ICES Journal of Marine Science

ICES Journal of Marine Science (2013), 70(4), 768–781. doi:10.1093/icesjms/fst073

Evaluating deepwater fisheries management strategies using a mixed-fisheries and spatially explicit modelling framework

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Marchal, P., and Vermard, Y. 2013. Evaluating deepwater fisheries management strategies using a mixed-fisheries and spatially explicit modelling framework. – ICES Journal of Marine Science, 70: 768–781.

Received 8 January 2013; accepted 15 April 2013.

We have used in this study a spatially explicit bioeconomic modelling framework to evaluate management strategies, building in both data-rich and data-limited harvest control rules (HCRs), for a mix of deepwater fleets and species, on which information is variable. The main focus was on blue ling (*Molva dypterygia*). For that species, both data-rich and data-limited HCRs were tested, while catch per unit effort (CPUE) was used either to tune stock assessments, or to directly trigger management action. There were only limited differences between the performances of both HCRs when blue ling biomass was initialized at the current level, but blue ling recovered more quickly with the data-rich HCR when its initial biomass was severely depleted. Both types of HCR lead, on average, to a long-term recovery of both blue ling and saithe (*Pollachius virens*) stocks, and some increase in overall profit. However, that improvement is not sufficient to guarantee sustainable exploitation with a high probability. Blue ling CPUE did not always adequately reflect trends in biomass, which mainly resulted from fleet dynamics, possibly in combination with density-dependence. The stock dynamics of roundnose grenadier (*Coryphaenoides rupestris*), black scabbardfish (*Aphanopus carbo*) and deepwater sharks (*Centrophorus squamosus* and *Centroscymnus coelolepis*) were little affected by the type of HCR chosen to manage blue ling.

Keywords: bioeconomic model, catch per unit effort, fleet dynamics, harvest control rules, management strategy evaluation, mixed fisheries.

Introduction

Long-term fisheries management plans and harvest strategies standards have been enforced by many fisheries management agencies worldwide in the past 15 years. The overarching objective of these fisheries plans has been to heave the abundance of depleted fish stocks in the short term, and in the long term to maintain these stocks and the economic viability of fleets exploiting them around sustainable levels. Central to the implementation of fisheries plans are the harvest control rules (HCRs), which prescribe a harvest limit as a function of estimated current biomass and/or fishing mortality levels (Deroba and Bence, 2008).

Many HCRs used to manage fisheries worldwide rely on analytical stock assessments, and also on reference points, which in combination trigger an adaptation of exploitation levels in the following year. Projected fishing mortalities (and/or catches) are often reduced linearly as estimated spawning biomass drops below some upper "target" level, and a very limited harvest is allowed when spawning biomass falls below a lower "limit" threshold. Examples of implementation of such HCRs include management plans for the US west coast groundfish fishery (Punt *et al.*, 2008), EU cod and flatfish fisheries (EC, 2008; Marchal *et al.*, 2009b), and those Australian "Tier 1" stocks harvested by the southern and eastern scalefish and shark fishery (SESSF) (Smith *et al.*, 2008). Stochastic variants of such HCRs have also been implemented to manage New Zealand fisheries (NZMFISH, 2008a; NZMFISH, 2008b).

Such HCRs are often referred to as "data-rich", as they build on the outcomes of high-quality catch-at-age stock assessments. However, for many fisheries, information is insufficient to carry out stock assessments and hence to estimate spawning biomass and fishing mortality levels with an acceptable precision. Fisheries scientists have then been requested to develop and evaluate "data-limited" HCRs, which can be implemented in such fisheries for which information is poor (Smith *et al.*, 2009; Little *et al.*, 2011). Importantly, even when information is sufficient to conduct annual stock assessments and implement data-rich HCRs, the amount of labour needed and the costs associated with advice-giving are generally high, and may not always be acceptable to supporting clients. This is particularly true when the costs of the advisory process are recovered through industry levies (like in Australia or New Zealand), but also when these costs are funded by tax-payers, like in the EU, where public money becomes a rare resource. It then would become an attractive option to provide advice building on data-limited HCRs. The question then becomes: could one expect similar management performances when using data-limited instead of data-rich HCRs?

