Spawning closures: ecological and economic trade-offs in management of mixed demersal flatfish fisheries in the North Sea

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Contents

Samenvatting

Seizoenvisserij, waarbij vissen in de voortplantingsperiode extra beschermd worden door sluiting van visserij in de paaigebieden, kan een belangrijke bijdrage leveren aan de verduurzaming van visserij. Het toepassen van deze benadering is echter gecompliceerd omdat de paaigebieden en paaiperioden van verschillende vissoorten niet altijd samenvallen. In een modelstudie is onderzocht hoe het principe van seizoenvisserij in de platvisvisserij een bijdrage kan leveren aan duurzame exploitatie van de doelsoorten als schol en tong en hoe de gevolgen zijn voor de ongewenste neveneffecten van de visserij. De scenarioverkenningen maken aannemelijk dat een sluiting van de visserij in de paaiperiode van schol overwegend positieve effecten zal hebben (verhoging van de volwassen stand van schol, vermindering van de bijvangst van ondermaatse platvis en kabeljauw, vermindering van de evolutionaire veranderingen en een verhoging van de besomming) met uitzondering van een toename van de negatieve effecten op het ecosysteem van de zeebodem. Sluiting van de visserij in de paaiperiode van tong resulteert alleen in combinatie met de sluiting van de scholperiode tot positieve effecten.

De voortplantingsperiode van geëxploiteerde vissoorten vormt een kritische fase waarin de basis wordt gelegd voor de aanwas van een nieuwe generatie jonge vis en de visserijmogelijkheden in de toekomst. Visserij in de paaiperiode kan mogelijk tot negatieve effecten op het voortplantingssucces leiden door het wegvangen van een deel van de ouderpopulatie voordat ze zich kan voortplanten en door de verstoring van het natuurlijke gedrag. Bescherming van de paaipopulatie is vooral belangrijk voor overbeviste bestanden waarvan de paaipopulatie onder de voorzorggrens ligt. Maar ook voor gezonde visbestanden die niet worden overbevist is bescherming tijdens de paaiperiode belangrijk omdat het de selectie voor ongewenste genetische veranderingen kan doen verminderen. Voor het voortplantingssucces van de populatie zijn vooral de grotere en oudere dieren belangrijk, omdat dezen relatief veel eieren van hogere kwaliteit produceren. Bij veel vissoorten zijn deze oudere dieren juist tijdens de paaiperiode gemakkelijker vangbaar omdat zij zich in de paaigebieden concentreren.

In het beheer van zoetwatervis is het gebruikelijk dat er tijdens de paaiperiode niet gevist mag worden. In de zeevisserij wordt aan het beschermen van vissen tijdens deze kritische periode nauwelijks aandacht gegeven. Het sluiten of verminderen van de visserij in de paaiperiode kan naast biologische redenen ook om economische redenen voordelig zijn indien kuitzieke of uitgepaaide vis een lagere prijs opbrengt. In Nederland pleit de Stichting Vis & Seizoen ervoor om vissen alleen buiten de paaiperiode te bevissen. In de visserij wordt al jaren gediscussieerd over het extra beperken van de visserij tijdens de paaiperiode van schol. Ook de Stichting Noordzee bepleit om schol "zwangerschapsverlof" te gunnen.

In dit rapport wordt een verkennende analyse gepresenteerd naar de effecten van seizoenvisserij in de Noordzee platvisvisserij. De studie analyseert de effecten van een sluiting van de visserij in de paaiperiode van schol en tong. Naast de effecten op de bestandsgrootte van de hoofdsoorten van de platvisvisserij, schol en tong, wordt ook het effect onderzocht op de commercieel belangrijke bijvangst soorten tarbot en griet, en op een aantal ecosysteem indicatoren. In de discussie over de ecologische duurzaamheid van de boomkorvisserij is de aandacht vooral gericht op de bijvangst van ondermaatse platvis, de bijvangst van kwetsbare vissoorten zoals roggen, het effect op het bodemecosysteem en de evolutionaire effecten. Ten slotte is de bijvangst van de kabeljauw in de platvisvisserij belangrijk.

Omdat de kabeljauw er erg slecht voor staat is het beheer erop gericht om de bijvangst zoveel mogelijk te beperken.

De onderzochte beheerscenario's zijn: scenario 1 – referentie scenario met waargenomen visserij in de periode 2003-2007; scenario 2 - sluiting van de visserij in de paaiperiode van schol (week 1 t.m. week 8); scenario 3 - sluiting van de visserij in de paaiperiode van tong (week 12 t.m. week 20); scenario 4 - combinatie van scenario 2 en 3. De visserij die door de sluiting niet meer in de paaigebieden kon vissen is op twee verschillende manieren herverdeeld. In herverdeling-scenario A werd de visserij inspanning binnen iedere week herverdeeld over de gebieden die niet waren gesloten. In herverdeling-scenario B werd de visserij herverdeeld buiten de gesloten periode. De zeedagen werden herverdeeld in evenredigheid met de waargenomen zeedagen. In het schol scenario werd 80% van de zeedagen in de sluitingsperiode herverdeeld. In het tong scenario werd 30% van de zeedagen herverdeeld. Het gesloten gebied is weergegeven in Figuur 3.

De basis van de analyse wordt gevormd door de ruimtelijke verdeling van de Nederlandse boomkorvisserij en de ruimtelijke verdeling van de leeftijdsgroepen van de belangrijkste vissoorten (schol, tong, tarbot, griet, kabeljauw, roggen: Figuur 4). Als door een gebied-sluiting de zeedagen worden herverdeeld naar gebieden waar meer of minder van een bepaalde leeftijdsgroep voorkomt zal de visserijsterfte veranderen. Uit de overlap in de verspreiding van de visserij en de vis kan dus het exploitatiepatroon - de visserijsterfte per leeftijdsgroep – worden bepaald (Figuur 5). De consequenties voor de geëxploiteerde bestanden kunnen worden berekend door in een 'Yield per Rekruut ' analyse het exploitatiepatroon te combineren met informatie over de biologie van de soorten (groeisnelheid, de lengte waarop een soort geslachtsrijp wordt), de selectiviteit van de visserij (maaswijdte selectie, minimum aanvoerlengte), en de seizoenveranderingen in de prijs van de vis per marktsortering (Figuur 2). Hiermee konden de volgende gegevens worden berekend: gewicht van de marktwaardige vis, gewicht van de ondermaats gevangen vis, gewicht van de volwassen stand, gemiddelde visserijsterfte en de waarde van de gevangen vis. Het effect van de verschillende paaisluiting scenario's kan worden bepaald door de resultaten te vergelijken met het referentie scenario. Deze resultaten hebben betrekking op een situatie waarbij de productie kenmerken van de populatie in evenwicht zijn met de visserij zoals deze is gespecificeerd in het scenario.

De belangrijkste resultaten van de studie zijn weergegeven in Figuur 6, waarin het totale effect van een selectie van indicatoren is samengevat. Een volledig overzicht van de resultaten wordt gegeven in Tabel 6. Figuur 6 geeft aan hoe de verschillende scenario's van elkaar verschillen. Voor de scholsluiting scenario's hangt het effect sterk af of de visserij wordt herverdeeld binnen de scholperiode (2A) of buiten de scholperiode (2B). Voor de tongsluiting blijkt het verschil tussen de scenario's 3A en 3B klein te zijn. De bijdrage van een de indicatoren is weergegeven met de lengte en richting van de pijl. Als de pijl in de richting van een scenario code wijst heeft het scenario een positief effect. Wijst de pijl in een tegengestelde richting dan is het effect negatief. Sluiting van de visserij in de paaigebieden van tong heeft overwegend een negatief effect en leidt tot een afname van de scholstand. Sluiting van de visserij in de paaigebieden van schol heeft overwegend positieve effecten. Ook in combinatie met de sluiting van de tongpaaigebieden is er een overwegend positief effect.

De belangrijkste effecten zijn een verhoging van de volwassen stand van schol en griet, een vermindering in de evolutionaire selectie, vermindering van de bijvangst van ondermaatse platvis (vooral schol), en in het bijzonder een reductie in de bijvangstssterfte van kabeljauw en roggen. Het enige negatieve effect is dat de invloed op het bodemecosysteem toeneemt doordat de visserij zich herverdeeld over met name relatief licht beviste gebieden. Een opvallend resultaat is ook dat het positieve effect op de besomming groter is dan het effect op het vangstgewicht. Dit impliceert dat de schol paaisluiting tot een hogere visprijs leidt. De effecten van de paaisluiting zoals berekend voor de referentieperiode 2003-2007 verschillen weinig van de verwachte effecten voor de situatie waarin de visserijinspanning is verminderd tot het niveau van MSY. Ook in een visserij bij MSY zijn de effecten van een schol, en een gecombineerde schol – tongsluiting, overwegend positief.

Bovenstaande resultaten moeten met de nodige voorzichtigheid worden geïnterpreteerd. De betrouwbaarheid van de uitkomsten wordt bepaald door de nauwkeurigheid van gebruikte basisgegevens en de modelformulering. De seizoenpatronen in de verspreiding van de vis is gebaseerd op de vangstgegevens van de boomkorvloot en de beschikbare biologische monsters waarmee de leeftijdsverdeling kon worden bepaald. De commerciële vangstgegevens en de verhouding van de marktsorteringen kunnen mogelijk vertekend zijn door het discarden van vis ten gevolge van het quotabeheer (over-quota vangsten en high-grading). De ruimtelijke verdeling van de jongste leeftijdsgroepen is mogelijk onnauwkeurig omdat deze is gebaseerd op de vangsten het deel van de leeftijdsgroep die de marktwaardige lengte heeft bereikt. Voor 1-jaar oude vis was geen gedetailleerde informatie beschikbaar en moest worden aangenomen dat de verdeling gelijk was aan die van 2-jaar oude vis. Waarschijnlijk dat het aandeel van de 1 jaar oude vis op de visgronden is overschat. Immers, alle vier de platvissoorten brengen hun jeugdjaren door in de ondiepe kustgebieden. Desondanks komen de gevonden verspreidingspatronen in grote lijnen overeen met de bekende migratie van jonge vis vanuit de kustgebieden naar volle zee en de migraties tussen de paaigebieden en de voedselgebieden. Door het ontbreken van internationaal aanvaarde duurzaamheidsindicatoren, is in deze studie een eigen keuze gemaakt. De gekozen indicatoren zijn een reflectie van de onderwerpen die in het maatschappelijk debat over de ecosysteemeffecten van de platvisvisserij worden genoemd, maar pretenderen geen volledig beeld te geven. Ook zijn er alternatieve indicatoren denkbaar.

