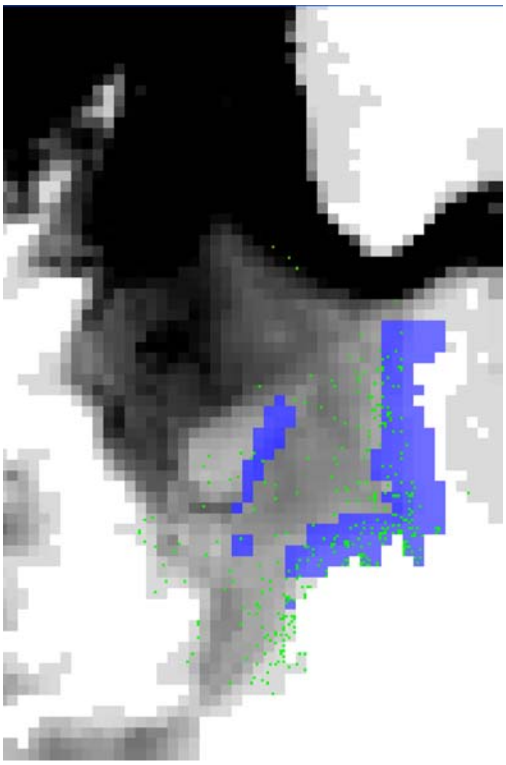

Figure 28. *<u>Spatial distribution</u> of the population, for <u>scenario 5</u> (Doggerbank and Claeverbank closed for beamtrawls > 300 hp), as derived from the simulation model (snapshot of the distribution at t=6000).*

SCENARIO 6, SINGLE CLOSED AREA OF SAME TOTAL SIZE AS PROPOSED MPAS

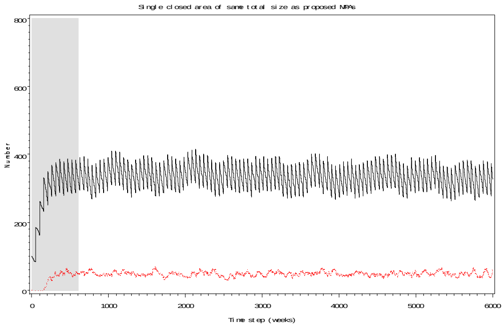

Figure 29. *'Time series' of the <u>numbers</u> in the population and the catch, for <u>scenario 6</u> (Single closed area of same total size as proposed MPAs), as derived from the simulation model. Solid black line indicates the population number; dotted red line the number in the catch.*

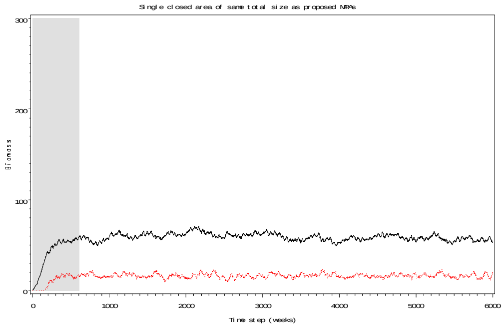

Figure 30. *'Time series' of the <u>biomass</u> in the population and the catch, for <u>scenario 6</u> (Single closed area of same total size as proposed MPAs), as derived from the simulation model. Solid black line indicates the population biomass; dotted red line the biomass of the catch.*

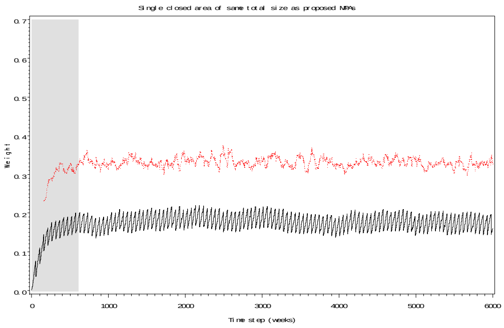

Figure 31. *'Time series' of the average <u>individual weight</u> in the population and the catch, for <u>scenario 6</u> (Single closed area of same total size as proposed MPAs), as derived from the simulation model. Solid black line indicates the average weight in the sea; dotted red line the average weight in the catch.*