A growing amount of research has been dedicated to the development of fisheries models allowing the implementation, simulation and subsequent testing of management strategies building in data-limited HCRs for several fisheries worldwide, e.g. in Australia (Dowling *et al.*, 2008; Dichmont and Brown, 2010; Little *et al.*, 2011), New Zealand (Holland *et al.*, 2005; Breen, 2009), the Subantarctic (Butterworth *et al.*, 2010), and also the European Union (Roel and De Oliveira, 2007; De Oliveira *et al.*, 2010). Due to the lack of absolute biomass and fishing mortality estimates, and generally also of fishery-independent information, the trigger variable in data-limited HCRs is generally a commercial catch per unit of effort (CPUE), the trends of which are used as abundance indicators.

There are, however, different reasons why CPUE trends may not mirror stock abundance fluctuations adequately. First, the technology on board and the harvest efficiency of fishing gears have developed over time for many fisheries (Pascoe and Robinson, 1996; Robins *et al.*, 1998; Marchal *et al.*, 2007). Technological development is also accentuated by structural changes in fishing fleets, where more modern and more efficient fishing vessels have replaced old vessels with obsolete technologies. In addition, CPUE is proportional to stock abundance only if both fish stocks and fishing effort are randomly distributed in space. In the reality, such an assumption is rarely met, as a result of fish aggregating in their most favourable habitats, combined with fishers targeting high density and profitable fishing grounds (Holland and Sutinen, 1999; Rindorf and Andersen, 2008). The mismatch between CPUEs and biomass levels may even be exacerbated in mixed fisheries, where fishers may operate different métiers and target various species assemblages.

In this study, we evaluate the respective merits of data-rich and data-limited HCRs for the deepwater mixed fisheries off the Western British Isles, which harvest a mix of species for which information is variable. Both HCRs require CPUE indices, either to tune a stock assessment (data-rich HCR), or to directly trigger some management actions (data-limited HCR). We considered five deepwater species: blue ling, roundnose grenadier, black scabbardfish, two deepwater sharks (*Centrophorus squamosus* and *Centroscymnus coelolepis*), and one demersal species: saithe (*Pollachius virens*). The main focus will be on blue ling, for which both HCRs will be tested. For saithe, the data-rich HCR built in the current EU–Norway management plan will be applied. Data-limited HCRs will be implemented for roundnose grenadier and black scabbardfish, for which no management plan is in place. Finally, the current deepwater sharks catch ban will be operated. To that purpose, we have developed a comprehensive bioeconomic and spatially explicit model that mimics many of the complexities that characterize mixed fisheries (technical interactions, spatial structures in biomass and fishing effort distribution, fleet dynamics), and which may cause CPUE trends to deviate from stock abundance fluctuations. The conservation and utilization performances of the different HCRs have then been evaluated by running a set of simulations, building uncertainty into some of the key parameters of the deepwater mixed-fisheries system under investigation.

Material

Stock information

The Southern blue ling stock covers ICES (International Council for the Exploration of the Sea) Division Vb and Subareas VI and VII (ICES, 2011b). At the time when our model was parameterized, ICES had not conducted operational stock assessments for blue ling. We have here used available biological information (Thomas, 1987; Lorance *et al.*, 2010; ICES, 2011b) as a basis to perform an exploratory XSA (eXtended Survivors Analysis) assessment (Shepherd, 1999) for that stock, the details of which may be found in the Supplementary Data S1. Note that ICES has more recently provided advice based on a MYCC (Multi-Year Catch Curve) analysis (ICES 2012c), the results of which are similar to those of the XSA assessment considered in this study. The North Sea and West of Scotland saithe stock considered here is distributed over ICES Subareas IV, VI and Division IIIa, and is subject to a regular age-structured stock assessment (ICES, 2011a). The black scabbardfish stock considered here is distributed over ICES Division Vb and Subareas VI and VII (ICES, 2011b). The roundnose grenadier stock is considered covering the same areas, but also ICES Divisions XIIb (western Hatton Bank) (ICES, 2011b). Deepwater sharks are distributed over the whole Northeast Atlantic and they are assessed as one stock, although they are composed of two different species, *Centrophorus squamosus* and *Centroscymnus coelolepis* (ICES, 2011c). ICES (2011b) has carried out an exploratory stock assessment for roundnose grenadier building on a Schaefer production model (Schaefer, 1957). ICES has not carried out any form of analytical assessment in relation to black scabbardfish and deepwater sharks, and we have fitted a Schaefer production model, to get some insights into the dynamics of these stocks. The details of the black scabbardfish and deepwater sharks assessments are shown in the Supplementary Data S2 and S3, respectively.