In de samenvatting van de belangrijkste indicatoren hebben alle indicatoren een gelijk gewicht gekregen. In het maatschappelijk debat zullen de betrokken partijen de indicatoren verschillend waarderen. Deze studie illustreert dat het mogelijk is om een wetenschappelijke onderbouwing te geven van de effecten van beheerscenario's op een aantal ecologische en economische indicatoren. Deze wetenschappelijke uitkomsten kunnen vervolgens worden gebruikt om in overleg met verschillende betrokken partijen – visserij, vishandel, NGO's, beheerder, etc. – een keuze te maken waarin de verschillende doelstellingen worden gewogen. Onze studie laat zien dat in het geval van de gemengde visserij een compromis gevonden zal moeten worden tussen de positieve en negatieve effecten van de verschillende beheerscenario's. Een belangrijk resultaat van onze studie is dat een reductie van de Nederlandse boomkorvisserij in de paaiperiode van schol een aanzienlijke reductie van de bijvangst van kabeljauw zal geven.

Abstract

The contribution of spawning closures to sustainable management of North Sea flatfish fisheries is explored using a spatial and temporal explicit model of four target species (sole, plaice, turbot and brill) and two bycatch species (cod, rays). Seasonal patterns in fishing effort and partial fishing mortality rates per day at sea by age group and area are estimated to quantify the effect of different spawning closure scenarios for sole and plaice on the exploitation pattern (F-at-age). The scenario performance is evaluated using indicators of the state of the stock (spawning stock biomass), the economic performance of the fishery (yield, revenue and costs) and the ecosystem impact (discards, bycatch of cod and rays, seabed integrity, fisheries-induced evolution). In a single species context, spawning closures may be beneficial for the target species, but in a mixed fisheries and ecosystem context, negative effects may occur. A spawning closure for plaice combines positive effects on the plaice stock and the revenue with reductions of the negative impact for several ecosystem indicators and only small negative effects. The effects did not differ when evaluated at current levels of effort or at Maximum Sustainable Yield effort (MSY). Tailor made solutions are required that need to be developed in stakeholder consultation to trade-off the ecological and economic objectives. Mixed species MSY was lower than the sum of the single species MSYs.

Keywords: ecosystem approach, closed areas, closed seasons, discards, bottom trawling impact, selection differential

1. Introduction

Fishing has substantially reduced biomass of exploited fish stocks, adversely affected the ecosystem (Hall and Mainprize, 2005; Jennings and Kaiser, 1998; Pauly et al., 1998; Worm et al., 2009) and resulted in fisheries-induced evolution (Heino, 1998; Jorgensen et al., 2007). Mixed demersal fisheries pose particular management problems to achieve not only acceptable fishing mortalities of the several target species but also minimise the negative impacts on the ecosystem such as the bycatch of undersized fish and over-quota fish, the trawling impact on benthic habitats (Jennings and Kaiser 1998; Stelzenmuller et al., 2010; Poos et al., 2010), All these are elements of the ecosystem approach to fisheries management (Pikitch et al., 2004; Rice, 2008; Jennings and Rice, 2011).

Protection of spawning fish may contribute to the ecosystem approach because it may (i) enhance the reproductive success of the population by reducing mortality on the large and old fish (Wright and Trippel, 2009; Trippel and Neil, 2004); (ii) reduce the evolutionary effects of exploitation (Law, 2007; Jorgensen et al., 2009); (iii) reduce the disturbance of reproduction process and impact on spawning habitats (van Overzee & Rijnsdorp, 2010). However, in practice it may be difficult to find a compromise between the protection of spawning fish of different species, reduce adverse ecosystem impacts on the ecosystem and maximise the sustainable harvest of the species complex (Fulton et al., 1999). Species differ in time and area of spawning and spawning closures will displace fishing effort that may lead to adverse consequences for the exploited populations or the ecosystem (Dinmore et al., 2003).

In this paper, the consequences of spawning closures on the dynamics of exploited species, the fishery and the ecosystem effects of the fishery are explored for the North Sea mixed flatfish fishery. This fishery is dominated by beam trawl vessels which deploy heavy trawl gear and tickler chains that penetrate into the bottom to catch the burying flatfish, in particular sole *Solea solea* (Daan, 1997). Other target species are *Pleuronectes platessa*, turbot *Psetta maximus* and brill *Scophthalmus rhombus*, whereas cod *Gadus morhua*, rays and other bottom dwelling fish are bycatch species (Gillis et al., 2008).

Specifically for this fishery, the ecosystem impacts are consider to be the mesh size (80 mm) required to exploit the slender sole causes a substantial bycatch of undersized commercially important fish, in particular plaice (van Beek, 1998; Pastoors et al., 2000; Kraak et al 2008). Secondly, the fishery catches heavily over exploited species such as cod and rays that are of concern (Walker and Heessen, 1996; Ulrich et al, 2011). Third, the use of tickler chains impacts benthic invertebrates and benthic habitats (Hiddink et al., 2006; Jennings et al., 2002; Kaiser et al., 2006). Finally, fisheries-induced evolutionary changes have been reported in the two main target species plaice and sole (Grift et al., 2003; Mollet et al., 2007; Rijnsdorp, 1993a; van Walraven et al., 2010).

To estimate the consequences of spawning closures a spatial and temporal explicit model of the North Sea flatfish fisheries was developed. Seasonal and spatial variations in age-specific catchability were estimated for the major target species (sole, plaice, turbot and brill) and used to calculate the exploitation pattern for different management scenarios (Murawski 1984; Rijnsdorp and Pastoors, 1995; Piet et al., 2007). The performance of the management scenarios is assessed in terms of the (i) revenue to the fisheries; (ii) biomass of the target species; (iii) bycatch of undersized flatfish; (iv) bycatch of cod *Gadus morhua* and rays; (v) fisheries-induced evolution; (vi) trawling impact on the benthos.

2. Methods

2.1 Data

We assumed the Dutch beam trawl fleet to be representative for the total international fleet fishing for flatfish. This is not unreasonable since this fleet contributes more than two thirds of the total international landings of flatfish in the North Sea.

2.1.1. Catch and effort data

Logbook data of all trips of commercial vessels landing in the Netherlands is available, holding information on the catch-weight of marketable fish by species, fishing gear, mesh size, fishing ground, time of leaving and returning in harbour, engine power and vessel code. The fishing ground is recorded as rectangles of 0.5 degree latitude and 1 degree longitude (ICES rectangles). A second data set (sale slips) comprises records of landed weight and price by market category and data on the vessel and landing date. For this study, data collected over a five year period 2003-2007 has been analysed.

2.1.2. Biological samples

All fish is landed in the fish auctions and sorted into size classes (market categories) before being sold. Samples are taken by month and market category and the size, weight, sex, maturity stage and age is determined of the sampled fish. Samples collected over the period 2003-2007 have been pooled to construct monthly age-length keys (ALKs) for each market category by fishing area (Figure 1). These month*area ALK's were subsequently applied to the catch weight per market category per fishing trip. For a small number trips no month*area specific ALK was available and a ALK of the pooled monthly data is used 's (plaice 13%, sole 8%, turbot 26%, brill 25%, cod 20%). The total number of fish sampled by area varied across species (Table 1). Plaice (n=23064) and sole (n=17656) are very well sampled as compared to turbot (n=4866), brill (n=6700) and cod (n=9801).

2.2 Catchability

Following Rijnsdorp et al. (2006), catchability was estimated by partitioning the annual F-at-age from the stock assessment into the partial fishing mortality per day at sea (F_{pue}) of individual fishing trips

$$Fpue_{ijk} = \frac{c_{ijk}}{c_k} \times \frac{F_k}{d_{ij}}$$

Where c_{ijk} are the numbers landed by vessel i in week j, of age k, C_k is the total numbers landed of age k, F_k is the fishing mortality of total international fleet of age k, and d_{ij} is the number of days at sea of vessel i in week j. Table 2 shows the fishing mortalities. For sole, plaice and cod we used the mean annual F at age for the years 2003-2007 from the 2010 ICES stock assessments of these stocks (ICES 2010), while for turbot and brill, estimates were available from Poos et al (in prep). For cod, we used the partial fishing mortality at age of the Dutch fleet to estimate the consequences of different management scenarios for the bycatch mortality of cod in the flatfish fishery.

All flatfish species are characterised by ontogenetic niche shifts between shallow coastal nursery grounds inhabited in the first years and offshore waters inhabited by the (sub-) adult stages (Gibson, 1994). Due to the ontogenetic shifts F_{pue} in a certain fishing area is expected to change with the age of a cohort (a). Further, F_{pue} will change periodically due to the seasonal migrations between the spawning and the feeding areas of adult fish. To capture these processes, the F_{pue} data were analysed with a Generalised Additive Model (Wood, 2008):

$$Fpue_i = area_i + f_i(age, week)$$

, where $f_i(age, week)$ is a tensor spline of age with a cubic regression marginal basis and a cyclic regression spline, estimated for each area. To take account of the skewed distribution of the response variable, we applied a log-link function and poisson error term. Quasi-likelihood estimation was used to take account of the over dispersion. All analyse were done in the R statistical program (version R2.12.1; R Development Core team, 2010).

In order to capture the ontogenetic and seasonal changes in Fpue in more detail, fishing areas 3, 5, 10, 11 and 12, used to construct the ALKs, were further subdivided into smaller areas. Because age-group 1 is absent from the commercial landings as they are still below the minimum landing size, we assumed that $Fpue_1 = p^2 Fpue_2$, where p is the proportion of the year elapsed reflecting the partial recruitment of age group 1 to the fishing grounds.

2.3   Simulation model

The exploitation pattern corresponding to a management scenario's (see below), characterised by a specific distribution of fishing effort in space and time, was estimated by multiplying fishing effort (e_{ij}) with $Fpue_{ij}$ in rectangle i and week j and summing over all rectangles and weeks:

$$F = \sum_i \sum_j e_{ij} Fpue_{ij}$$

The exploitation pattern was then used in the 'Yield per Recruit' model (YpR) of Beverton and Holt (1957) to estimate the yield and spawning stock biomass per recruit. The YpR-model calculates the fate of a cohort in terms of its growth, maturation and natural and fishing mortality. Population numbers decline with time according to:

$$N_{t+1} = N_t e^{(-F-M)t}$$

, where F and M are the instantaneous rates of fishing and natural mortality, respectively. The fishing mortality is a function of the level of fishing effort E_{ij} (fishing days) and the partial fishing mortality ($F_{pue_{ij}}$) in week i and area j summed over the study area and the time period considered:

$$F = \sum_{ij} Fpue_{ij} E_{ij}$$

The size distribution of the cohort was modelled assuming a normal distribution with a coefficient of variation (cv=15%) around the mean length (L_t) at time t given by the Von Bertalanffy growth equation:

$$L_t = L_\infty (1 - e^{-K(t-t_0)}).$$

The proportion r retained of size class L (cm) is given by

$$r = \frac{e^{\alpha + \beta L}}{1 + e^{\alpha + \beta L}}$$

, where α and β are the parameters of the selection ogive. These parameters can be calculated from the selection factor sf and the selection range sr from:

$$\alpha = \ln\frac{0.25}{0.75} * \frac{sf * mesh}{sr}$$

$$\beta = \frac{-\ln\left(\frac{0.25}{0.75}\right)}{sr}$$

The retained fish smaller than the minimum landing size represent the discard fraction, those larger represent the landings. The survival of discards is very low and was assumed to be negligible (van Beek et al., 1990). For each age group, we calculated the mean weight in the population, the mean weight of discards and landings, and the proportion maturity.