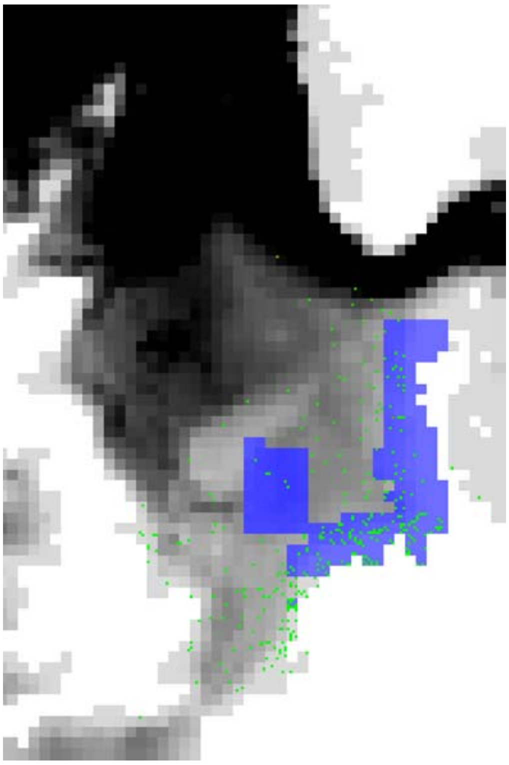

Figure 32. *<u>Spatial distribution</u> of the population, for <u>scenario 6</u> (Single closed area of same total size as proposed MPAs), as derived from the simulation model (snapshot of the distribution at t=6000).*

SCENARIO 7, SINGLE PROTECTED AREA, 25% OF NORTH SEA

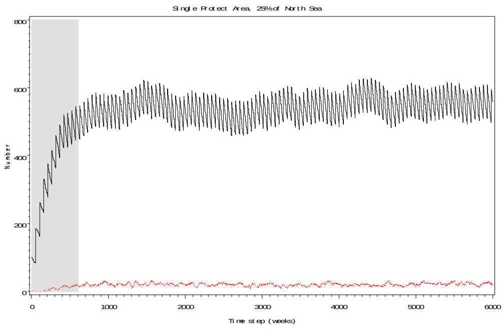

Figure 33. *'Time series' of the <u>numbers</u> in the population and the catch, for <u>scenario 7</u> (Single protected area, 25% of North Sea), as derived from the simulation model. Solid black line indicates the population number; dotted red line the number in the catch.*

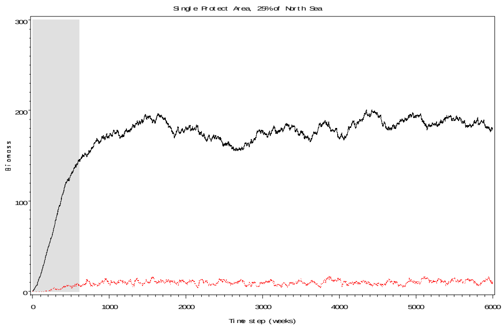

Figure 34. *'Time series' of the <u>biomass</u> in the population and the catch, for <u>scenario 7</u> (Single protected area, 25% of North Sea), as derived from the simulation model. Solid black line indicates the population biomass; dotted red line the biomass of the catch.*

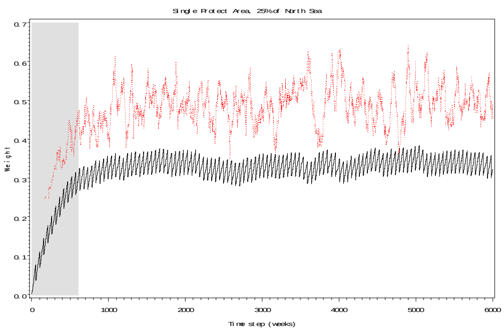

Figure 35. *'Time series' of the average <u>individual weight</u> in the population and the catch, for <u>scenario 7</u> (Single protected area, 25% of North Sea), as derived from the simulation model. Solid black line indicates the average weight in the sea; dotted red line the average weight in the catch.*

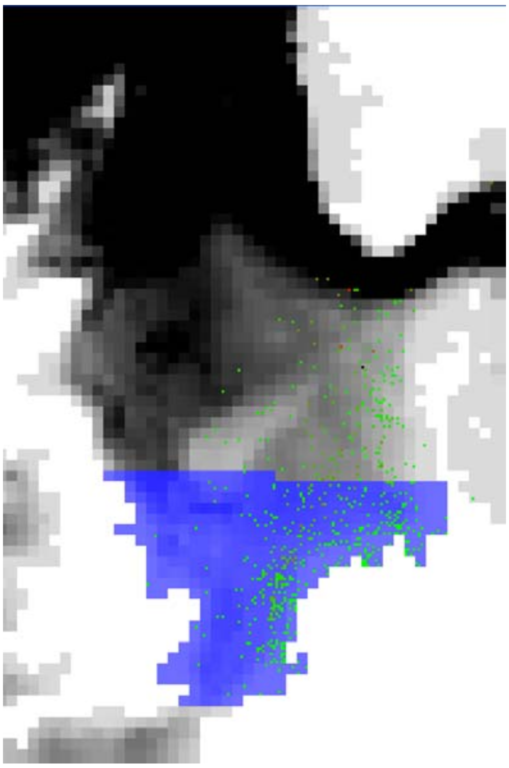

Figure 36. *<u>Spatial distribution</u> of the population, for <u>scenario 7</u> (Single protected area, 25% of North Sea), as derived from the simulation model (snapshot of the distribution at t=6000).*