Fleets and métiers information

Fleets

Three fishing fleets were implemented in this investigation. The first two fleets consist of large French trawlers (exceeding 40 m in length) in one fleet, and all other French vessels in the other fleet; in both cases at least 1 kg is caught of any of the species under consideration. These are hereafter referred to as “the large French trawlers fleet” and “the other French fleet”, respectively. The third fleet represents the non-French vessels contributing to the international catch. It is hereby referred to as “the non-French fleet”. The large French trawlers have often contributed more than half the landings of deepwater species (blue ling, roundnose grenadier, black scabbardfish, deepwater sharks) since the start of their exploitation. However, about 40% of their fishing revenue consists of saithe, while deepwater species contribute to only 30% of the total harvest value. The remaining 30% of the total gross revenue result from landing other species. Annual operating costs could also be made available for the large French trawlers (JRC, 2010). It was not possible from the data available to distinguish between fixed and variable costs for that fleet, so all operating costs were assumed variable in this study.

Detailed catch and effort data were available for the two French fleets. These data were extracted from fishers’ logbooks and fish auction market statistics extracted from Harmonie, the database of the French Fisheries Information System. Annual catches for the non-French fleet were available from ICES (2011a, b, c). About 90% of the other French fleet's fishing revenue consists of such species. Fish landing prices were derived from the French fisheries auction database.

Métiers

Fishing fleets may operate different activities, depending on the gear they use, the fishing ground they visit, and/or the species they target. The term "métier" has sometimes been suggested to define a type of fishing activity (ICES, 2003). We considered here that both French fleets could operate ten métiers each. These included the six deep-water métiers identified by Lorance *et al.* (2010) (hereby referred to as DeepEdge6, DeepNew5, DeepNew6, DeepOther6, DeepRef5 and DeepRef7), and four additional demersal métiers operated by the two French fleets in shallower waters (hereby referred to as Dem4, Dem5, Dem6 and Dem78). No information was available on the métiers operated by the non-French fleet.

Methods

ISIS-Fish modelling platform

The ISIS-Fish (version 4.2.0.1) modelling platform (Mahévas and Pelletier, 2004; Pelletier and Mahévas, 2005; Drouineau *et al.*, 2006) has been chosen to model the mixed-fisheries system and to simulate management strategies. ISIS-Fish is a generic, spatially- and seasonally-explicit simulation tool for evaluating the effect of management measures on mixed fisheries. The base (default) model consists of biological and harvest modules. The base biological module processes the dynamics of cohort survival, growth and migrations for each species, month and area. The base harvest module builds in technical interactions between several fleets (i.e. sets of vessels of similar physical characteristics) and métiers (i.e. sets of fishing trips operated with the same gear, visiting similar fishing grounds and targeting the same assemblage of species).

The different fleets operate in a region defined by its boundary and a regular grid. The spatial resolution of the grid is that of an ICES rectangle (1° × 0.5°). Within the region, zones (i.e. sets of contiguous grid cells) are defined independently for each population, métier and management measure. The model has a monthly time-step. Seasons (i.e. sets of successive months) are also defined independently for each population, métier and management measure.

In this study, we expanded the existing modules and also developed new sub-models to build in (i) specific population and harvest dynamic processes, (ii) fleet dynamics, (iii) stock assessment, and (iv) HCRs. These developments have been achieved using the Java language, and also by calling some built-in FLR (Fisheries Library in R) (Kell *et al.*, 2007). We describe below the different processes built in to conceptualize our fishery system, with particular focus on the new developments specifically brought about by this investigation.

