Ecological and economic trade-offs in the management of mixed fisheries: a case study of spawning closures in flatfish fisheries

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ABSTRACT: As a contribution to the ecosystem approach to fisheries management, we estimated the effects of spawning closures on stock status, ecosystem impacts and economic performance. We focused on the flatfish fishery in the North Sea and explored how spawning closures for plaice and sole contribute to sustainable management of 4 target species (sole, plaice, turbot and brill). Seasonal patterns in fishing effort and catchability by age group and area were estimated to quantify the effect of different spawning closure scenarios on the selection pattern. The scenario performance was evaluated using indicators of stock status (spawning stock biomass), economic performance of the fishery (yield, revenue) and 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, while 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 a small negative effect on sea bed integrity. The effects did not differ when evaluated at current levels of effort or at maximum sustainable yield (MSY) effort. 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.

KEY WORDS: Ecosystem approach · Closed areas · Closed seasons · Discards · Bottom trawling impact · Selection differential · Indicators · Good environmental status

INTRODUCTION

Over the years, fishing has substantially reduced biomass of exploited fish stocks, affected ecosystems (Jennings & Kaiser 1998, Hall & Mainprize 2005, Worm et al. 2009) and resulted in fisheries-induced evolution (Heino 1998, Jørgensen et al. 2007). Fisheries management is challenged to develop an ecosystem approach to fisheries in order to achieve sustainable exploitation as well as minimising the ecosystem impacts of fishing (Pikitch et al. 2004, Rice 2008, Jennings & Rice 2011). Management of mixed demersal fisheries is faced with particular problems

because it has to achieve acceptable fishing mortalities for a number of target species and at the same time minimise the bycatch of undersized fish and over-quota fish (Poos et al. 2010, Ulrich et al. 2011).

Protection of spawning fish may contribute to sustainable management. A spawning closure will reduce the fishing mortality of large and old fish that contribute disproportionally to the reproductive success of the population (Green 2008, Wright & Trippel 2009). It may also reduce the impact on spawning habitats, and may reduce the disturbance of the reproduction process (van Overzee & Rijnsdorp 2010), all potentially contributing to an increase in

recruitment. Finally, it may reduce the evolutionary effects of exploitation (Law 2007, Jørgensen et al. 2009). A spawning closure, however, may also have adverse consequences, since it will displace fishing effort leading to unforeseen ecological implications (Dinmore et al. 2003). In a mixed fisheries context, it may be difficult to find a compromise between achieving a sustainable harvest of the species complex in combination with the protection of spawning fish of the different species and the reduction of adverse ecosystem impacts (Fulton et al. 1999).

Here, we developed a model to explore the trade-offs between different objectives pertinent to the ecosystem approach to fisheries management, using spawning closures in the North Sea flatfish fishery as an example. The flatfish fishery is dominated by beam trawl vessels deploying heavy trawl gear with tickler chains penetrating into the bottom to catch the burying flatfish, in particular sole *Solea solea* (Daan 1997). The ecosystem impacts to be considered for this fishery are (1) the substantial bycatch of undersized commercially important fish, in particular plaice (van Beek 1998, Kraak et al. 2008), (2) catches of over-exploited species such as cod and rays (Walker & Heessen 1996, Ulrich et al. 2011), (3) the impact on benthic invertebrates and benthic habitats by the tickler chains (Jennings et al. 2002, Hiddink et al. 2006, Kaiser et al. 2006) and (4) fisheries-induced evolutionary changes for the 2 main target species plaice and sole (Rijnsdorp 1993a, Grift et al. 2003, Mollet et al. 2007, van Walraven et al. 2010).

The model used to explore the trade-offs is spatially and temporally explicit. Fisheries impacts are quantified based on the overlap in space (ICES rectangles ~30 × 30 nautical miles) and time (week) of fishing effort and biota (Murawski 1984, Rijnsdorp & Pastoors 1995, Pope et al. 2000, Piet et al. 2007). A spawning closure will affect the selection pattern of the fishery by affecting the overlap in distribution of the fish and the fishery. To calculate the selection pattern, we first estimated the seasonal and spatial variation in age-specific catchability for the major target species (sole, plaice, turbot and brill) and combined this with the patterns in fishing effort for different management scenarios. The consequences of the changes in selection pattern for the target species were quantified using a cohort analysis that estimates the equilibrium weight of the catch and stock, conditional on the selection pattern and rates of mortality and growth (Beverton & Holt 1957). The performance of the management scenarios was assessed in terms of a suite of response indicators: revenue to the fisheries, biomass of the target species, bycatch of

undersized flatfish, bycatch of cod *Gadus morhua* and rays, fisheries-induced evolution and trawling impact on the benthos.

MATERIALS AND METHODS

Catch and effort data

Logbook data of all trips of commercial vessels landing in the Netherlands are available. These hold information on the catch weight of marketable fish by species, market category, fishing gear, mesh size, fishing ground, time of leaving from and returning to harbour, engine power and vessel code. The fishing ground is recorded as rectangles of 0.5° latitude and 1° longitude (ICES rectangles). A second data set of sales slips comprises records of landed weight and price by market category by vessel and landing date. For this study, data over 2003 to 2007 were analysed for plaice, sole, brill, turbot, cod and rays.

Biological samples

The age compositions of the landed fish by species per trip were estimated using records of landed weight by market category per trip and the biological samples per market category by month. In the biological samples, the size, weight, sex, maturity stage and age of the sampled fish were determined. Samples collected over the period 2003 to 2007 were pooled to construct monthly age–length keys (ALKs) and sample weight for each market category by fishing area (Fig. 1). The rationale for pooling the data by month and area is that we were interested in ALKs that are representative for the seasonal and spatial variations during the 5 yr study period. The fishing areas reflect the spatial distribution of sole and plaice in relation to management and are similar to a previous study (Rijnsdorp et al. 2006). These month × area ALKs were subsequently applied to the catch-weight per market category per fishing trip extracted from the catch and effort data. For a percentage of trips (plaice: 13%, sole: 8%, turbot: 26%, brill: 25%, cod: 20%), no month × area specific ALK was available, so an ALK of the data pooled over the areas by month was used. The total number of fish sampled by area varied across species (Table 1); plaice (n = 23 064) and sole (n = 17 656) appeared to be very well sampled compared to turbot (n = 4866), brill (n = 6700) and cod (n = 9801). No samples were available for rays.