The parameters settings used in the simulation model are summarised in Table 3. Growth and maturation parameters were estimated from the available biological samples at IMARES for the study period. Selectivity parameters were based on van Beek et al. (1983). For turbot and brill, selectivity parameters were extrapolated from the parameters of plaice and sole, taking account of the differences in body shape.

The simulation model is used to calculate a number of indicators to assess the performance of the different management scenarios (described in section 3.4). The model provides weekly information of the landings and population and allowed us to calculate the total weight (kg) of the landings (Yield), discards (Discards) and spawning stock biomass (SSB) over the lifetime of a cohort (25 years). These indicators are calculated on a per recruit basis and represent the equilibrium conditions assuming constant growth and fishery characteristics (Beverton and Holt, 1957).

The revenue was calculated by summing up the product of the weekly landings and fish price taking account of the seasonal variation in fish price. Fish price increases with size, except in the months prior to spawning and during the spawning period when the price difference is much smaller or may even be absent or reversed (Figure 2). The weekly mean price at age was calculated from the mean price per market category (sale slip data), the proportion of each 1-cm length class occurring in a market category (market sampling data), and the weekly size distribution at age. Revenue of the total flatfish landings is calculated from the revenue per recruit for the different species and the differences in recruitment strength between the four species. The differences in recruitment strength are estimated from the ratio of the equilibrium yield and the total international landings: Plaice=133; Sole=42; Turbot=1; Brill=1.

Although spawning closures intend to increase the production of viable offspring and increase the number of potential recruits, the effect cannot be quantified and we assume recruitment to be unaffected.

The cost of fishing was included in the model by estimating the Fpue per day at sea, including the steaming time between the fishing ground and the harbour. Mean fishing mortality over ages 2-6 (F_(2-6)) was used as an indicator of the exploitation level. The evolutionary effect of fishing was evaluated for the onset of maturation by estimating the slope in the lifetime reproductive success against length at first maturity at the current maturation size (Rijnsdorp 1993b).

By varying the level of fishing effort between 0 and 1.5 times the effort observed in the study period, we estimated the maximum sustainable yield (MSY) and the maximum sustainable revenue (MSR) and corresponding fishing mortality rates (Fmsy, Fmsr) for the individual species, as well as for the species complex (Murawski, 1984).

Ecosystem impacts were evaluated using the catch weight of undersized fish (discards), the fishing mortality imposed on cod, the bycatch of rays and the impact of the seabed integrity. The impact on rays was estimated by calculating the average fishing effort weighted over the relative catch per unit of effort of rays in the different areas. The trawling impact indicator (I) reflected the change in mean annual trawling frequency (f_{is}) by rectangle i in scenario s as compared to the baseline scenario (f_{ib}).

$$I = \frac{\sum_{i=1}^{n} w_i \ln\left(\frac{f_{is}}{f_{ib}}\right)}{\sum_{i=1}^{n} w_i}$$

$$w_i = e^{f_{ib}}$$

w_i is a weight factor reflecting the degree at which the rectangle i has already been impacted in the baseline scenario. The rationale for applying this weight factor is that the impact of trawling on the benthos decreases with trawling intensity.

Performance of the management scenarios with regard to the response indicators (see below) were analysed with principal component analysis (PCA). In order to account for the quantitative difference (per cent change relative to the baseline scenario), the response indicators were not standardised. Only the sign of the effect was adjusted to obtain a positive value if the management scenario had a positive effect on the indicator (increase in spawning stock biomass and revenue, or a decrease in discards, trawling impact and fisheries-induced selection pressure).

2.4   Management scenarios

The management scenarios considered in this study comprise of a baseline scenario reflecting the effort distribution observed in the period 2003-2007 (scenario 1), and three spawning closure scenarios for the main target species: plaice (scenario 2), sole (scenario 3) and plaice and sole combined (scenario 4) (Figure 3, Table 4). The selection of spawning areas is based on data on egg distribution and spawning time (Harding et al., 1978; Bolle et al., in prep).

Closing specific areas implies reallocation of fishing effort to other fishing areas or other seasons. We considered two main reallocation schedules. Schedule A considered spatial reallocation, with fishing effort reallocated within the same week over the rectangles still open to the fisheries. Schedule B considered temporal reallocation, with fishing effort reallocated to other seasons. Displaced fishing effort was distributed over the open rectangles and/or weeks in proportion to the effort exerted in those rectangles and/or weeks.

3. Results

3.1 Catchability

GAM models of the ontogenetic changes in Fpue explained between 38 and 59% of the deviance (Table 5). The predicted Fpue showed distinct seasonal and ontogenetic changes. The salient results are illustrated in Figure 4 for a selection of areas and will be presented for the species separately. The areas chosen include both coastal nursery areas as well as spawning and feeding areas.

Fpue of age 2 sole increases in summer and early autumn, reflecting the offshore movement of the recruiting year class. For age 3 and above, the Fpue show a seasonal peak in spring in areas #2 and #3 reflecting coastal spawning, whereas in offshore areas such as the Doggerbank (#13), Fpue peaks in winter time, reflecting the offshore movement of sole in winter. Fpue of sole in northern areas is very low.

Plaice Fpue shows a similar increase of younger age groups 2 in summer and early autumn, whereas for age groups 4 and older a seasonal pattern is observed with a peak in late December and January in offshore areas in the southern North Sea (area #3 and #7). In the deeper waters of the central North Sea, the Fpue of older fish are low in winter and peak between spring and autumn. These alternating patterns reflect the migrations to the spawning areas in the southern North Sea. The peak in Fpue of the older age groups is decrease with age in the Southern bight, in contrast to the German Bight where the peak in Fpue increases with age.

Fpue of age 2 turbot increases in most areas reflecting the recruitment from the coastal nursery areas. Seasonal patterns were less consistent than in sole and plaice, although a peak in late spring is apparent in the German Bight (areas #4 and #7) and the Fisher Bank (area #12). Highest Fpue occurred the German Bight and the central North Sea areas.

Fpue of brill is already at a high level at age 2 and does not show the increase observed in the other flatfish species. The seasonal patterns suggest that Fpue peaks in spring in most areas and reach a minimum level in summer.

Fpue in cod shows a consistent pattern with a peak in the beginning of the year in the southern and southeastern North Sea. In the northern North Sea Fpue was high but did not show a consistent seasonal pattern across age groups.

3.2 Effect of spawning closures

The plaice spawning closures resulted in a reallocation of 12% of the annual fishing effort to either other fishing areas in the same weeks (schedule A), or to other weeks (schedule B). A sole spawning closure resulted in a reallocation of 5% of the annual effort (Table 4). This difference is due to the difference in fishing pressure in the spawning grounds of these two species. Plaice spawns in the heavily fished offshore areas of the southern North Sea, whereas sole spawns in the coastal waters and the Plaice Box where fishing is limited to mainly vessels of <225 kW.

3.2.1. Exploitation pattern

The spawning closures influence the exploitation patterns of the different species which will be described by species. The exploitation pattern of plaice is affected mostly by the plaice spawning closure (scenario 2) and the combined spawning closure (scenario 4, Figure 5a). These scenarios result in a reduction in the fishing mortality on the oldest age groups (up to 22%) and an increase on the youngest age groups (15-25%). Reallocation of the effort outside the closed period (scenario 2B and 4B), resulted in the largest change in exploitation pattern. A spawning closure of sole resulted in a small increase in the fishing mortality of the older age groups of plaice (scenario 4 and 5).

The exploitation pattern of sole was marginally affected by the spawning closures (Figure 5b). Plaice spawning closure increased the fishing mortality of older age groups of sole by 4%, whereas a sole spawning closure slightly reduced the F by 1%-3%. Combined closure of plaice and sole spawning resulted in an intermediate result.

The exploitation pattern of turbot was slightly affected by spawning closures (Figure 5c). A decrease in fishing mortality on older age groups was obtained under a plaice spawning closure with effort reallocation within the closed period (scenario 2A). If effort is reallocated to other seasons (scenario 2B), or when a sole spawning closure is put into place, this results in a slight increase in fishing mortality on turbot.

The exploitation pattern of brill showed a variable response (Figure 5d). Fishing mortality on the older age groups increases substantially under a plaice spawning closure scenario, in particular when effort is re-allocated within the closed period (2A and 4A). A reduction in the fishing mortality on brill is shown when effort is re-allocated outside the closed periods (scenarios 2A and 4B).

The exploitation pattern of cod shows a 40-50% drop in fishing mortality in response to the spawning closure of plaice, in particular when the effort was reallocated outside the closure period (Figure 5e). The sole spawning closures give a small increase in fishing mortality on cod.

3.2.2. Response indicators at current effort level

The effect of the different management scenarios at status quo fishing effort on the response indicators are presented in Table 6. Details of the results are presented in Appendix 1. To facilitate the comparison of the management scenarios the results of the multiple indicators were summarised by a PCA (Figure 6). Response indicators were re-scaled to reflect a positive effect of the management scenario. The first two principal components explained 83% and 15% of the deviance. The effects of a spawning closure for plaice and sole are clearly different. A spawning closure for plaice (scenario 2) or sole (scenario 3) have opposite effects, whereas the re-allocation scenario (A and B) is mainly important for the spawning closure for plaice (scenario 2) or the combined scenario (scenario 4). The loading of the response indicator on the effect of the scenario is indicated by the size of the arrow, whereas the direction of the arrows relative to the position of the scenarios, reflect which indicators are positively affected (Figure 6).

Plaice spawning closure. A spawning closure for plaice results in a 26% increase in equilibrium SSB and a reduction of 7% in the average fishing mortality for this species (Table 6 scenario 2B).

While the equilibrium landings increase slightly (0.3%), the revenue increases by 8% because of a higher price of the landed plaice. The number of plaice discards decreases slightly (-2%). Similar but smaller effects are estimated for reallocation scenario 2A.

The effects on the other flatfish species are smaller and depend on the re-allocation scenario. A plaice spawning closure results in a slight increase fishing mortality on sole and a reduction in SSB. The effects on turbot and brill depend on the re-allocation scenario. The effect on the ecosystem indicators show a substantial reduction in the ecosystem impact (Table 6 scenario 2B), in particular the bycatch mortality of cod (-30%), rays (-17%) and to a lesser extend flatfish discards (-2%), but the trawling impact indicator increase by 10% due to the re-allocation of fishing effort to less intensively trawled fishing areas. The selection pressure for earlier maturation decreases by 43% for plaice, and increase by 2% for sole.

The above results are obtained if the fishing effort during the spawning period is reduced by reallocated the spawning time effort to the weeks outside the spawning period (scenario 3A). If the fishing effort on the spawning grounds is re-allocated to other fishing areas within the plaice spawning period, similar effects are apparent but generally at lower levels (scenario 3B).