Population dynamics

Annual stock abundance and biomass

The base ISIS-Fish model equations have been used to track cohort survival for the age-structured populations of blue ling and saithe, and these are fully detailed in Mahévas and Pelletier (2004). Stock abundance (N) is calculated by year (y), month (k), area (z) and age group (a). The annual spawning stock biomass B may be formulated as:

$$B_y = \sum_k \sum_z \sum_a N_{y,k,z,a} \times mo_a \times \overline{w}_a(1 + \varsigma_y \times cv_w), \quad with\ \varsigma_y \sim N(0,1), \tag{1}$$

where mo is the maturity ogive, $\overline{w}$ is the arithmetic mean of the weight-at-age time-series, ς is an uncorrelated random variable distributed as $N(0,1)$, and cv_w is the coefficient of variation of the weight-at-age time-series. The random numbers used to simulate interannual variations in weights-at-age were constrained to the $[-1/cv_w, 1/cv_w]$ interval, as higher or lower values would lie outside a region of reasonable precision. We have used the inputs (weights at age, maturity ogive, natural mortality) and some of the outputs (exploitation patterns and abundance numbers at age in 2009) from the blue ling and saithe stock assessments to parameterize the cohort dynamics of these stocks (Table 1). The CV of both blue ling and saithe weights at age were set at 20%.

Finally, deterministic Schaefer production models have been implemented in the ISIS-Fish modelling platform to forecast the non-age-structured population and harvest dynamics of roundnose grenadier, black scabbardfish and deepwater sharks. For these three stocks, growth was applied with a constant rate over all months.

Note that, in order to simplify the notations used in this study, B is referring to either the spawning stock biomass for age-structured stocks (blue ling and saithe), or the total biomass in the case of non-age-structured stocks (roundnose grenadier, black scabbardfish, deepwater sharks).

Stock-recruitment relationships

Stock-recruitment relationships were implemented for both blue ling and saithe. For blue ling, which recruits at age 7, available stock assessment outputs suggested that a Beverton–Holt relationship could reasonably fit recruitment (R) in year y and spawning stock biomass (B) in year ($y-7$), with the following specification:

$$R_y = \frac{aB_{y-7}}{b + B_{y-7}} e^{\varepsilon y}, \quad with\ \varepsilon_y \sim N(0, \sigma^2_{Rb}), \tag{2}$$

where a is the maximum number of recruits produced, b is the spawning stock biomass needed to produce on average $a/2$ recruits, and ε_y is an uncorrelated random variable distributed as $N(0,\sigma^2_{Rb})$. The parameters of the Beverton–Holt stock-recruitment relationship used for blue ling were estimated with a non-linear regression between the logarithm of both terms in the equation ($a = 4.92 \times 10^6$, $b = 1.39 \times 10^6$, $\sigma^2_{Rb} = 0.013$), where σ^2_{Rb} is the variance of the residuals. For saithe, it was not possible to use any of the usual stock-recruitment relationships found in the fisheries science literature to fit available stock assessment output data. Consistent with ICES (2008), we modelled recruitment (at age 3) using a pragmatic "hockey-stick" relationship:

$$R_y = \begin{cases} \overline{R}e^{\zeta_y - \sigma^2_{Rs}/2}, \ if\ B_{y-3} \geq B_{lim} \\ \overline{R}\left(\frac{SSB_{y-3}}{B_{lim}}\right)e^{\zeta_y - \sigma^2_{Rs}/2}, \ if\ B_{y-3} < B_{lim} \end{cases} \quad with\ \zeta_y \sim N(0, \sigma^2_{Rs}), \tag{3}$$

where $\bar{R}$ is the arithmetic mean recruitment derived from the saithe stock assessment, B_{lim} is the spawning biomass below which recruitment is impaired, and ζ_y is an uncorrelated random variable

Table 1. Biological age-dependent inputs used in the forecast for blue ling (*Molva Dypterygia*) and saithe (*Pollachius virens*).