Model

The model to explore the trade-offs between different objectives pertinent to the ecosystem approach of fisheries management is shown in Fig. 2. Spawning closures affect the distribution of fishing effort in
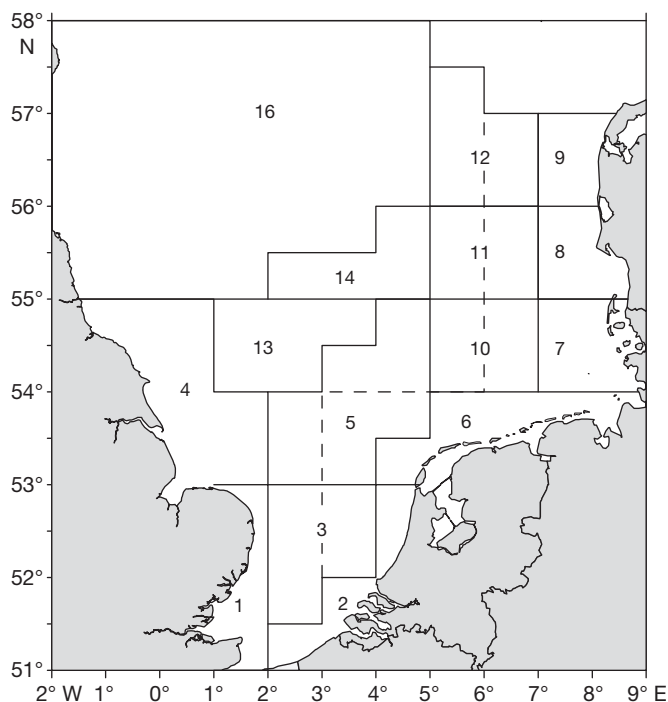

Fig. 1. Study area and the fishing areas distinguished. Numbers denote the sampling areas for the monthly age–length keys. For the analysis of the partial fishing mortality per day at sea (*Fpue*), the spatial resolution was increased by subdividing Areas 3, 10, 11 and 12 into 2 and Area 5 into 3 sub-areas

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

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

space and time, and hence the impact of fishing on biota. First, we estimated the seasonal and spatial differences in catchability of different species and age groups. Next, we estimated the selection pattern (fishing mortality at age: *F*-at-age) of the fishery given the distribution of fishing effort, and the estimated catchabilities. Implications of the changes in *F*-at-age on the targeted fish stocks were quantified using a cohort analysis, assuming all other parameters (growth, natural mortality, recruitment) to be constant (yield per recruit analysis: Beverton & Holt 1957). Finally, we estimated the effect of the spawning closures by reallocating the fishing effort and combining it with the estimated catchabilities.

Catchability

For each of the target species, the catchability generated during individual fishing trips in a certain area and week was estimated from the partial fishing mortality per day at sea (*Fpue*, where *pue* = per unit effort) following Rijnsdorp et al. (2006):

$$Fpue_{ijk} = \frac{c_{ijk}}{c_k} \times \frac{F_k}{d_{ij}} \tag{1}$$

where c_{ijk} is the number of fish landed by vessel i in week j of age k, d_{ij} is the number of days at sea of vessel i in week j, and c_k is the total number of age k landed by the Dutch fleet. F_k is the annual fishing mortality of age k by the entire international fleet. For sole, plaice and cod, the mean annual fishing mortalities for the yr 2003 to 2007 were used from the 2010 ICES stock assessments (ICES 2010). For turbot and brill, estimates were available from J. J. Poos et al. (unpubl.) (Table 2). We assumed the selection pattern of the Dutch beam trawl fleet to be representative of the entire international flatfish fishery. This is not unreasonable, since this fleet contributes more than two-thirds of the total international landings of flatfish in the North Sea (ICES 2010).

For cod, a bycatch species in the flatfish fishery, the mean annual fishing mortality was re-scaled in proportion to the ratio of the Dutch landings over the international landings to estimate the effect of spawning closures on the cod bycatch selection pattern.

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). Because of the ontogenetic shifts, *Fpue* in a certain fishing area is expected to change with the age of a cohort. Further, *Fpue* will change seasonally owing to migration between spawning and feeding
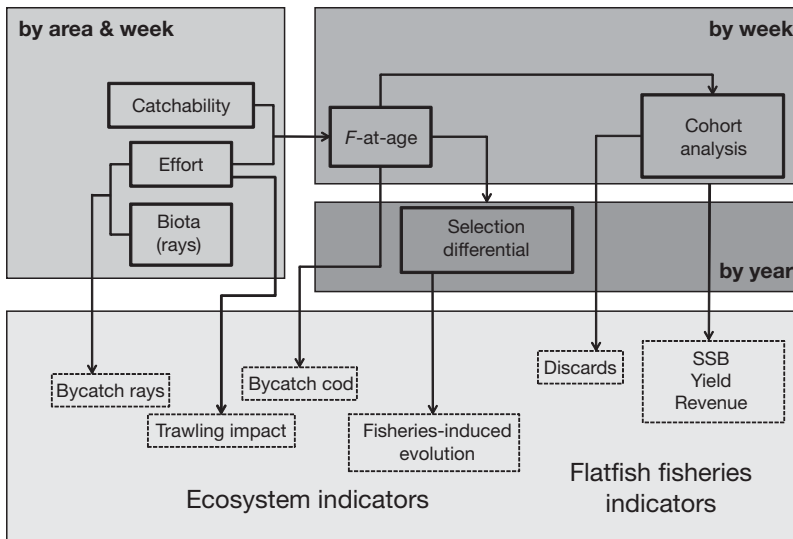
Fig. 2. Model framework to quantify the effect of management scenarios (spawning closures) on a set of indicators of the state of the exploited fish stocks, the fishery and the ecosystem effects of the fishery. Spawning closures affect the distribution of fishing effort in space and time, and hence affect biota (by-catch of cod and rays, trawling impact on the sea bed) and the selection pattern (fishing mortality at age: F-at-age) of the fishery. The selection pattern will influence the spawning stock biomass (SSB) and the yield, discards and revenue of the fishery, as well as the fisheries-induced evolution of life history traits

Table 2. Selection pattern (fishing mortalities at age, yr^{-1}) used in the simulation. [a]Including discards. [b]Partial fishing mortality

	Plaice[a]	Sole	Turbot	Brill	Cod[b]
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

areas of adult fish. In our model, we were interested in the age-dependent Fpue for each area and week. Therefore, we analysed the Fpue data by fishing trip with a generalised additive model (GAM; Wood 2008). Before the analysis, fishing Areas 3, 5, 10, 11 and 12 used to construct the ALKs (Fig. 1) were further subdivided into smaller areas to capture the ontogenetic and seasonal changes in more detail. The final model to estimate the $Fpue_{ra}$ by area r and age a was:

$$Fpue_{ra} = area + f(age, week, area) \qquad (2)$$

Because we express age in weeks, a includes the seasonal signal expressed by week. The term $f(age, week, area)$ is a tensor spline smooth with a cubic

regression marginal basis for age and a cyclic regression marginal basis for week, estimated for each area. The cubic regression spline uses basis functions that take the value 1 at 1 knot and 0 at all other knots. The knots of the spline are placed evenly throughout the covariate values. The basis functions are multiplied by their coefficient and subsequently combined to represent a smooth curve (Wood 2006). The cyclic cubic regression spline is a penalised spline whose ends match up to the second derivative. This results in a marginal smooth with ends having equal values and slopes. The actual effective degrees of freedom for each marginal smooth are estimated from the data by generalised cross validation.

Because of the nature of the response variable, we applied a log-link function and Poisson error term (Wood 2006). Quasi-likelihood estimation was used to take account of the overdispersion in the data and to estimate the dispersion parameter. All analyses were done in the R statistical program (version 2.12.1; R Development Core Team 2010).