Sole spawning closure. A spawning closure of sole results in a 2% decrease in fishing mortality, a 3% increase in equilibrium SSB and 2% increase in revenue of sole (Table 6 scenario 3B). The already low number of sole discards decrease slightly <1%. The revenue and SSB's of other flatfish species are reduced with a few percent, coinciding with the 2-5% increase in fishing mortality on sole. Differences between the re-allocation schedules are relatively small. The effect on the ecosystem indicators show only small changes (generally <5%), except for the 12-19% increase in the bycatch of cod and an increase in fisheries-induced evolution pressure on plaice by 10%.

Combined spawning closure. A combined spawning closure of plaice and sole with a re-allocation of fishing effort outside the closed periods results in a positive effect on SSB (3%-18%) and revenue of both species (3-6%). The effects on the other flatfish species and ecosystem are variable but tend to be positive. Numbers of flatfish discarded are reduced and the bycatch mortality of rays and cod is substantially lower, but the trawling impact increases. Combined spawning closure with effort allocated to the open areas during the closed period generally have smaller positive effects.

3.2.4. Response indicators at MSY

Since the above explorations assume a level of fishing effort as observed in the period 2003-2007, the results do not necessarily apply to a situation where fishing effort conforms to the management objective of Maximum Sustainable Yield (MSY). The MSY of the flatfish complex occurs at a level of fishing effort of 40%-46% of the current level, depending on the scenario, with an average level of 42%. The F_{MSY} of the species complex differed from that of the individual species, although the difference was relatively small. To achieve the maximum sustainable revenue, effort needs to be reduced further to 32% of the status quo effort (results not shown).

The effect of the different spawning closures on the response indicators at FMSY differ only marginally from the effect at Fstatus quo , except for the fisheries-induced evolution (Figure 6). At FMSY, spawning closures further increase the revenue, while discarding of flatfish is further decreased with a plaice spawning closure, but slightly increased with a sole spawning closure. The effect on SSB at FMSY is lower as compared to status quo effort. The effect on fishing mortality is similar, but the increase in trawling impact is slightly reduced as compared to Fstatus quo. The substantial reduction of fishing effort at MSY level results in a much lower pressure for evolutionary changes. In plaice, the direction of the selection pressure for earlier maturation even changes towards larger size at first maturation. The effect of spawning closures at maximum sustainable revenue (FMSR=0.34*Fstatus quo) was broadly similar to the results at FMSY (results not shown).

4. Discussion

4.1 Management evaluation model

The credibility of the results of the management scenario simulations depends on the mechanisms included in the simulation model and its parameterisation. The model included the key population dynamic processes growth, natural mortality and estimated fishing mortality as the result of the overlap of fishing effort and fish. The model explicitly included the ontogenetic and seasonal changes in distribution of fish. The biological parameters were based on an analysis of biological samples and are representative for the female component. We deliberately decided not to include males, because this would have added complexity in the analysis of the yield per recruit, estimating discards and the fisheries-induced selection.

The ontogenetic and seasonal changes in distribution are estimated in terms of the partial fishing mortality Fpue by week in each fishing area. The GAM-analysis explained between 38-59% of the deviance in Fpue. Although the Fpue will be mainly determined by the density of fish on a fishing ground, it will also incorporate the effect of fish behaviour for instance in relation to migrations (Hunter et al., 2004b) or spawning activity (Solmundsson et al., 2003). Variations in estimates of Fpue will be related to inter-annual variations in the distribution of fish, as well as variations in the level of aggregation of fish (Temming et al., 2007; Shucksmith et al., 2006) or the fishery (Rijnsdorp et al. 2011).

Fpue is estimated from the catch per unit of effort of the commercial vessels representing the dominant fleet in the North Sea flatfish fishery covering the total distribution area of the fleet (Jennings et al., 1999). Because the fishery operates under an Individual Transferable Quota system for sole and plaice, and a total Allowable Catch for the other species, the Fpue estimates may be biased due to high-grading and over-quota discarding (Rijnsdorp et al., 2007). Over-quota discarding will most likely have affected the Fpue of cod because of the severely restricted quota for this stock (Ulrich et al., 2011). For flatfish, we consider it unlikely that our estimates are seriously affected. Although there is some evidence for over-quota discarding and high-grading in flatfish species (Poos et al., 2010), beam trawl fishers may to some extend avoid it by choosing fishing grounds that match the relative fishing rights (Quirijns et al., 2008). Also TACs for turbot and brill were introduced only recently and were set at a relatively high level. It is unclear to what extent Fpue is influenced by competitive interactions among fishing vessels (Gillis and Peterman, 1998; Poos and Rijnsdorp, 2007), which may occur when fishing vessels aggregate on a local fishing ground (Rijnsdorp et al., 2000; Poos and Rijnsdorp, 2007).

Despite of these potential distortions, the estimated distribution patterns in Fpue do reflect the known changes in distribution and migrations. The offshore movement of juvenile flatfish recruits out of their coastal nurseries (Beverton and Holt, 1957; Gibson, 1994) is reflected in the increase in Fpue of 2-year olds in summer and autumn. In plaice, the migrations between feeding and spawning areas (Rijnsdorp and Pastoors, 1995; Hunter et al., 2004a) is reflected in the high Fpue in the beginning of the year and the low Fpue in summer in the known spawning areas in the Southern Bight (#3) and German Bight (#7), whereas an opposite pattern is observed for a typical feeding area (#19).

In sole, the inshore – offshore migrations of adults (ICES, 1965) is reflected in the high Fpue during spring in their known spawning areas (#2, #3) and the high Fpue in autumn and winter in the offshore areas of the southern North Sea (#13). The lack of a clear seasonal pattern in the coastal waters of the German Bight (area #7) is likely due to the fact that the spawning grounds of sole mainly occur in the shallow coastal waters where the larger beam trawlers are not allowed to fish. For turbot and brill, there is insufficient information available to relate the observed patterns in Fpue with migrations between spawning and feeding areas. The clear seasonality in cod with high Fpue in winter in the Southern Bight (#3) and the German Bight (#7) coincides with the spawning aggregations in the 1st quarter (Daan, 1978).

The spatial allocation of fishing effort assumed that the fleet remains fishing in the open rectangles in proportion to the effort in the baseline period. This pattern of effort allocation in the baseline period reflects the relative profitability of the rectangles given the distribution and abundance of the main fish species during this period. Because the flatfish species included in our study contribute on average more than two thirds of the total revenue of the fisheries, our simulations will give a reasonable first estimate of the expected effects of the spawning closures.

4.2 Mixed fisheries management

The indicators used in our study to assess the effect of the management scenarios were chosen to reflect the multiple objectives for demersal fisheries. The main objective of fisheries management is to reduce the fishing mortality to a level corresponding to maximum sustainable yield and to reduce the negative ecological impacts of the fisheries (ICES 2010). To achieve the specific objective for the North Sea flatfish fisheries, restrictive TACs are set to gradually reduce the fishing mortality to a level of F=0.3 for plaice and F=0.2 for sole. For the additional ecosystem objectives: (i) decreasing the bycatch of species at risk; (ii) decreasing the bycatch of undersized flatfish; (iii) reducing the trawling impact on the benthic ecosystem, no specific measures have yet been implemented. Stocks of particular concern in the North Sea comprise cod and several ray species. A substantial reduction fishing mortality of cod is required to rebuild the stock. Because cod is caught in almost all fisheries targeting demersal species, the required reduction in fishing mortality of cod will have drastic consequences for other demersal fisheries in which cod is part of the bycatch such as the flatfish fisheries (Ulrich et al., 2011). Local populations of the thornback rays *Raja clavata* have disappeared from the south-eastern North Sea due to fishing (Walker and Heessen, 1996). The flatfish fishery is characterised by high discarding of undersized flatfish, in particular plaice (van Beek, 1998; Pastoors et al., 2000) and have a negatively impact benthos and benthic habitats (Jennings and Kaiser, 1998). In addition, there is a growing concern about fisheries-induced evolution and managers have been urged to take actions to reduce the selection pressures on the exploited fish stocks (Jorgensen et al., 2007).

It is unlikely that TAC management alone will be able to achieve sustainability in mixed demersal fisheries, because restrictive TACs will lead to discarding of over-quota fish or less valuable size classes (Daan, 1997; Rijnsdorp et al., 2007; Ulrich et al., 2011). In order to achieve sustainable exploitation of the complex of demersal fish species and to minimise the negative ecological impacts, additional measures are required, such as spatial management and gear modifications.

4.3   Impact of spawning closures

In this study, we focussed on the potential effect of spawning closures as a contribution to sustainable exploitation. The rationale for spawning closures is mainly based on theoretical grounds (van Overzee and Rijnsdorp, 2010). In general, spawning closures may be beneficial as they may offer additional protection to the large and older fish which contribute disproportionally to the reproduction of the population and may increase the level and decrease the variability in recruitment (Law, 2007; Wright and Trippel, 2009; van Overzee and Rijnsdorp, 2010). It has been notoriously difficult, however, to statistically detect the expected positive effect on recruitment (Brunel, 2010) and the empirical evidence is thin (Hsieh et al., 2006). We therefore focussed our analysis on the effects of spawning closures on the yield and SSB per recruit ignoring the expected positive effect on the level of recruitment.

A spawning closure for plaice has been advocated by some fishers, NGO's and retailors. Our modelling results suggests that a spawning closure for plaice or a combined spawning closure for plaice and sole, will positively contribute to most of the desired improvements in exploitation. The most important effects of the plaice spawning closure was the increase in SSB of plaice and turbot, the reduction in flatfish discards and in particular the substantial reduction in the bycatch mortality on cod and rays. A plaice spawning closure will probably further reduce the evolutionary selection pressure for early maturation in plaice. The reduction in evolutionary pressure is mainly due to the reduction of the fishing mortality on the older age groups. A spawning closure for sole generally results in opposite effects, although the size of the effect was relatively small. In combination with a spawning closure for plaice, the overall positive effects of the plaice spawning closure dominated. The positive effects on the fish stocks and the ecosystem coincided with an increase in the revenue for the fishery, in spite of the slight reduction in the landed weight. The increase in revenue was due to the higher price of the landed fish outside the spawning period. The effects of spawning closures were not restricted to the current levels of fishing effort. Similar effects were also found at a lower level of fishing effort (Fmsy) for the flatfish complex. At Fmsy, spawning closures will further enhance revenue and decrease flatfish discards and trawling impact. The positive effect on SSB, however, will be reduced.

Spawning closures do not have exclusively desirable effects. Our simulations suggested that a plaice spawning closure would result in a decrease in the SSB of sole and turbot, and an increase in the trawling impact on the benthos. The trade-off between the pros and cons of spawning closures on the different response indicators for the various management objectives will be valuated differently by various stakeholders. Innes and Pascoe (2010) showed that fishers valued the discarding levels higher than the trawling impacts on benthic habitats, while ecologist valued the habitat impact higher. Groeneveld (2011) showed that citizens are most concerned about the impact of beam trawling on benthic megafauna, but reducing fishing pressure in the plaice spawning period and restoring spawning-stock biomass of plaice and sole to the levels of maximum sustainable yield are also supported. Fishers seem to support enhanced fines for the use of illegal fishing gear, but they are most opposed to increasing the minimum landing size of sole.