	Mean weight (kg)		Exploitation pattern		Maturity ogive		Natural mortality		Initial abundance ('000)	
Stock Age	Blue ling	Saithe	Blue ling	Saithe	Blue ling	Saithe	Blue ling	Saithe	Blue ling	Saithe
3	–	0.9	–	0.6	–	0.0	–	0.20	–	41 462
4	–	1.1	–	0.9	–	0.2	–	0.20	–	40 437
5	–	1.4	–	1.2	–	0.7	–	0.20	–	42 667
6	–	1.8	–	1.3	–	0.9	–	0.20	–	11 914
7	2.1	2.4	0.7	1.2	0.5	1.0	0.15	0.20	3 131	27 291
8	2.6	3.2	0.8	1.1	1.0	1.0	0.15	0.20	2 686	9 872
9	3.1	4.2	0.8	0.9	1.0	1.0	0.15	0.20	2 056	6 764
10	3.6	5.6	1.0	0.9	1.0	1.0	0.15	0.20	1 392	9 612
11	4.0	–	0.9	–	1.0	–	0.15	–	850	
12	4.4	–	0.9	–	1.0	–	0.15	–	447	
13	4.8	–	1.1	–	1.0	–	0.15	–	304	
14	5.2	–	1.1	–	1.0	–	0.15	–	140	
15	5.5	–	1.7	–	1.0	–	0.15	–	69	
16	5.7	–	1.0	–	1.0	–	0.15	–	23	
17	7.2	–	1.0	–	1.0	–	0.15	–	321	

Exploitation patterns (S) in any year were calculated as the ratio between fishing mortality (F) at age (as output from stock assessment) and the mean F averaged over all age groups. Ages 17 and 10 are plus-groups for blue ling and saithe, respectively. Natural mortality (M) is assumed constant across years and age groups. Initial abundance are the 2009 estimated numbers.

distributed as $N(0,\sigma^2_{Rs})$. The parameters of the "hockey stick" stock-recruitment parameters used for saithe [equation (3)] were estimated using stock assessment outputs ($\bar{R} = 1.35 \times 10^8, \sigma^2_{Rs} = 0.26$).

Spawning migrations

A seasonal migration ogive has been implemented for blue ling to mirror the aggregative behaviour of that species during the spawning season (Large *et al.*, 2010; Lorance *et al.*, 2010). All spawners move instantaneously to their spawning areas on the 1st March, where they stay during the whole spawning season (from March to May). At the end of the spawning season (on the 1st June), blue ling are assumed to redistribute instantaneously and homogeneously over all available grid cells, where they stay until the end of February. The number of available grid cells was assumed to depend on blue ling abundance level (density-dependence), as explained below. Data were insufficient to build in spawning migrations for the other stocks.

Density-dependence

Because of its aggregative behaviour (Lorance *et al.*, 2010), we assumed that blue ling could aggregate towards its most favourable habitats as a result of severe abundance reduction, a phenomenon referred to as density-dependence (Swain and Sinclair, 1994; Marshall and Frank, 1995; Blanchard *et al.*, 2005). We assumed that such a stock contraction would occur whenever blue ling biomass falls below a biomass threshold (B_{aggreg}). The value of B_{aggreg} is unknown, and we assumed that B_{aggreg} is randomly distributed, following a uniform process, between 0.1^*B_0 and 0.3^*B_0, where B_0 is the unfished biomass. We then forced the blue ling population to aggregate towards the most favourable grid cells as follows. When $0.75 \times B_{aggreg} < B \leq B_{aggreg}$, the blue ling population aggregates towards the 75% most favourable grid cells, in both the spawning and non-spawning areas. When $0.50 \times B_{aggreg} < B \leq 0.75 \times B_{aggreg}$, the blue ling population aggregates in the 50% most favourable grid cells. When $0.25 \times B_{aggreg} < B \leq 0.50 \times B_{aggreg}$, the blue ling population aggregates in the 25% most favourable grid cells. When $B \leq 0.25 \times B_{aggreg}$, the blue ling population aggregates in only two grid cells, the most favourable cell in the spawning area, and the most favourable cell in the non-spawning area. When $B > B_{aggreg}$, no density-dependence occurs. In order to rank the different grid cells according to blue ling spatial preference, we modelled the logarithm of non-null blue ling catch rates using a Generalized Linear Model (GLM) (explanatory factors: ICES rectangle, year, season, vessel; probability distribution: Gaussian; link function: identity). Finally, we ranked separately the grid cells (ICES rectangles) included in the spawning and non-spawning areas, according to the ICES rectangle effect estimated by the GLM, from the largest (most favourable habitat) to the lowest (least favourable habitat).

There was insufficient evidence to implement any density-dependence mechanism for the other species, which were assumed to be homogeneously distributed over their stock area (ICES 2011b).