Age 1 is absent from the commercial landings because fish of this age are still below the minimum landing size. Therefore, we arbitrarily assumed that $Fpue_1 = p^2 Fpue_2$, where p is the proportion of the year elapsed reflecting the partial recruitment of age 1 to the fishing grounds. For the age groups that are partly below the minimum landing size, we assumed that the distribution of the age group was well represented by the larger specimens in the fisheries landings.

Catch per unit of effort

For rays, the catch per unit of effort (Cpue) per fishing trip was analysed as a function of area and week using a similar GAM approach as was used to estimate Fpue:

$$Cpue_{ra} = area + f(week, area) \qquad (3)$$

Cohort analysis

The 'yield per recruit' model (YpR) of Beverton & Holt (1957) was used to quantify the consequences of

different management scenarios on indicators of the commercially exploited flatfish species. The YpR model calculates the fate of a cohort in terms of its growth, maturation and mortality (natural and fishing), assuming constant recruitment ($N_1 = 1$). The decay in numbers at age of the cohort is determined by the sum of fishing and natural mortality at each time step. This approach allows estimating the effect of changes in the selection pattern while keeping the other parameters constant. Rather than the classical approach using annual increments, we used weekly increments in age.

The total fishing mortality rate (F_a) by age a (weeks) is calculated as the product of the fishing effort e_r in area r and week j and the predicted $Fpue_{ra}$ in area r at age a. Because we express age in weeks, a includes the seasonal signal expressed in j.

$$F_a = \sum_r e_r Fpue_{ra} \quad (4)$$

The weight of the catch (C) and spawning stock biomass (SSB) is given by:

$$C = \sum_{a=1}^{a_{max}} W_a \frac{F_a}{(F_a + M_a)} N_a (1 - e^{-(F_a + M_a)a}) \quad (5)$$

$$SSB = \sum_{a=1}^{a_{max}} p_a W_a N_a e^{-(F_a + M_a)a} \quad (6)$$

where W_a is the weight, N_a is the number of fish, p_a is the proportion mature fish, F_a is the fishing mortality, and M_a is the natural mortality at age a. We used a maximum age (a_{max}) of 1300 wk (25 yr).

For each age (weeks), the mean length of the cohort (L_a) at age a was calculated using the Von Bertalanffy growth equation

$$L_a = L_\infty (1 - e^{-K(a - a_o)}) \quad (7)$$

The mean weight (W_a) and proportion mature were estimated using a length L kernel for each age, assuming a normal size distribution with a mean L_a and coefficient of variation of 15%. Discards at age were calculated as the fraction of the catch at age that was below the minimum landing size. The survival of discarded fish was assumed to be negligible (van Beek et al. 1990). All growth and maturation parameters were estimated from the available biological samples at IMARES for the study period (Table 3).

Indicators

The performance of the different management scenarios (see below) was evaluated using a suite of indicators for the flatfish stocks and its fishery, as well as for the ecosystem effects of fishing.

Table 3. Parameter values used in the simulations. CV: coefficient of variation of the length

	Sole	Plaice	Turbot	Brill
Natural mortality (yr^{-1})				
M	0.1	0.1	0.1	0.1
$L_a = L_\infty (1 - e^{-K(a-a_o)})$				
L_∞ (cm)	42.9	48.1	65.1	47.7
K (year)	0.263	0.232	0.326	0.653
ta0 (year)	0.03	0	0.5	0.5
CV	0.15	0.15	0.15	0.15
Weight (g) – length (cm): $W = \alpha L^\beta$				
α	−5.738	−5.055	−4.751	−4.510
β	3.293	3.107	3.229	3.064
Minimum landing size (cm)				
L_{min}	24	27	30	30
Maturity proportion (p) – length (cm): $\ln\left(\frac{p}{1-p}\right) = \alpha + \beta L$				
α	22.124	16.244	13.758	12.948
β	−0.925	−0.600	−0.364	−0.386

Indicators for target stocks and their fisheries

For the flatfish stocks and the fishery, the YpR model provides weekly data of the landings and population biomass, allowing us to calculate the total weight (kg) of the landings (Yield), discards and SSB over the lifetime of a cohort (25 yr) representing the equilibrium situation. The gross revenue was calculated by summing the product of the weekly landings and weekly fish price, accounting for fish size.

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. Fish price increases with size, except in the months prior to spawning and during the spawning period when the price increase is absent or even reversed (Fig. 3). The lower fish price during the spawning period is likely because of the poor quality of the fish (larger gonad, lower fat content, higher water content)

Revenue of the total flatfish landings was calculated from the revenue per recruit for the different species. Because the average number of recruits differs among species, estimation of the total revenue of the flatfish landings requires accounting for the differences in recruitment. The recruitment strength of each species was estimated from the ratio of their total international landings and estimated yield per recruit for the reference period. Scaled to the recruit-

ment levels of turbot and brill, the relative recruitment strengths were estimated at: plaice = 133, sole = 42, turbot = 1, brill = 1. By fixing the relative recruitment strengths, our YpR model ignores the potential effect of spawning closures on recruitment.

The maximum yield per recruit, the maximum revenue per recruit and the corresponding fishing mortality rates (F_{max}, F_{msr}) were estimated for the individual species and for the species complex (Murawski 1984). This was done by varying the level of fishing effort between 0 and 1.5 times the effort observed in the reference period. Assuming recruitment to be unaffected by SSB, F_{max} was considered a proxy for F_{msy}.

Ecosystem indicators

The ecosystem impacts evaluated were the catch weight of undersized fish (discards), the fishing mortality imposed on cod, the bycatch of rays, the impact of the fishery on the seabed integrity and the evolution of the onset of maturation (Fig. 2). The procedure

to estimate the discards of undersized flatfish and the fishing mortality imposed on cod is explained in the section on cohort analysis. The bycatch of rays was estimated by multiplying the average weekly fishing effort with the *Cpue* of rays in the different areas.

The trawling impact indicator (T) reflects the change in mean annual trawling frequency (f_{is}) by ICES rectangle i in scenario s as compared to the baseline scenario (f_{ib}):

$$T = \frac{\sum_{i=1}^{n} w_i \ln\left(\frac{f_{is}}{f_{ib}}\right)}{\sum_{i=1}^{n} w_i} \tag{8}$$

$$w_i = e^{-f_{ib}} \tag{9}$$

where 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 as the more sensitive species will be removed from the ecosystem and the proportion of less sensitive species will increase (Kaiser et al. 2006).

The evolutionary effect of fishing was evaluated for the onset of maturation. For each management scenario, the lifetime reproductive output of a cohort was estimated as a function of the size at first maturity, assuming a cost of maturation in terms of a reduced adult growth (Rijnsdorp 1993b). The change (%) in the slope of the regression of the lifetime reproductive output against maturation size was used as the indicator for the fisheries-induced evolution.