Our study presented a quantitative framework to estimate the effects of management measures on a variety of indicators representing the effects of fishing on the exploited fish stocks, the ecosystem and the economic performance of the fishery in a fishery system targeting a mix of bottom dwelling species.

As such the results may be used as input in a process of stakeholder consultation which may lead to a final political decision taking account of the different valuation systems across stakeholders (Verweij and van Densen, 2010, Verweij et al., 2010). The approach can easily be extended to include different fisheries to include technical interactions (Murawski, 1984). The model framework was used to assess the effects of spawning closures on the sustainability of flatfish fisheries. It was shown that a spawning closure in the beginning of the year to reduce the fishing pressure on the adult component of plaice, will have a positive contribution to most of the objectives set for the demersal fisheries in the North Sea.

5. Acknowledgments

6. Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 57846-2009-AQ-NLD-RvA). This certificate is valid until 15 December 2012. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Environmental Division has NEN-AND-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 27 March 2013 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

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8. Tables and Figures
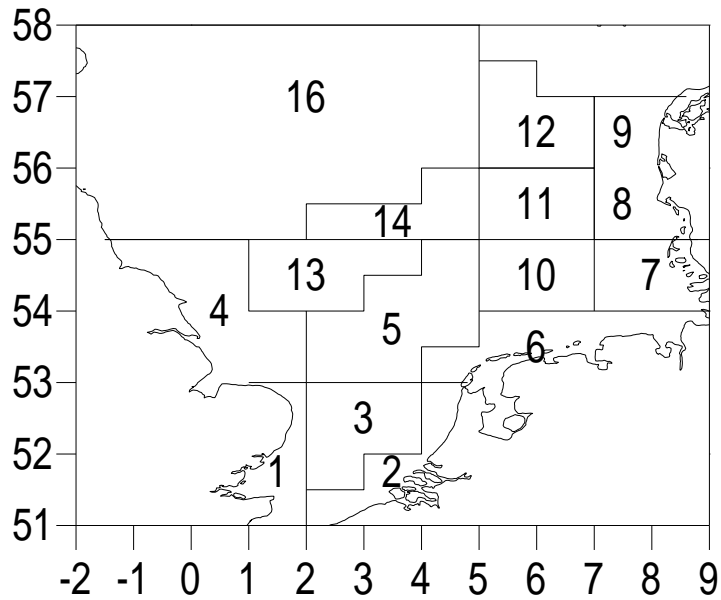
Figure 1. Map of study area and the fishing areas distinguished. Numbers denote the sampling areas for the monthly age-length-keys. For the analysis of the Fpue, the spatial resolution was increased by subdividing areas 3, 10, 11 and 12 in two and area 5 in 3 subareas.
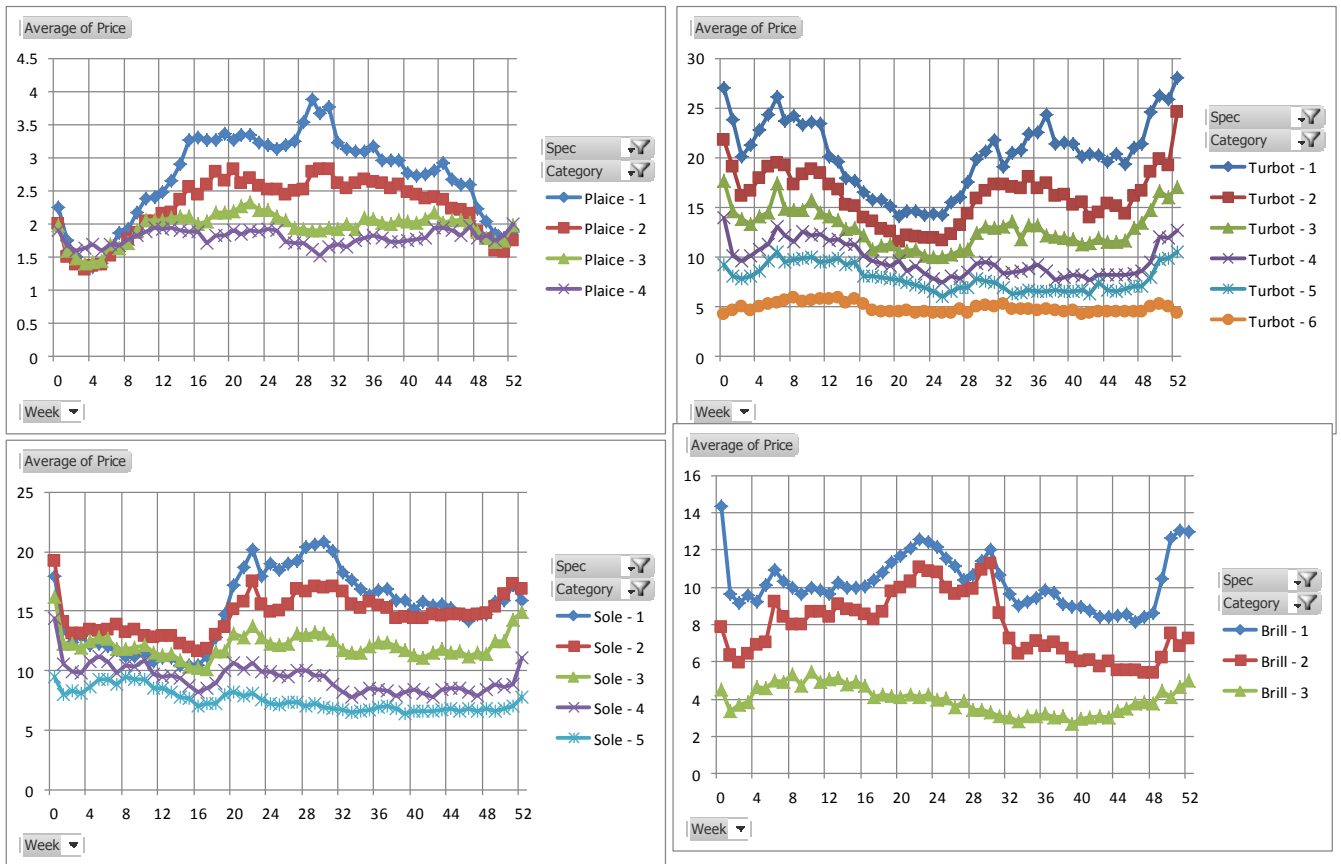
Figure 2. Average first sale price of the market size categories of plaice, sole, turbot and brill in the period 2003-2007. Market categories are sorted in decreasing order of fish size.