Yield dynamics

Age-structured stocks

For the French fleets, the partial fishing mortality (φ) of species s (either blue ling or saithe), belonging to age group a, in year y and month k, which can be attributed to fleet f operating métier m, is formulated as:

$$\varphi_{s,y,k,f,m,a} = q_{s,f} \times S_{s,a} \times T_{s,f,m} \times V_{s,k} \times \rho_{s,m} \times E_{y,k,f,m}, \quad (4)$$

where q is a scaling factor, S is the exploitation pattern that reflects how the different age groups are impacted by fishing, T is a targeting factor that quantifies how strongly a given species is targeted by a métier operated by a fishing fleet, V quantifies species vulnerability, ρ is the proportion of a métier area that is intersected by a species distribution area, E is fishing effort. The exploitation pattern S of blue ling and saithe was calculated as the ratio between fishing mortality (F) at age and the mean F averaged over all age groups (Table 1). All fleets were assumed to have the same exploitation pattern. ρ was calculated as the proportion of each métier area that was occupied by the species under consideration. The targeting factor (T) and the vulnerability (V) were estimated by modelling the CPUE of each species via a stepwise delta-GLM (Maunder and Punt, 2004) over the period 1999–2008. First, the probability of presence of a species in the catch was modelled using the binomial distribution. Second non-zero CPUE was modelled using a log-normal distribution. In both steps, the explanatory variables were a year effect and an interaction term between the (two) fleets and the (ten) métiers. An additional seasonal effect was added for blue ling with two seasons (spawning, not spawning). The targeting factor (T) was set for all species to the effect of the interaction between fleets and métiers. In other words, T represents for any species the mean CPUE that could be achieved by each fleet and métier, all other things being equal (Table 2). Blue ling vulnerability (V) was set to the seasonal effect derived from the delta-GLM. Note that the interaction between seasons and spatial units is already built into our model, through our migration ogive, as all spawners move to their spawning area between March and May, and then redistribute homogeneously in all available spatial units between June and February. So, we assume that, within a season (spawning or non-spawning), all grid cells occupied by blue ling have equal vulnerability to fishing. There remains an overall difference in vulnerability between the spawning and the non-spawning season, which is here represented by V. V was set to 1 for all other species. Finally, q was estimated for each fleet and each species by calibrating the partial fishing mortality derived from equation (4) with the actual 2009 estimates apportioned to the catches of the two fleets.

Fishing effort (in fishing hours) may be further disaggregated into three components:

$$E_{y,k,f,m} = W_{y,f} \times \Lambda_f \times \theta_{y,k,f,m}, \tag{5}$$

where $W_{y,f}$ is the number of vessels in year y for fleet f, Λ_f is the average number of hours fishing per vessel belonging to that fleet, and $\theta_{y,k,f,m}$ is the proportion of the total monthly fishing effort operated by fleet f that has been allocated to métier m.

The total monthly fishing mortality at age (F) is then the sum of the partial fishing mortalities (φ) from the French fleets and métiers expressed in equation (4), and of the non-French fleet annual partial fishing mortality (ψ). $\psi_{s,y,a}$ is here assumed to equate to the desired fishing mortality in year y, as derived from HCRs, apportioned to the non-French fleet yield relative to the total yield summed across all fleets in year ($y-1$). F is formulated as:

$$F_{s,y,k,a} = \sum_f \sum_m \varphi_{s,y,k,f,m,a} + \psi_{s,y,a}/12. \tag{6}$$

$W_{2009,f}$, $\theta_{2009,k,f,m}$, $E_{2009,k,f,m}$ and $\psi_{2009,s,a}$ were initialized using 2009 observations. The yield Y of stock s by any of the French fleets f, operating métier m, in year y and month k is (Beverton and Holt, 1957):

$$Y_{s,y,k,f,m} = \sum_a \frac{\varphi_{s,y,k,f,m,a}}{F_{s,y,k,a} + M_s/12} \times \left(1 - \exp\left(-F_{s,y,k,a} - M_s/12\right)\right) \times B_{s,y,k,m,a} \tag{7}$$

where M is the natural mortality of species s.