Integration of indicators

Performance of the management scenarios with regard to the response indicators were summarised with principal component analysis (PCA). In order to account for the quantitative difference (% 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 de-
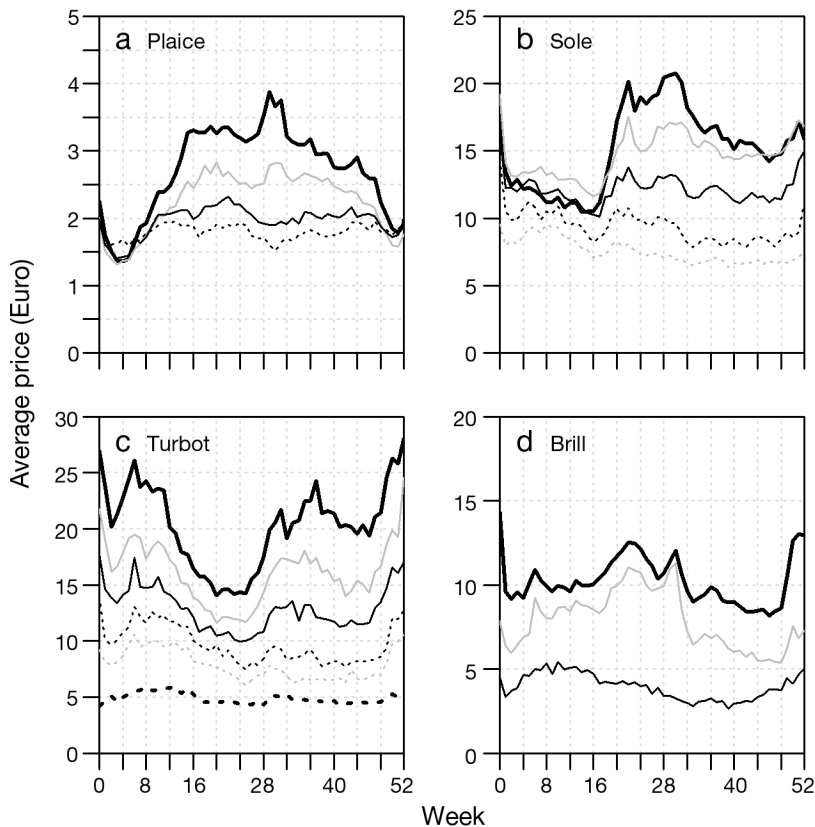

Fig. 3. Average first sale price of the market size categories of (a) plaice, (b) sole, (c) turbot and (d) brill in the period 2003 to 2007. Market categories are sorted in decreasing order of fish size (1: heavy black line = largest fish, 2: grey; 3: thin black; 4: dashed black; 5: dashed grey; 6: dotted black = smallest fish)

crease in discards, trawling impact and fisheries-induced selection pressure towards a decrease in maturation size).

Management scenarios

The management scenarios considered in this study comprise of a baseline scenario reflecting the effort distribution observed in the period 2003 to 2007 (Scenario 1), and 3 spawning closure scenarios for the main target species: plaice (Scenario 2), sole
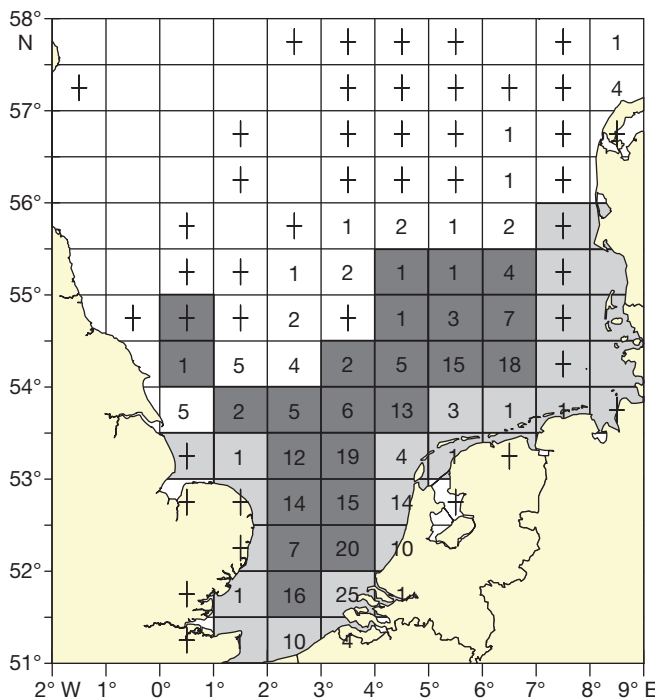

Fig. 4. Spawning closures explored in this study for plaice (Weeks 1–8: dark grey) and sole (Weeks 13–20: light grey). Note that areas are mutually exclusive. The numbers show the average annual fishing effort of the beam trawl fleet (100 d at sea) in the period 2003 to 2007. +: <100 d at sea

(Scenario 3) and plaice and sole combined (Scenario 4; Fig. 4, Table 4). The selection of spawning areas was based on data on egg distribution and spawning time (Harding et al. 1978)

Closing specific areas implies reallocation of fishing effort to other fishing areas or other seasons. We considered 2 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 is distributed over the open rectangles and/or weeks in proportion to the effort exerted in those rectangles and/or weeks.

RESULTS

Catchability

GAMs of the ontogenetic changes in *Fpue* explain between 38 and 59% of the deviance (Table 5). The predicted *Fpue* shows distinct seasonal and ontogenetic changes. The salient results are illustrated in Fig. 5 for a selection of areas and are presented for the species separately.

Plaice *Fpue* of age 2 shows an increase in summer and early autumn, whereas for age 4 and older, a seasonal pattern is observed with a peak in late December and January in spawning areas in the southern North Sea (Areas 3 and 10 in Fig. 5a). In the non-spawning offshore waters, *Fpue* values of older fish are low in winter and peak between spring and autumn (Area 13). These alternating patterns reflect the migrations to the spawning areas in the southern North Sea. The peaks in *Fpue* of the older ages decrease with age in the Southern Bight (Area 3), in contrast to the German Bight and Fisher Bank (Areas 10 and 12), where the peaks in *Fpue* increase with age.

Fpue of age 2 sole increases in summer and early autumn, reflecting the offshore movement of the recruiting year class (Fig. 5b). For age 3 and above, *Fpue* shows a seasonal peak in spring (Areas 2 and 3) reflecting coastal spawning, whereas in offshore areas such as the Doggerbank (Area 13), *Fpue* peaks in winter time, reflecting the offshore feeding of sole in winter. *Fpue* of sole in northern areas such as the Fisher Bank area (12) is very low.

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

Scenario	Description	Week	% Effort reallocation of	
			Annual total	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 generalised additive model of partial fishing mortality per day at sea (*Fpue*; flatfish and cod) and catch per unit effort (*Cpue*; rays) data per fishing trip

	Deviance explained (%)	Estimated df	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

Fpue of age 2 turbot increases in most areas reflecting the recruitment from the coastal nursery areas (Fig. 5c). Seasonal patterns were less consistent than in sole and plaice, although a peak in late spring is apparent in the German Bight (Area 10) and the Fisher Bank (Area 12). Highest *Fpue* values occurred in the German Bight and the central North Sea areas.