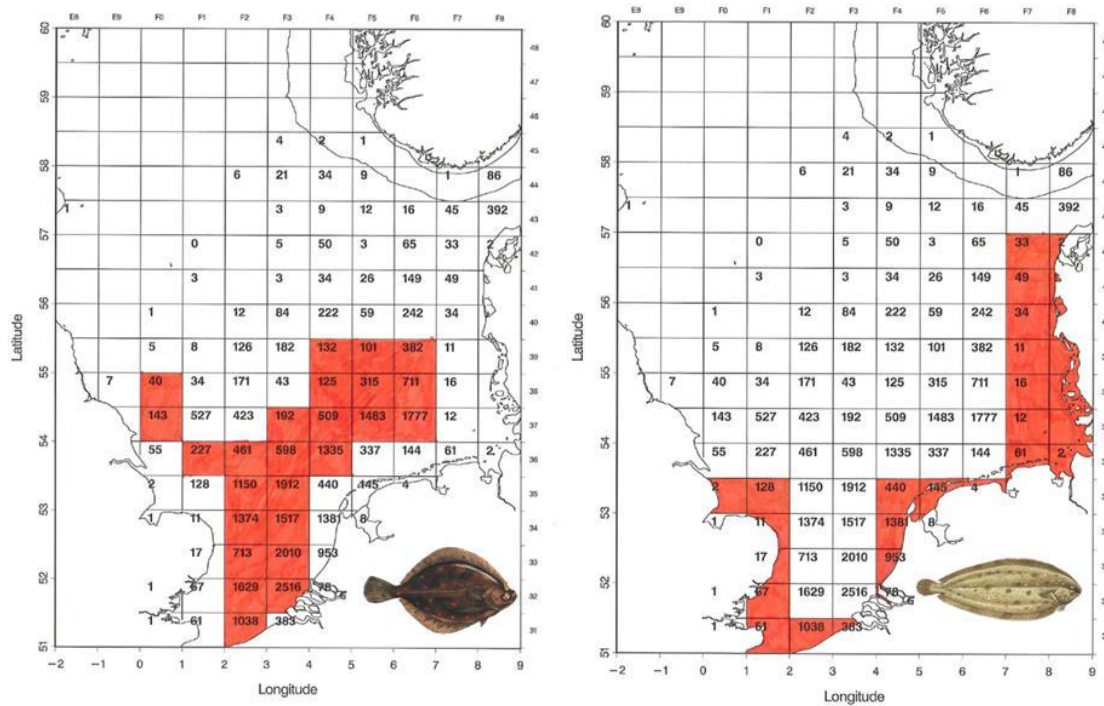
Figure 3. Rectangles closed to fishing during the spawning period of plaice (week 1-8: left panel) and sole (week 13-20: right panel). The numbers in each rectangle denote the average number of fishing days per year in the period 2003-2007.
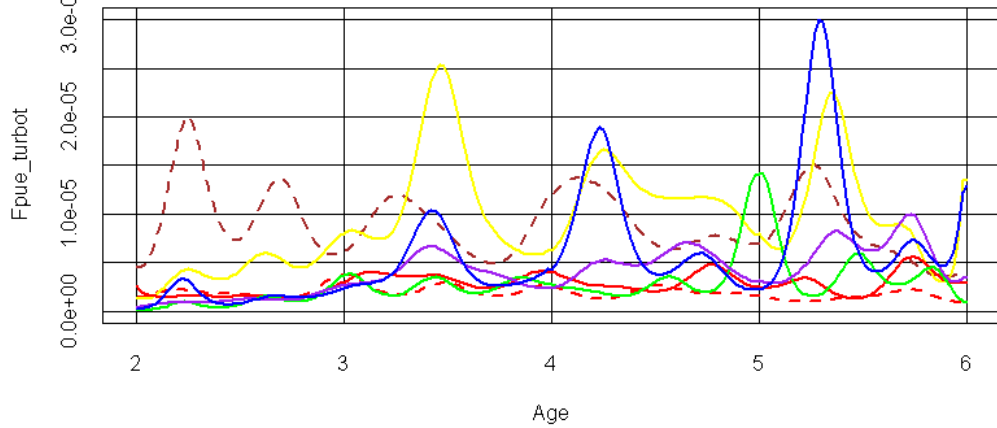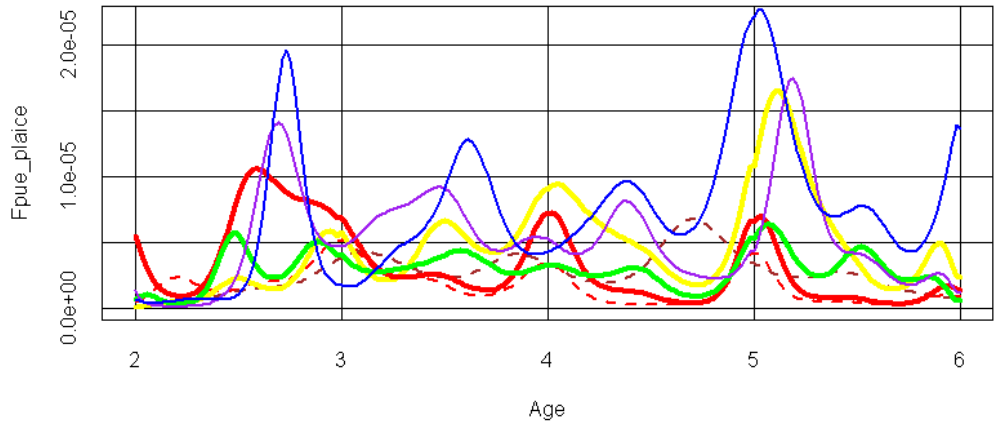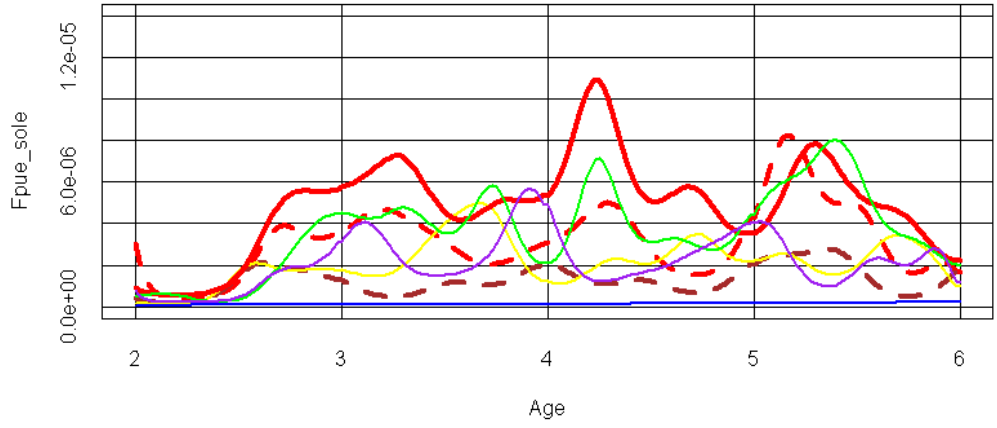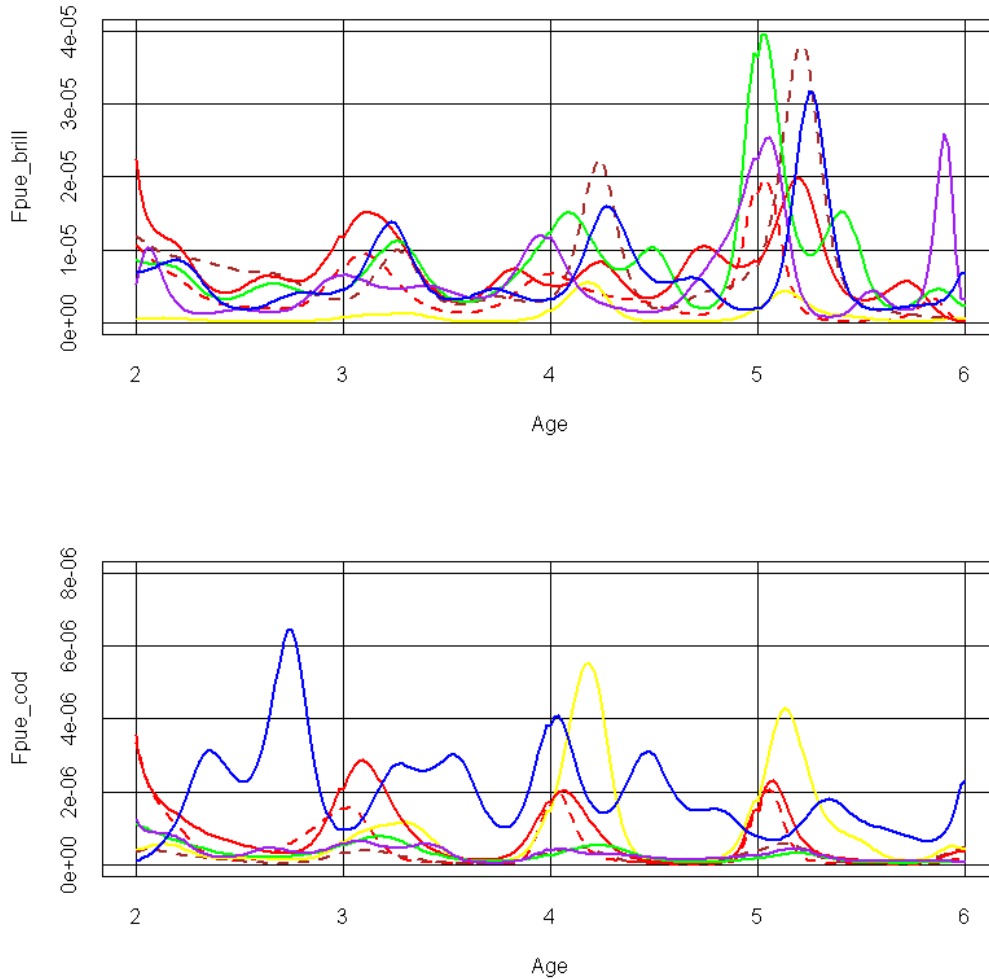
Figure 4. Seasonal and ontogenetic changes in the Fpue for (a) sole, (b) plaice, (c) turbot, (d) brill and (e) cod and (f) seasonal changes in Cpue of rays for a selection coastal areas (dashed lines: #2 Dutch coast – red; #7 German coast - brown) and offshore waters (full lines: #3 Southern Bight – red; #4 Flamborough – green; #10 German Bight – yellow; #12 Fisher bank – blue; #13 Doggerbank – purple). Fishing area codes refer to Figure1. The thick lines represent Fpue in spawning areas (sole and plaice).
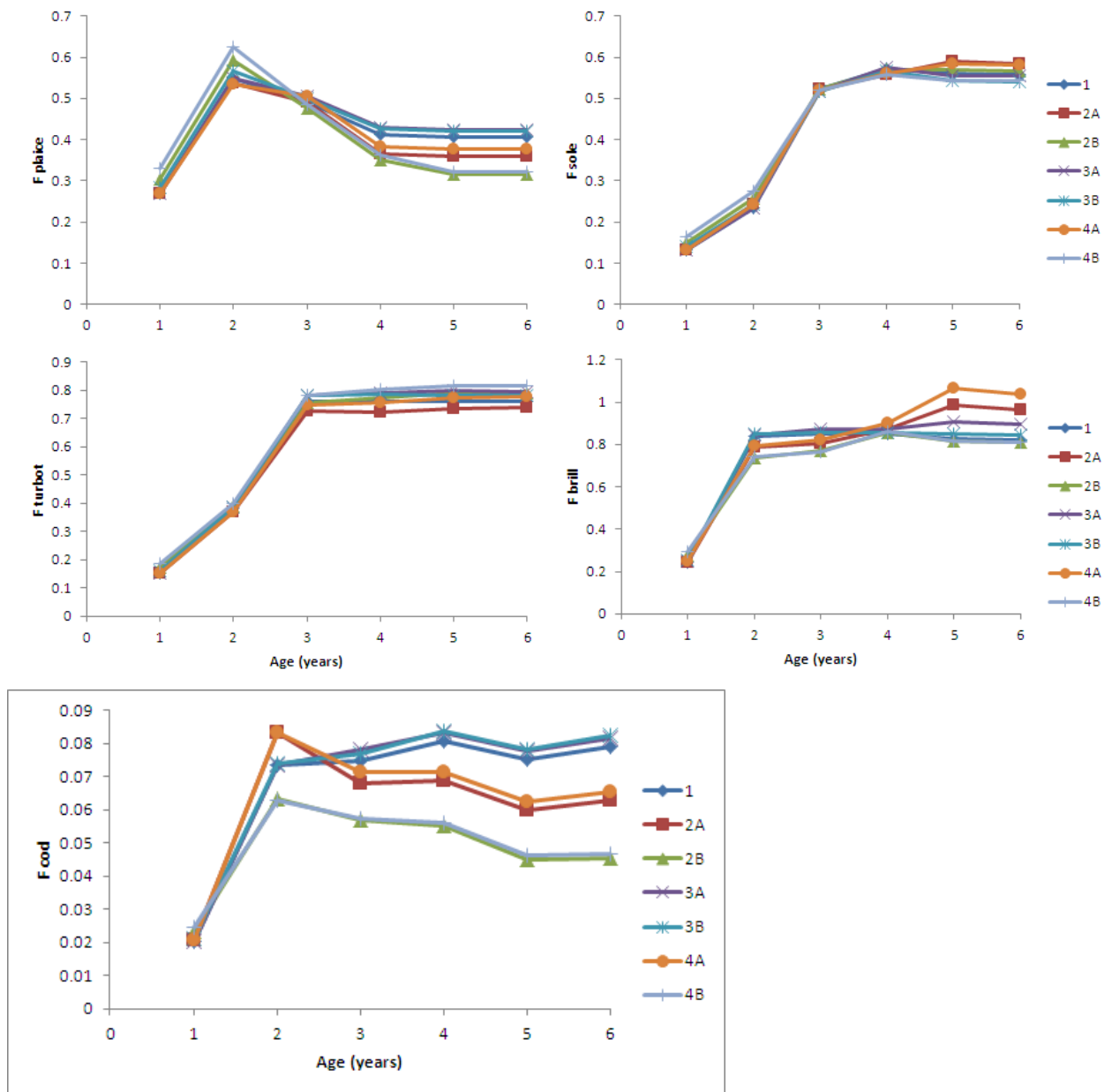
Figure 5. Exploitation patterns for plaice, sole, turbot and brill for the base line scenario (1) and the spawning closure for plaice (scenario 2), sole (scenario 3) and combined (scenario 4) assuming reallocation within the closed period (reallocation schedule A) and outside the closed period (reallocation schedule B)
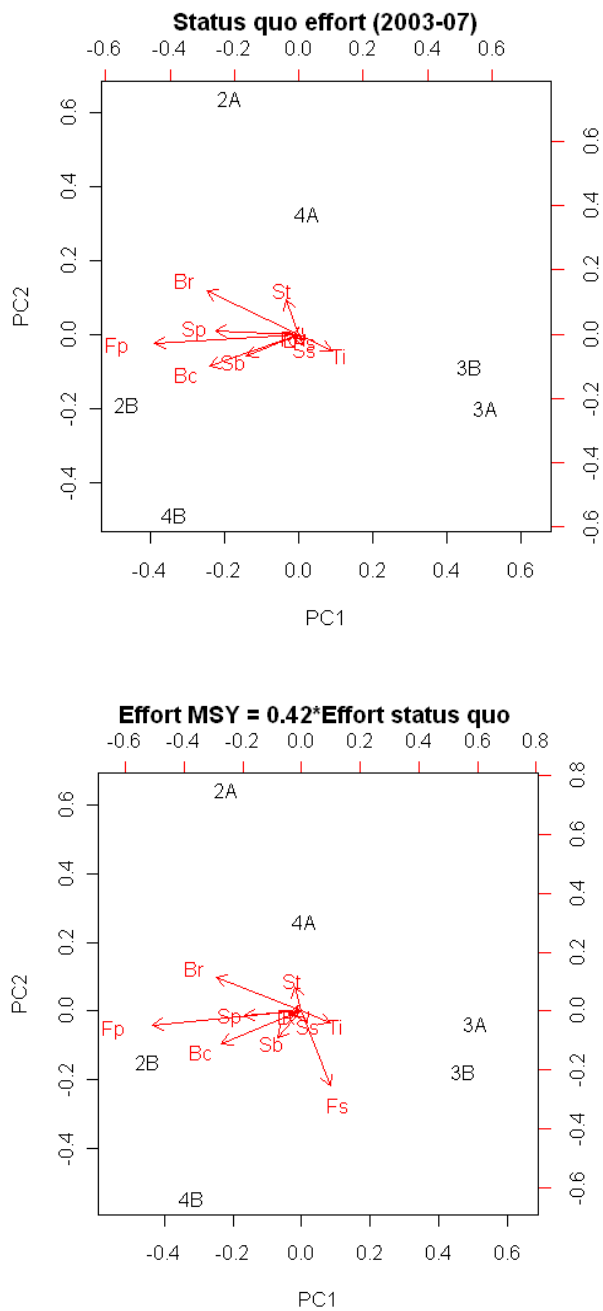
Figure 6. Results of the Principal Component Analysis (PCA) on the response variables of the management scenarios (Plaice spawning closure: 2A, 2B; Sole spawning closure: 3A, 3B; Combine plaice and sole spawning closure: 4A, 4B) for status quo effort (upper panel) and MSY effort (lower panel). Arrows show the loadings of the response indicators (R= revenue flatfish; Sp=SSB plaice; Ss=SSB sole; St=SSB turbot; Sb= SSB brill; Bc = bycatch cod; Br = bycacth rays; Ti = trawling impact on benthos; .Fp=fisheries-induced selection plaice; Fs=fisheries induced evolution sole. Response indicators were re-scaled to reflect a positive effect (see text).