Non-age-structured stocks

For both French fleets, the partial harvest rate (h) of species s (either roundnose grenadier, black scabbardfish or deepwater sharks), in year y and month k, which can be attributed to fleet f operating métier m, is formulated as:

$$h_{s,y,k,f,m} = q_{s,f} \times T_{s,f,m} \times V_{s,k} \times \rho_{s,m} \times E_{y,k,f,m} \tag{8}$$

The partial harvest rate equation (8) is equivalent to the age-structured partial fishing mortality equation (4), with subscript a removed and S set to 1. q is here estimated for each fleet and each species by calibrating harvest rates with the actual 2009 estimates apportioned to the catches of the two fleets. Fishing effort E is modelled as in equation (5).

The yield Y achieved by both the large French trawlers ($f = fr1$) and the other French fleet ($f = fr2$) fishing non-age-structured stocks was derived using the formulation from Coppola and Pascoe (1998). With this model, catch is non-linearly increasing with fishing effort, and reaches an asymptote, corresponding to the available biomass, as fishing effort tends to the infinity. In order to accommodate the non-French fleet catches into this model, we assumed that the non-French fleet ($f = nfr$) would operate before the two French fleets at the beginning of each month, thereby catching 1/12 of their annual yield $Y_{s,y,f=nfr}$. The non-French fleet yield in year y ($Y_{s,y,f=nfr}$) is here assumed to

Table 2. Target factor quantifying how strongly each species is targeted by each métier (the average between the two fleets is given first, followed by the value for each of the two French fleets in bracket).

Métiers		**Target factor**				
Code	**Full name**	**Blue ling**	**Saithe**	**Black scabbardfish**	**Roundnose grenadier**	**Deepwater sharks**
Dem4	Demersal fishing in ICES Subarea IV	0 (0–0)	325 (5–645)	0 (0–0)	0 (0–0)	0 (0–0)
Dem5	Demersal fishing in ICES Subarea V	6 (6–6)	41 (11–72)	1 (0–2)	4 (0–9)	12 (2–23)
Dem6	Demersal fishing in ICES Subarea VI	11 (7–14)	30 (10–51)	22 (11–33)	27 (11–43)	9 (6–12)
Dem78	Demersal fishing in ICES Subareas VII and VIII	1 (0–1)	0 (0–0)	16 (0–33)	7 (0–15)	10 (0–20)
DeepEdge6	Edge in Subarea VI	21 (10–33)	23 (9–36)	24 (12–35)	31 (15–46)	12 (7–18)
DeepNew5	New grounds in ICES Subarea V	37 (17–57)	0 (0–0)	6 (3–8)	55 (40–70)	16 (10–22)
DeepNew6	New grounds in ICES Subarea VI	36 (23/–49)	0 (0–0)	9 (4–15)	102 (39–165)	41 (28–54)
DeepOther6	Other deepwater grounds in Subarea VI	29 (17–41)	10 (5–15)	42 (21–62)	38 (21–54)	13 (6–20)
DeepRef5	Reference deepwater grounds in Subarea V	71 (41–101)	2 (2–2)	10 (7–12)	37 (7–67)	8 (2–14)
DeepRef7	Reference deepwater grounds in Subarea VII	4 (1–8)	1 (0–1)	25 (5–45)	27 (9–45)	16 (2–30)

DeepEdge6, DeepNew5, DeepNew6, DeepOther6, DeepRef5 and DeepRef7 refer to the deepwater métiers (fishing grounds) identified by Lorance *et al.* (2010). Dem4, Dem5, Dem6 and Dem78 are the other demersal métiers operated by the two French fleets in shallower waters.

Table 3. Main economic variables related to the two French fleets and their landed species.

Fleet / Species	Parameter	Value
Large French trawlers	Operating cost (€/hour fishing)	2 773
	Proportion of other species in gross revenue	0.36
	Slope of No. vessels vs. profit regression	7.6×10^{-8}
	No. vessels (1999)	13
	Average hours fishing/vessel	2 638
Other French fleet	No. vessels (1999–2008)	3 199
	Average hours fishing/vessel	846
Blue ling	Price – (€/kg)	2.0 (0.10)
Saithe	Price – (€/kg)	1.1 (0.10)
Roundnose grenadier	Price – (€/kg)	1.7 (0.15)
Black scabbardfish	Price – (€/kg)	2.1 (0.20)
Deepwater sharks	Price – (€/kg)	1.4 (0.12)