Fpue of brill is already relatively high at age 2 and does not show the increase observed in the other flatfish species (Fig. 5d). The seasonal patterns suggest that *Fpue* peaks in spring in the Southern Bight, Ger-
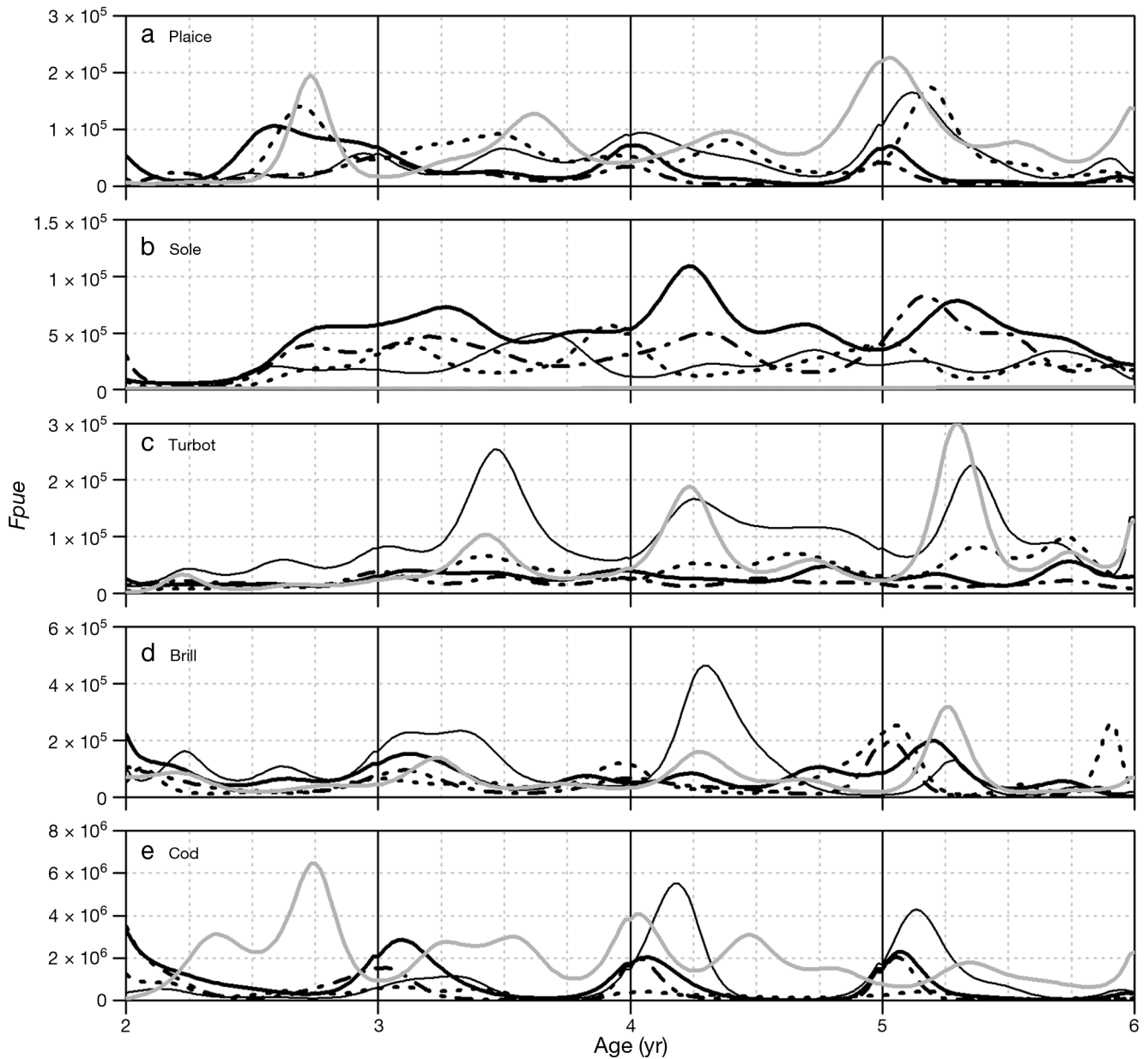

Fig. 5. Seasonal and ontogenetic changes in the partial fishing mortality per day at sea (*Fpue*) for (a) plaice, (b) sole, (c) turbot, (d) brill and (e) cod for a selection of areas (2, Dutch coast: dot-dashed line; 3, Southern Bight: heavy black; 10, German Bight: black; 12, Fisher Bank: grey; 13, Doggerbank: dotted). Area codes as in Fig. 1

man Bight and Fisher Bank areas (3, 10, 12) and peak in winter on the Doggerbank (13).

Fpue in cod shows a consistent pattern with a peak in the beginning of the year in the southern and south-eastern North Sea (Areas 3 and 10 in Fig. 5e). In the northern North Sea (Area 12), *Fpue* was high but did not show a consistent seasonal pattern across ages.

Management scenarios

Selection patterns

The management scenarios lead to a reallocation of fishing effort resulting in a change in the selection patterns. A plaice spawning closure results in a real-location 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 clo-sure results in a reallocation of 5 % of the annual effort (Table 4). This difference between the closures is caused by the difference in fishing pressure in the spawning grounds of these 2 species. Plaice spawns in the heavily fished offshore areas in the southern North Sea, whereas sole spawns in the coastal waters and the Plaice Box (Areas 6–9 in Fig. 1) where fishing is limited to vessels of <225 kW.

The effects of the spawning closures on the selec-tion patterns differ between the species. The selec-tion pattern of plaice is mostly affected by the plaice spawning closure (Scenario 2) and the combined spawning closure (Scenario 4, Fig. 6b). These scenar-ios result in a reduction in the fishing mortality on the oldest ages (up to 22 %) and an increase on the youngest ages (15–25 %). Reallocation of the effort outside the closed period (Scenarios 2B and 4B) re-sults in the largest change in selection pattern. A spawning closure of sole (Scenario 3) results in a small increase in the fishing mortality of the older ages of plaice (Scenarios 3A and 3B).

The selection pattern of sole is only marginally affected by the spawning closures (Fig. 6c). A plaice spawning closure increases the fishing mortality of older ages of sole by 4 %, whereas a sole spawning clo-sure slightly reduces the fishing mortality by 1 to 3 % of these older ages. A combined closure of plaice and sole (Scenario 4) results in an intermediate result (Fig. 6c).

The selection pattern of turbot is slightly affected by spawning closures (Fig. 6d). A decrease in fishing mortality on older age groups is obtained under a plaice spawning closure with effort reallocation within the closed period (Scenario 2A). If effort is re-allocated to other seasons (Scenario 2B), or when a sole spawning closure is put into place, fishing mor-tality on turbot increases.

The selection pattern of brill shows a variable re-sponse (Fig. 6e). Fishing mortality on the older ages increases substantially under a plaice spawning clo-sure scenario, in particular when effort is reallocated within the closed period (2A and 4A). If effort is real-located outside the closed periods (Scenarios 2B and 4B), fishing mortality on brill reduces.