Table 1. Number of fish sampled between 2003 and 2007 to construct the age-length-key

Area	Plaice	Sole	Turbot	Brill	Cod
1	120	0	0	0	0
2	1007	2683	675	758	1782
3	5419	5802	1375	1613	3427
4	960	645	39	59	101
5	6586	4240	1043	1484	2253
6	882	1091	109	202	0
7	480	399	137	223	45
8	119	249	400	683	112
9	179	0	30	60	0
10	3477	2047	593	820	503
11	720	150	195	280	224
12	600	0	89	120	276
13	1138	350	74	240	633
14	957	0	34	0	228
16	420	0	73	158	217
Total	23064	17656	4866	6700	9801

Table 2. Fishing mortalities at age used in the simulation

Age	Plaice*	Sole	Turbot	Brill	Cod**
1	0.172	0.018	0.001	0.111	0.032
2	0.550	0.234	0.383	0.838	0.073
3	0.491	0.522	0.760	0.850	0.075
4	0.411	0.573	0.760	0.849	0.081
5	0.405	0.560	0. 760	0.829	0.075
6	0.390	0.550	0. 760	0. 829	0.075

*including discards and landings

**Partial fishing mortality of the modelled fleet – explain further- I presume you mean for the area covered?

Table 3. Parameter values used in the simulations

	Sole	Plaice	Turbot	Brill
Natural mortality				
M	0.1	0.1	0.1	0.1
Growth				
Linf (cm)	42.9	48.1	65.13	47.7
K	0.263	0.232	0.326	0.653
t0	0.03	0	0.5	0.5
Cv	0.15	0.15	0.15	0.15
Weight(g) – length(cm) relationship				
Intercept	-5.738	-5.055	-4.751	-4.510
slope	3.293	3.107	3.229	3.064
Selection ogive				
Selection factor	3.33	2.24	1.5	1.5
Selection range	0.13	0.14	0.15	0.15
L_{min} (cm)	24	27	0	0
Maturation ogive				
Intercept	22.124	16.244	13.758	12.948
slope	-0.925	-0.600	-0.364	-0.386

Table 4. Management scenarios considered in this study and the percentage of the percentage re-allocated effort of the annual total and spawning period total. Effort was re-allocated within the spawning period (a-scenario's) or outside the spawning period (b-scenario's).

Scenario	Description	Week	%Effort reallocation	
			of annual total	of spawning period total
1	Baseline		0	0
2	Plaice spawning closure	1-8	11.6%	80.3%
3	Sole spawning closure	13-20	4.7%	29.5%
4	Combination #2+#3	1-8; 13-20	16.3%	52.9%

Table 5. Results of the GAM of Fpue

	Deviance explained	Estimated degrees of freedom	n
Plaice	59.0%	378.4	153 234
Sole	50.6%	261.1	153 234
Turbot	52.6%	360.3	153 234
Brill	37.8%	347.0	153 234
Cod	53.9%	327.0	153 234
Rays	51.3%	58.6	38 310

Table 6. Change (%) in the response indicators for six spawning closure scenario's relative to the baseline at status quo fishing mortality ($F_{2003-2007}$)

Response indicators		Scenario					
		2A	2B	3A	3B	4A	4B
Revenue	Plaice	3.7%	7.6%	-0.2%	-1.5%	3.4%	5.5%
	Sole	-0.5%	0.3%	0.2%	1.6%	-0.3%	2.9%
	Turbot	3.9%	-1.5%	-2.4%	-2.1%	1.4%	-3.9%
	Brill	3.3%	8.1%	-0.3%	-1.3%	2.9%	6.8%
	Flatfish	1.3%	2.7%	-0.2%	0.3%	1.1%	3.2%
Landings	Plaice	1.2%	0.3%	-0.4%	-0.9%	0.8%	-0.9%
	Sole	-0.1%	-0.1%	0.1%	0.4%	0.0%	0.6%
	Turbot	2.8%	0.3%	-1.1%	-1.2%	1.6%	-1.2%
	Brill	2.4%	4.8%	-0.3%	-0.7%	2.0%	4.3%
	Flatfish	1.0%	0.3%	-0.4%	-0.7%	0.7%	-0.5%
Discards	Plaice	-0.6%	-2.5%	0.4%	0.0%	-0.1%	-2.8%
	Sole	0.5%	0.2%	0.0%	-0.2%	0.4%	0.0%
	Turbot	-0.6%	-0.1%	0.3%	0.3%	-0.3%	0.2%
	Brill	-0.4%	-1.1%	0.2%	0.2%	-0.2%	-1.0%
	Flatfish	-0.5%	-2.1%	0.4%	0.0%	0.0%	-2.3%
SSB	Plaice	16.1%	26.2%	-5.6%	-6.4%	8.9%	18.1%
	Sole	-2.7%	-1.0%	0.5%	2.5%	-2.3%	2.5%
	Turbot	8.9%	-1.1%	-5.8%	-4.9%	2.4%	-6.4%
	Brill	4.1%	16.8%	-3.7%	-2.4%	0.7%	16.0%
Fmean	Plaice	-6.7%	-9.3%	3.0%	3.3%	-3.8%	-6.3%
	Sole	2.5%	2.6%	-0.4%	-2.1%	2.0%	-0.2%
	Turbot	-3.7%	2.3%	3.8%	2.9%	0.1%	5.8%
	Brill	5.4%	-4.6%	4.9%	1.6%	10.4%	-4.6%
	Cod	-10.4%	-30.5%	2.8%	3.2%	-7.6%	-29.8%
Bycatch	Rays	-22.2%	-16.8%	18.9%	12.2%	-7.5%	-8.4%
Trawling impact	Benthos	10.9%	9.7%	-1.5%	-2.4%	10.7%	7.7%
Fisheries-induced evolution	Plaice*	-25.1%	-43.0%	10.7%	8.9%	-14.8%	-38.2%
	Sole*	-0.4%	2.0%	-0.7%	-3.3%	1.2%	-3.6%

*Baseline slope in fisheries-induced evolution is towards a decrease in maturation length in plaice (-0.0138 cm^{-1}) and sole (-0.0322 cm^{-1})

Table 7. Changes in response indicators relative to the baseline scenario for the different spawning closure scenarios and the fishing effort at a level of $F_{msy}=0.42* F_{2003-2007}$

		2A	2B	3A	3B	4A	4B
Revenue	Plaice	1.9%	5.7%	1.0%	-0.6%	3.1%	4.8%
	Sole	0.1%	1.1%	0.0%	1.0%	0.1%	2.9%
	Turbot	1.7%	-1.5%	-1.7%	-0.9%	0.0%	-2.4%
	Brill	2.5%	4.3%	0.6%	-0.5%	2.9%	3.6%
	Flatfish	1.4%	4.6%	0.8%	-0.2%	2.4%	4.3%
Landings	Plaice	-1.5%	-4.4%	0.4%	0.0%	-0.9%	-4.5%
	Sole	0.6%	0.2%	-0.1%	-0.3%	0.6%	-0.2%
	Turbot	1.4%	0.4%	-0.5%	-0.6%	0.9%	-0.4%
	Brill	2.5%	2.5%	0.5%	-0.2%	2.8%	2.2%
	Flatfish	-1.0%	-3.2%	0.3%	-0.1%	-0.5%	-3.4%
Discards	Plaice	-3.1%	-6.2%	1.2%	0.9%	-1.6%	-5.4%
	Sole	1.2%	0.4%	-0.2%	-0.8%	1.1%	-0.7%
	Turbot	-1.1%	0.2%	0.8%	0.7%	-0.2%	0.9%
	Brill	0.3%	-1.6%	0.7%	0.4%	0.9%	-1.5%
	Flatfish	-2.0%	-4.5%	0.9%	0.5%	-1.0%	-4.2%
SSB	Plaice	11.3%	19.8%	-4.1%	-4.1%	6.6%	15.7%
	Sole	-3.2%	-1.1%	0.5%	2.5%	-2.8%	2.4%
	Turbot	5.7%	-2.5%	-5.2%	-3.9%	0.1%	-6.7%
	Brill	-3.8%	7.9%	-4.7%	-2.0%	-7.7%	7.6%
Fmean	Plaice	-6.7%	-9.3%	3.0%	3.3%	-3.8%	-6.3%
	Sole	2.5%	2.6%	-0.4%	-2.1%	2.0%	-0.2%
	Turbot	-3.7%	2.3%	3.8%	2.9%	0.1%	5.8%
	Brill	5.4%	-4.6%	4.9%	1.6%	10.4%	-4.6%
	Cod	-10.4%	-30.5%	2.8%	3.2%	-7.6%	-29.8%
Bycatch	Rays	-22.2%	-16.8%	18.9%	12.2%	-7.5%	-8.4%
Trawling impact	Benthos	9.8%	8.7%	-1.7%	-2.4%	9.6%	6.8%
Fisheries-induced evolution	Plaice*	29.1%	48.0%	-12.7%	-10.5%	17.8%	43.2%
	Sole*	-1139%	-4.4%	2.5%	11.9%	-7.7%	12.7%