SCENARIO 8, COMPLETE BAN ON FISHING

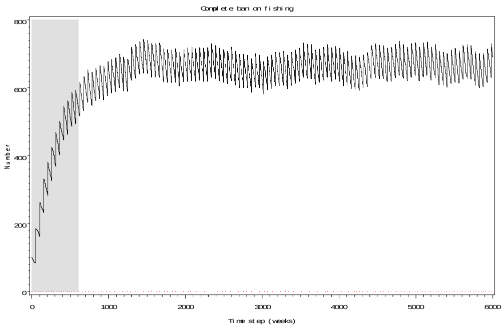

Figure 37. *'Time series' of the* *<u>numbers</u>* *in the population and the catch, for* *<u>scenario 8</u>* *(Complete ban on fishing), as derived from the simulation model. Solid black line indicates the population number; dotted red line the number in the catch.*

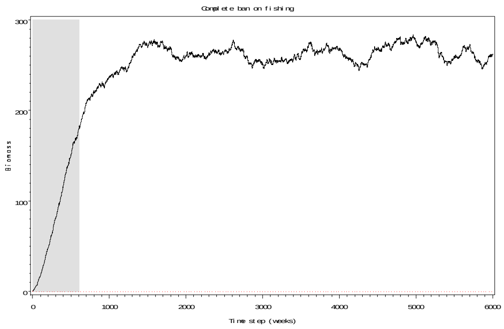

Figure 38. *'Time series' of the* *<u>biomass</u>* *in the population and the catch, for* *<u>scenario 8</u>* *(Complete ban on fishing), as derived from the simulation model. Solid black line indicates the population biomass; dotted red line the biomass of the catch.*

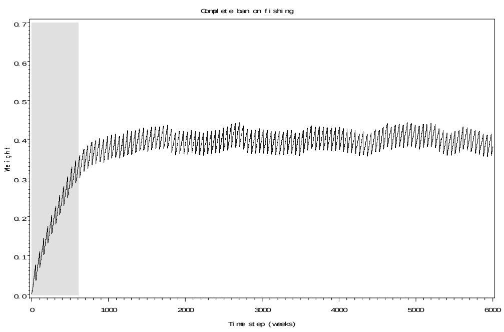

Figure 39. *'Time series' of the average* *<u>individual weight</u>* *in the population and the catch, for* *<u>scenario 8</u>* *(Complete ban on fishing), as derived from the simulation model. Solid black line indicates the average weight in the sea; in this scenario, no Plaice are caught, so average weight in the catch is effectively undefined.*

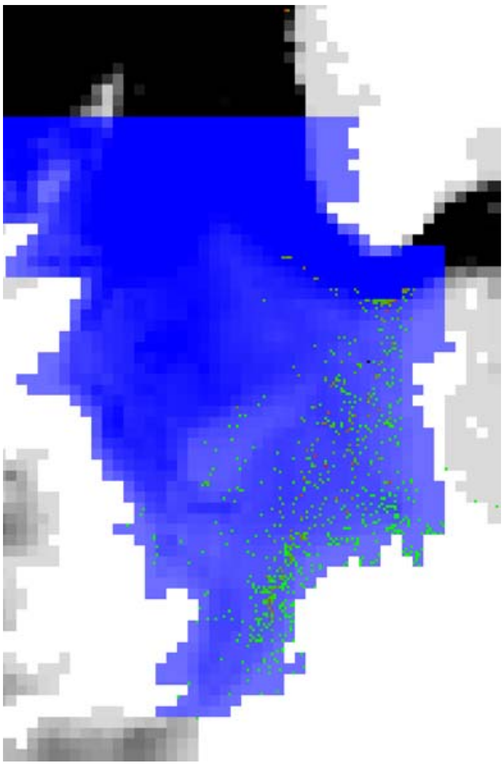

Figure 40. *<u>Spatial distribution</u>* *of the population, for* *<u>scenario 8</u>* *(Complete ban on fishing), as derived from the simulation model (snapshot of the distribution at t=6000).*