The selection pattern of cod shows a 40 to 50 % drop in fishing mortality in response to the spawning closure of plaice, in particular when the effort is real-located outside the closure period (Fig. 6f). The sole spawning closures give a small increase in fishing mortality on cod.

Response indicators

The effect of the different management scenarios on the response indicators are presented in Table 6. The change was expressed as a percentage relative to the response indicator of the baseline scenario cor-responding to the fishing pattern of 2003 to 2007.

Plaice spawning closure. A spawning closure for plaice results in a 21 % increase in equilibrium SSB and a reduction of 9 % in the average fishing mortal-ity for this species (Table 6, Scenario 2B). While the equilibrium landings increase slightly (0.6 %), the revenue increases by 11 % because of a higher price of the landed plaice. The number of plaice discards is not affected (0 %). Similar but smaller effects are esti-mated for reallocation Scenario 2A.

The effects on the other flatfish species are smaller and depend on the reallocation scenario. A plaice spawning closure results in a slight increase fishing mortality on sole and a slight reduction in SSB. The ef-fects on turbot and brill depend on the reallocation scenario. The ecosystem indicators show a substantial reduction in the ecosystem impact (Table 6, Scenario 2B), in particular the bycatch mortality of cod (−30 %) and rays (−17 %). However, the trawling impact indi-cator increases by 10 % due to the reallocation of fish-ing effort to less intensively trawled fishing areas. The selection pressure for earlier maturation decreases by 43 % for plaice, and increases by 2 % for sole. These results are obtained if the fishing effort during the spawning period is reduced by reallocating the spawning time effort to the weeks outside the spawn-ing period (Scenario 2B). If the fishing effort on the spawning grounds is reallocated to other fishing areas within the plaice spawning period, similar effects are apparent but generally at lower levels (Scenario 2A).
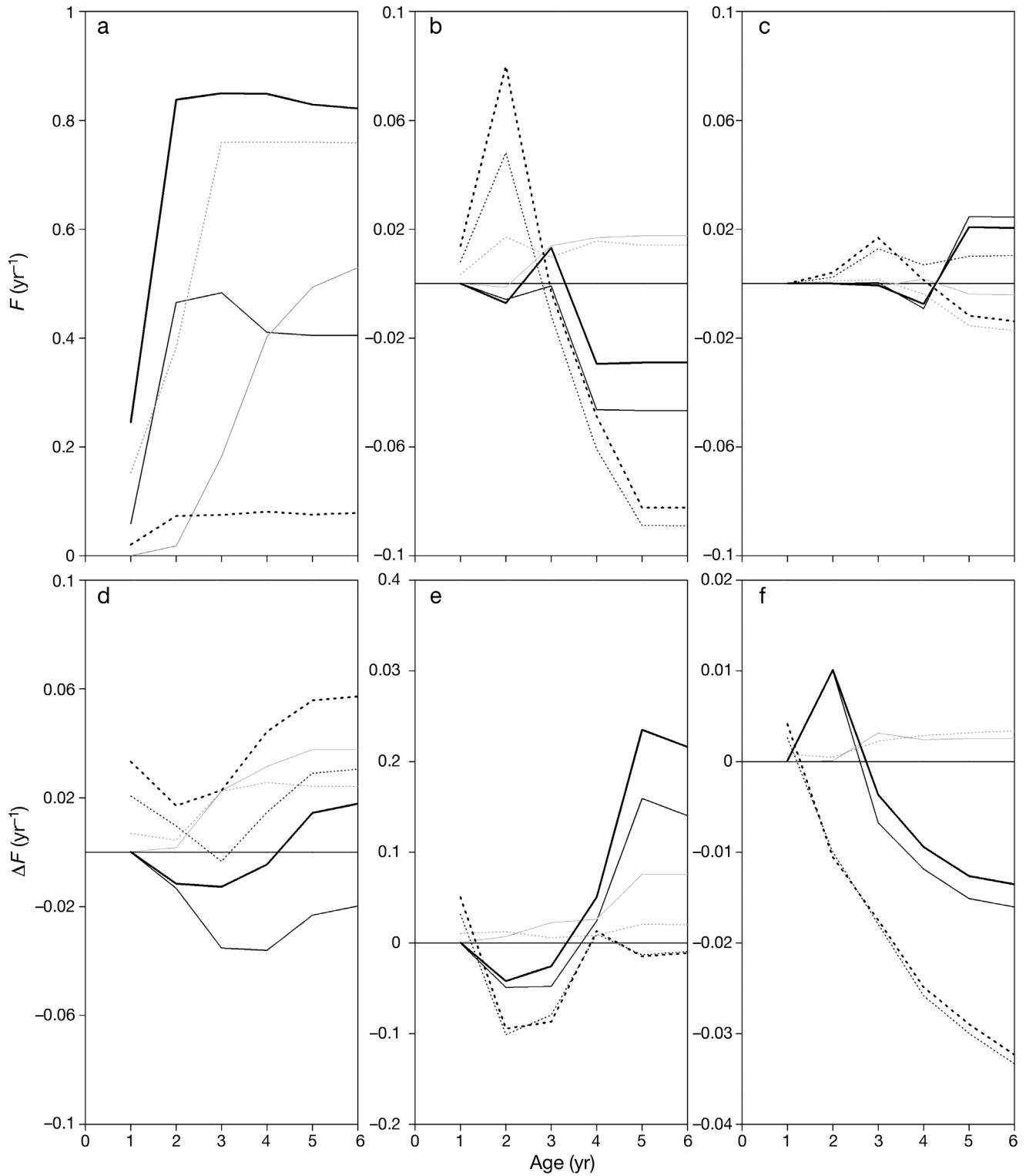
Fig. 6. Baseline selection patterns (F yr^{-1}) (a) for plaice (black line), sole (grey line), turbot (dashed grey line), brill (thick black line) and cod (dashed black line) and the (b–f) difference in F ($\Delta F = F_{\mathrm{scenario}} - F_{\mathrm{baseline}}$, yr^{-1}) compared to the baseline level for Scenario 2 (plaice spawning closure: black line); Scenario 3 (sole spawning closure: grey line); and Scenario 4 (combined spawning closure: thick black line). Solid lines show results for reallocation within the closed period (reallocation Schedule A), dotted lines show results for reallocation outside the closed period (reallocation Schedule B). Results are presented for (b) plaice, (c) sole, (d) turbot, (e) brill and (f) cod

Table 6. Change (%) in the response indicators for 6 spawning closure scenarios relative to the baseline at reference fishing mortality ($F_{2003\text{-}2007}$). 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}). SSB: spawning stock biomass. Fmean: average fishing mortality of age groups 2 to 6