*Baseline slope in fisheries-induced evolution is towards an **increase** in maturation length in plaice (0.002454 cm^{-1}) and a **decrease** in maturation length in sole (-0.00265 cm^{-1})

9. Justification

Rapport C067/11
Project Number: 4301104701

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

Approved: Dr M.C. Dickey-Collas
                       Senior researcher

Signature:

Date: 29 June 2011

Approved: Dr T. Bult
                       Head Department Fisheries

Signature:

Date: 29 June 2011

Appendix 1. Change of the response indicators relative to the baseline scenario for the flatfish species at status quo fishing mortality

Spec	run	ssb	landings	discards	nlandings	ndiscards	revenue	meanf
Brill	2	1.041	1.024	0.996	0.996	0.979	1.033	1.054
Brill	3	1.168	1.048	0.989	0.987	1.035	1.081	0.954
Brill	4	0.963	0.997	1.002	1.001	1.023	0.997	1.049
Brill	5	0.976	0.993	1.002	1.003	0.941	0.987	1.016
Brill	6	1.007	1.020	0.998	0.997	1.002	1.029	1.104
Brill	7	1.160	1.043	0.990	0.990	0.940	1.068	0.954
Plaice	2	1.161	1.012	0.994	0.993	0.988	1.037	0.933
Plaice	3	1.262	1.003	0.975	0.955	1.010	1.076	0.907
Plaice	4	0.944	0.996	1.004	0.999	1.006	0.998	1.030
Plaice	5	0.936	0.991	1.000	0.985	1.019	0.985	1.033
Plaice	6	1.089	1.008	0.999	0.994	0.995	1.034	0.962
Plaice	7	1.181	0.991	0.972	0.931	1.037	1.055	0.937
Sole	2	0.973	0.999	1.005	1.003	1.004	0.995	1.025
Sole	3	0.990	0.999	1.002	1.001	0.995	1.003	1.026
Sole	4	1.005	1.001	1.000	0.999	0.996	1.002	0.996
Sole	5	1.025	1.004	0.998	0.996	1.005	1.016	0.979
Sole	6	0.977	1.000	1.004	1.003	1.000	0.997	1.020
Sole	7	1.025	1.006	1.000	0.996	1.003	1.029	0.998
Turbot	2	1.089	1.028	0.994	0.994	0.995	1.039	0.963
Turbot	3	0.989	1.003	0.999	0.994	1.115	0.985	1.023
Turbot	4	0.942	0.989	1.003	1.003	1.004	0.976	1.038
Turbot	5	0.951	0.988	1.003	1.002	1.015	0.979	1.029
Turbot	6	1.024	1.016	0.997	0.997	0.999	1.014	1.001
Turbot	7	0.936	0.988	1.002	0.996	1.149	0.961	1.058

Appendix 2. Change of the response indicators relative to the baseline scenario for the flatfish species at Maximum Sustainable Yield of the flatfish complex (factor=0.42)

Spec	Scenario	F-factor	SSB	Landing weights	Discard weight	landing number	Discard number	revenue	Mean F
All	2A	0.42	7.7%	-1.0%	-2.0%	-2.6%	-1.2%	1.4%	-4.5%
All	2B	0.42	14.6%	-3.2%	-4.5%	-6.3%	0.6%	4.6%	-6.4%
All	3A	0.42	-3.0%	0.3%	0.9%	0.8%	0.6%	0.8%	2.2%
All	3B	0.42	-2.5%	-0.1%	0.5%	0.1%	1.9%	-0.2%	2.0%
All	4A	0.42	4.2%	-0.5%	-1.0%	-1.5%	-0.6%	2.4%	-2.3%
All	4B	0.42	12.4%	-3.4%	-4.2%	-6.8%	3.4%	4.3%	-4.8%
Plaice	2A	0.42	11.3%	-1.5%	-3.1%	-3.8%	-1.7%	1.9%	-6.7%
Plaice	2B	0.42	19.8%	-4.4%	-6.2%	-8.5%	0.9%	5.7%	-9.3%
Plaice	3A	0.42	-4.1%	0.4%	1.2%	1.2%	0.9%	1.0%	3.0%
Plaice	3B	0.42	-4.1%	0.0%	0.9%	0.4%	2.4%	-0.6%	3.3%
Plaice	4A	0.42	6.6%	-0.9%	-1.6%	-2.3%	-0.7%	3.1%	-3.8%
Plaice	4B	0.42	15.7%	-4.5%	-5.4%	-8.7%	4.4%	4.8%	-6.3%
Sole	2A	0.42	-3.2%	0.6%	1.2%	1.1%	0.4%	0.1%	2.5%
Sole	2B	0.42	-1.1%	0.2%	0.4%	0.4%	-0.5%	1.1%	2.6%
Sole	3A	0.42	0.5%	-0.1%	-0.2%	-0.2%	-0.4%	0.0%	-0.4%
Sole	3B	0.42	2.5%	-0.3%	-0.8%	-0.9%	0.4%	1.0%	-2.1%
Sole	4A	0.42	-2.8%	0.6%	1.1%	0.9%	-0.1%	0.1%	2.0%
Sole	4B	0.42	2.4%	-0.2%	-0.7%	-0.8%	0.2%	2.9%	-0.2%
Turbot	2A	0.42	5.7%	1.4%	-1.1%	-1.1%	-0.5%	1.7%	-3.7%
Turbot	2B	0.42	-2.5%	0.4%	0.2%	0.0%	11.7%	-1.5%	2.3%
Turbot	3A	0.42	-5.2%	-0.5%	0.8%	0.8%	0.4%	-1.7%	3.8%
Turbot	3B	0.42	-3.9%	-0.6%	0.7%	0.6%	1.6%	-0.9%	2.9%
Turbot	4A	0.42	0.1%	0.9%	-0.2%	-0.2%	-0.1%	0.0%	0.1%
Turbot	4B	0.42	-6.7%	-0.4%	0.9%	0.7%	15.2%	-2.4%	5.8%
Brill	2A	0.42	-3.8%	2.5%	0.3%	0.3%	-2.1%	2.5%	5.4%
Brill	2B	0.42	7.9%	2.5%	-1.6%	-1.7%	3.5%	4.3%	-4.6%
Brill	3A	0.42	-4.7%	0.5%	0.7%	0.7%	2.3%	0.6%	4.9%
Brill	3B	0.42	-2.0%	-0.2%	0.4%	0.4%	-5.8%	-0.5%	1.6%
Brill	4A	0.42	-7.7%	2.8%	0.9%	0.9%	0.2%	2.9%	10.4%
Brill	4B	0.42	7.6%	2.2%	-1.5%	-1.5%	-5.9%	3.6%	-4.6%

Appendix 3. Change of the response indicators relative to the baseline scenario for the flatfish species at Maximum Sustainable Revenue for the flatfish complex (F-factor=0.34)

Spec	Scenario	F-factor	SSB	Landing weights	Discard weight	landing number	Discard number	revenue	Mean F
All	2A	0.34	6.7%	-1.7%	-2.5%	-3.1%	-1.2%	0.8%	-4.5%
All	2B	0.34	12.8%	-4.6%	-5.4%	-7.3%	0.6%	3.4%	-6.4%
All	3A	0.34	-2.6%	0.5%	1.1%	1.1%	0.6%	1.1%	2.2%
All	3B	0.34	-2.2%	0.2%	0.7%	0.3%	2.0%	0.0%	2.0%
All	4A	0.34	3.7%	-0.9%	-1.3%	-1.8%	-0.6%	2.1%	-2.3%
All	4B	0.34	11.0%	-4.6%	-5.0%	-7.5%	3.5%	3.3%	-4.8%
Plaice	2A	0.34	9.9%	-2.6%	-3.8%	-4.6%	-1.7%	0.9%	-6.7%
Plaice	2B	0.34	17.3%	-6.2%	-7.4%	-9.8%	0.8%	4.1%	-9.3%
Plaice	3A	0.34	-3.6%	0.8%	1.5%	1.5%	1.0%	1.5%	3.0%
Plaice	3B	0.34	-3.6%	0.4%	1.2%	0.8%	2.5%	-0.2%	3.3%
Plaice	4A	0.34	5.8%	-1.5%	-2.1%	-2.8%	-0.8%	2.7%	-3.8%
Plaice	4B	0.34	14.0%	-6.0%	-6.4%	-9.7%	4.5%	3.5%	-6.3%
Sole	2A	0.34	-3.1%	1.0%	1.5%	1.3%	0.4%	0.4%	2.5%
Sole	2B	0.34	-1.0%	0.3%	0.5%	0.5%	-0.5%	1.3%	2.6%
Sole	3A	0.34	0.5%	-0.1%	-0.2%	-0.2%	-0.4%	0.0%	-0.4%
Sole	3B	0.34	2.3%	-0.5%	-1.0%	-1.0%	0.4%	0.8%	-2.1%
Sole	4A	0.34	-2.6%	0.9%	1.3%	1.1%	-0.1%	0.4%	2.0%
Sole	4B	0.34	2.2%	-0.4%	-0.9%	-1.0%	0.2%	2.8%	-0.2%
Turbot	2A	0.34	5.0%	1.0%	-1.2%	-1.2%	-0.6%	1.2%	-3.7%
Turbot	2B	0.34	-2.5%	0.5%	0.3%	0.2%	11.7%	-1.3%	2.3%
Turbot	3A	0.34	-4.8%	-0.2%	1.0%	1.0%	0.4%	-1.3%	3.8%
Turbot	3B	0.34	-3.6%	-0.3%	0.8%	0.8%	1.6%	-0.5%	2.9%
Turbot	4A	0.34	-0.2%	0.9%	-0.2%	-0.2%	-0.1%	-0.1%	0.1%
Turbot	4B	0.34	-6.4%	0.0%	1.2%	1.0%	15.3%	-1.8%	5.8%
Brill	2A	0.34	-4.8%	2.9%	0.7%	0.7%	-2.1%	2.7%	5.4%
Brill	2B	0.34	6.6%	1.9%	-1.8%	-1.8%	3.5%	3.5%	-4.6%
Brill	3A	0.34	-4.8%	0.8%	1.0%	1.0%	2.3%	1.0%	4.9%
Brill	3B	0.34	-1.9%	0.0%	0.4%	0.5%	-5.8%	-0.3%	1.6%
Brill	4A	0.34	-8.8%	3.4%	1.5%	1.5%	0.2%	3.4%	10.4%
Brill	4B	0.34	6.3%	1.7%	-1.7%	-1.6%	-5.9%	2.9%	-4.6%