Response indicators		Scenario					
		2A	2B	3A	3B	4A	4B
Revenue	Plaice	6.1	10.5	−1.0	−3.4	5.1	6.5
	Sole	−0.4	0.2	0.1	1.3	−0.3	2.2
	Turbot	3.8	−1.5	−2.4	−2.1	1.4	−4.1
	Brill	3.2	7.5	−0.3	−1.4	2.9	6.4
	Flatfish	1.4	2.4	−0.3	0.1	1.0	2.7
Landings	Plaice	2.6	0.6	−1.4	−2.8	1.3	−3.1
	Sole	−0.1	0.0	0.0	0.2	0.0	0.2
	Turbot	2.7	0.2	−1.1	−1.3	1.6	−1.3
	Brill	2.3	4.6	−0.3	−0.6	2.0	4.2
	Flatfish	1.7	0.5	−0.9	−1.7	0.9	−1.7
Discards	Plaice	−0.9	0.0	0.9	1.7	0.0	2.2
	Sole	0.3	−0.8	−0.4	0.4	−0.2	−0.1
	Turbot	−0.5	10.2	0.3	2.8	−0.3	14.5
	Brill	−1.5	6.0	2.3	−6.7	0.8	−3.5
	Flatfish	−0.9	0.0	0.9	1.7	0.0	2.2
SSB	Plaice	13.9	20.8	−6.0	−6.9	8.2	15.3
	Sole	−2.8	−1.0	0.5	2.4	−2.3	2.5
	Turbot	8.2	−1.1	−6.1	−5.2	2.3	−6.9
	Brill	4.0	14.4	−3.8	−2.5	0.7	13.8
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

positive effect on SSB (2–15%) and revenue of both species (2–6%). The effects on the other flatfish species and ecosystem are variable but tend to be positive; the bycatch mortalities of rays (−8%) and cod (−30%) are substantially lower, but the number of flatfish discards (+2%) and the trawling impact (+8%) are higher. A combined spawning closure with effort reallocated to the open areas during the closed period generally has smaller effects.

Summary of multiple indicators. To facilitate the comparison of the effect of different spawning closure scenarios on the multiple indicators, the results are summarised using a PCA (Fig. 7). The first 2 principal components explain 89% and 10% 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, as reflected in their position along the first principal component. The reallocation scenario (A and B) is mainly important for the spawning closure for plaice (Scenario 2) or the combined scenario (Scenario 4), and is reflected in the position along the second principal component. The loading of the response indicators 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 reflects which indicators are positively affected. Scenario 2, which represents a spawning closure for plaice, has overall positive effects because of the reduction in the fisheries-induced selection for earlier maturation, a decrease in the bycatch mortality of rays and cod, and an increase in the SSB of plaice and brill. Only the impact of trawling on the sea bed is increased (Fig. 7).

Sole spawning closure. A sole spawning closure results in a 2% decrease in fishing mortality, a 2% increase in equilibrium SSB and 1% increase in revenue of sole (Table 6, Scenario 3B). The already low number of sole discards increases by <1%. Revenue and SSB of the other flatfish species are reduced by a few percent. This coincides with the 2 to 5% increase in fishing mortality on the other species. Differences between the reallocation schedules are relatively small. The effects on the ecosystem indicators show only small changes (generally <5%), except for the 12 to 19% increase in the bycatch of rays and an increase in fisheries-induced evolution pressure on plaice by 9 to 10%.

Combined spawning closure. A combined spawning closure of plaice and sole with reallocation of fishing effort outside the closed periods results in a

Response indicators at MSY

Since the above explorations assume a level of fishing effort as observed in the period 2003 to 2007, the results do not necessarily apply to a situation where fishing effort conforms to the management objective
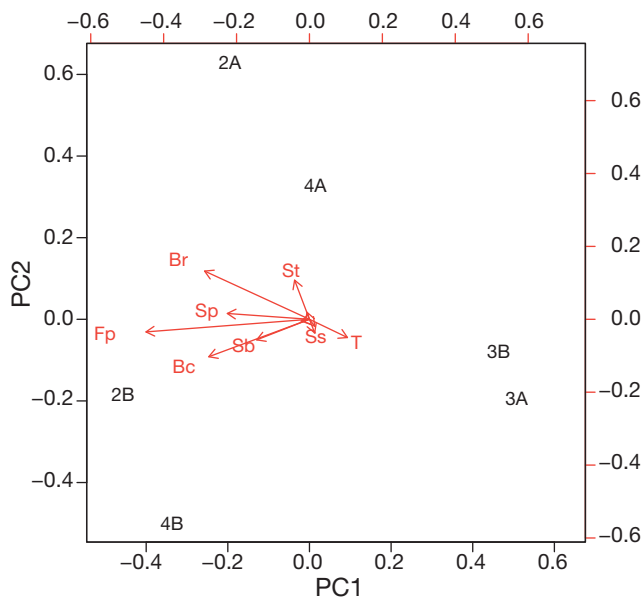
Fig. 7. Distance bi-plot of the principal component analysis (PCA) of the response indicators of the management scenarios (2A, 2B, 3A, 3B, 4A, 4B) at the 2003 to 2007 level of fishing effort. Arrows show the loading of the response indicators (Sp = spawning stock biomass [SSB] plaice; Ss = SSB sole; St = SSB turbot; Sb = SSB brill; Bc = bycatch cod; Br = bycatch rays; T = trawling impact on benthos; Fp = fisheries-induced selection plaice). The sign of the response indicators was adjusted to reflect a positive effect (see 'Materials and methods')

of MSY. The MSY of the flatfish complex occurs at a level of fishing effort of 40 to 46% of the reference level, depending on the scenario, with an average level of 42%. The F_{msy} of the species complex differs from that of the individual species, although the difference is relatively small. To achieve the maximum sustainable revenue, effort needs to be reduced further to 32% of the reference level (results not shown).

The effect of the different spawning closures on the response indicators at F_{msy} differs only marginally from the effect at F_{ref}, except for the fisheries-induced evolution (results not shown). At F_{msy}, spawning closures further increase the revenue, while discarding of flatfish is decreased with a plaice spawning closure, but slightly increased with a sole spawning closure. The effect on SSB at F_{msy} is lower compared to the reference effort. The effect on fishing mortality is similar, but the increase in trawling impact is slightly reduced compared to F_{ref}. The substantial reduction of fishing effort at the MSY level results in a much lower selection pressure for evolutionary changes. For 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 (F_{msr} = 0.34× at F_{ref}) is similar to the results at F_{msy}.

DISCUSSION

Management evaluation model

The credibility of the results of the management scenario simulation model depends on the mechanisms included in the simulation model and their parameterisations, as well the response indicators chosen. Our model included the key population dynamic processes growth, natural mortality and fishing mortality, the latter reflecting the ontogenetic and seasonal changes in distribution of fish. The growth and maturation parameters were based on an analysis of biological samples and are representative for the female component only. We deliberately decided not to include males, as this would have added complexity in the analysis of the YpR, estimating discards and the fisheries-induced selection, since the species studied have sexually dimorphic growth.

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 and 59% of the deviance in *Fpue*. Although the *Fpue* will be mainly determined by the density of fish on a fishing ground, it also incorporates the effect of fish behaviour on catchability, for instance in relation to migrations (Hunter et al. 2004b) or spawning activity (Solmundsson et al. 2003). Variations in estimates of *Fpue* are 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 (Quirijns et al. 2008).

Fpue is estimated from the *Cpue* of the commercial vessels representing the dominant fleet in the North Sea flatfish fishery that covers the total distribution area of the international fleet (Jennings et al. 1999). Because the fishery operates under an individual transferable quota system for sole, plaice and cod with a total allowable catch (TAC) for the other species, the *Cpue* 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), beamtrawl fishers may, to a certain

extent, avoid it by choosing fishing grounds that match the relative fishing rights (Quirijns et al. 2008, Rijnsdorp et al. 2011). Also, TACs for turbot and brill have only recently been introduced and were set at relatively high levels. It is unclear to what extent *Fpue* is influenced by competitive interactions among fishing vessels, which may occur when fishing vessels aggregate on a local fishing ground (Gillis & Peterman 1998, Rijnsdorp et al. 2000, Poos & Rijnsdorp 2007).

Despite these potential distortions, the estimated distribution patterns in *Fpue* do reflect the known changes in distribution. The offshore movement of juvenile flatfish out of their coastal nurseries (Beverton & Holt 1957, Gibson 1994) is reflected in the increase in *Fpue* of 2 yr olds in summer and autumn. In plaice, the migrations between feeding and spawning areas (Rijnsdorp & Pastoors 1995, Hunter et al. 2004a) is reflected in the high *Fpue* at the beginning of the year and the low *Fpue* in summer in known spawning areas, the Southern Bight (3) and German Bight (10), whereas an opposite pattern is observed for a typical feeding area (13). In sole, the inshore–offshore migrations of adults (ICES 1965) are 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 (10) is likely due to the fact that the spawning grounds of sole mainly occur in the shallow coastal waters where the larger vessels are not allowed to fish. For turbot and brill, there is insufficient information available to relate the observed patterns in *Fpue* to migrations between spawning and feeding areas. The clear seasonality that was found for cod with high *Fpue* in winter in the Southern Bight (3) and the German Bight (10) coincides with the spawning aggregations in the first quarter (Daan 1978).

The spatial reallocation of fishing effort assumed that the fleet remains fishing in the open rectangles in proportion to the effort in the reference period. This pattern of effort allocation in the reference period reflects the relative profitability of the rectangles given the distribution and abundance of the main fish species during this period. Our simulations give a crude estimate of the expected effects of spawning closures as they ignored the dynamic interaction between fisheries management, fishing fleet and fish populations. These interactions may affect spatial distribution patterns of the fishery and the fish. It remains a challenge for future work to incorporate the dynamic response of the fleet and the fish to management measures.

Biomass and fishing mortality indicators conform with the indicators used in annual stock assessments (ICES 2010). For the ecosystem impact of fisheries, indicators are still in development (Piet et al. 2008). Our trawling impact indicator gives a first approximation by taking account of the non-linear effect of the trawling frequency, but ignores the spatial patterns in the sensitivity or biodiversity (Kaiser et al. 2006). By specifying a vector of relative weights, the different conservation values of different spatial units can be easily incorporated in our model. The indicator for the evolutionary effects of fishing only dealt with the selection pressure for the onset of maturation. Fisheries-induced evolution, however, will not be restricted to the onset of maturation, but may also affect other traits such as reproductive investment and growth rate (Heino 1998). Methods are being developed to estimate the selection differentials of fishing on these traits which can be incorporated to improve and extend the indicator for fisheries-induced evolution (Arlinghaus et al. 2009).

In our simulation, we assessed the change in response indicators assuming a fixed level of fishing effort. However, because flatfish fisheries are managed by TACs, one might argue that the fishery will adjust its fishing effort in order to catch the TAC. Hence, if a spawning closure scenario results in an increase in the weight of the landings, as observed for Scenario 2 for plaice (Table 6), fishing effort will be reduced with a positive effect on the ecosystem indicators. If the weight of the landings is reduced, as observed in Scenario 3 for plaice, fishers will increase their effort, negatively affecting the ecosystem indicators. In reality, the response of the fleet will be more complicated, as this will be affected by the TACs set for the individual species.

Mixed fisheries management

The indicators used in our study to assess the effect of the management scenarios were chosen to reflect the multiple management objectives for demersal fisheries. Currently, the main objectives of the North Sea fisheries management is to ensure that fishing mortality is at a level resulting in MSY and to reduce the negative ecological impacts of the fisheries (ICES 2010). To achieve such a 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 (Council Regulation [EC] No 676/2007). For the additional ecosystem objectives, namely (1) decreasing the bycatch of spe-

cies at risk, (2) decreasing the bycatch of undersized flatfish and (3) reducing the trawling impact on the benthic ecosystem, no specific measures have yet been implemented. However, in the light of these objectives, several aspects of the North Sea flatfish fisheries are of concern, such as the catches of cod and several ray species. For cod, a substantial reduction in the fishing mortality is required to rebuild the stock. Because cod is caught in almost all fisheries targeting demersal species, the required reduction in fishing mortality on 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 ray *Raja clavata* have disappeared from the south-eastern North Sea because of fishing (Walker & Heessen 1996). Other concerns include the high discarding rates of undersized flatfish, in particular plaice, in the flatfish fishery (van Beek 1998), and the negative impact on benthos and benthic habitats caused by mortality as a result of the heavy gear (Jennings & 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 (Jørgensen et al. 2007).

TAC management alone may not 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, such as spatial management and gear modifications, need to be considered.

Impact of spawning closures

In this study, we focused 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 & 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 (Law 2007, Wright & Trippel 2009, van Overzee & Rijnsdorp 2010). It has been notoriously difficult, however, to statistically detect the expected positive effect on recruitment (Brunel 2010) and the empirical evidence is weak (Hsieh et al. 2006). We therefore focused our analysis on the effects of spawning clo-

sures 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, nongovernmental organisations and retailers. Our modelling results suggest 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 that we found in this study are the increase in SSB of plaice and a reduction in the bycatch mortality of cod and rays. A plaice spawning closure will further reduce the evolutionary selection pressure for early maturation of plaice. The reduction in evolutionary pressure is mainly due to the reduction of the fishing mortality on the older ages. A spawning closure for sole generally results in opposite effects, although the size of the effect was relatively small. A combined spawning closure of plaice and sole showed that 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. This increase in revenue was due to the higher price of the landed fish outside the spawning period which had a better condition than spawning fish. 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 (F_{msy}) for the flatfish complex. At F_{msy}, spawning closures will further enhance revenue and decrease flatfish discards and trawling impact. The positive effect on SSB, however, will be smaller.

This study has shown that spawning closures do not exclusively have desirable effects. Our simulations suggest that a plaice spawning closure will likely result in a decrease in the SSB of sole 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. Fishers will value the discarding levels higher than the trawling impacts on benthic habitats, while ecologist will value the habitat impact higher (Innes & Pascoe 2010). 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 MSY are also supported. Meanwhile, 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 presents 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 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 & van Densen 2010, Verweij et al. 2010). The approach can easily be extended by including different fisheries (Murawski 1984) and integrated in a multi-criteria analysis to quantify the cumulative impacts of human pressures (Stelzenmüller et al. 2010).

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