"Other species" are all landed species excluding blue ling (*Molva dypterygia*), saithe (*Pollachius virens*), roundnose grenadier (*Coryphaenoides rupestris*), black scabbardfish (*Aphanopus carbo*) and deepwater sharks (*Centrophorus squamosus* and *Centroscymnus coelolepis*). The CVs of fish prices are shown in brackets.

equate to the total allowable catch (TAC) in year y, apportioned to the non-French fleet yield relative to the total yield summed across all fleets in year $(y-1)$. That quantity is then withdrawn from the initial biomass, and both French fleets fish on the remaining biomass $(B_{s,y,k} - Y_{s,y,f=nfr}/12)$. $Y_{2009,f=nfr}$ was initialized using 2009 observations. We formulate the yield for non-age-structured stocks, partitioned into the two French fleets and métiers, as:

$$Y_{s,y,k,f\in\{fr1,fr2\},m} = \frac{h_{s,y,k,f\in\{fr1,fr2\},m}}{h_{s,y,k,f=fr1,m} + h_{s,y,k,f=fr2,m}} \times \left(1 - \exp\left(-h_{s,y,k,f=fr1,m} - h_{s,y,k,f=fr2,m}\right)\right) \times \left(B_{s,y,k} - Y_{s,y,f=nfr}/12\right) \quad (9)$$

Fleet dynamics

We have explicitly built in three major fleet dynamics processes for the large French trawlers: fishing profit, vessels' entry–exit [through variable W in equation (5)], and fishing effort allocation [through variable θ in equation (5)]. The dynamics of the other French fleet could not be modelled explicitly here, as it is mainly determined by the exploitation of species other than those investigated in this study.

Fishing profit

The annual and monthly profit $\Pi_{y,k,f1,m}$ achieved by the large French trawlers (f_1) operating métier m may be expressed by:

$$\Pi_{y,k,f1,m} = \frac{\sum_s \left(\overline{p_s}\left(1 + cv_{ps}\eta_{s,y}\right) - \lambda_{s,y,k,f1,m}\right) Y_{s,y,k,f1,m}}{1 - \mu_{y,f1}} - \chi_{y,f1} E_{y,k,f1,m}. \quad (10)$$

$\bar{p}$ is the average annual landing price per unit yield (€/kg), η is an uncorrelated random noise distributed as $N(0,1)$ depicting variability, and cv_{ps} is the coefficient of variation of the different fish species landing prices. The random numbers used to simulate interannual fluctuations in fish prices were constrained to the $[-1/cv_{ps}, 1/cv_{ps}]$ interval. χ is the annual operating CPUE (€/hour fishing) of the large French trawlers. μ is the proportion of the gross revenue of the large French trawlers derived from species other than those considered in the study. Both χ and μ fluctuate randomly, following a uniform distribution. The mean and the CV of landing price and proportion of other species were derived from 1999–2008 observations (Table 3). The CV of fish prices (cv_{ps}) are shown in Table 3. We bounded the values taken by the proportion of other species between 25% and 45%. To reflect that operating costs will likely increase compared to the reference year (2009), the two boundaries of the uniform distribution chosen to represent interannual variations in χ were χ_{2009} and $1.20 \times \chi_{2009}$.

Finally, λ is a tax imposed for quota overshooting. $\lambda = 0$ if the quota of species s, in year y, month k, and in the fishing area operated by métier m is not exceeded, and λ is set to current fish price otherwise. When the quota of a given species is reached, the fleets do not gain any economic return from selling it.

We also use in subsequent paragraphs the notation $\Pi_{y,f1}$ for the annual profit achieved by the large French trawlers, obtained by summing $\Pi_{y,k,f1,m}$ over all months and métiers operated.

Vessels' entry–exit

Our vessels' entry–exit model is a simplification of the fleet capacity equation by Hoff and Frost (2008). It is assumed that fleet size is constant within a calendar year but may be subject to interannual changes as a result of past profits. The number of hours fishing per vessel is assumed constant throughout the simulation period. The number of large French trawlers in year y may be formulated as:

$$W_{y,f1} = W_{y-1,f1} + \delta_{y,f1} \times \left(\frac{1}{1+u_f}\sum_{i=0}^{u_f} \Pi_{y-1-i,f1}\right), \quad (11)$$

where δ is a fleet-dependent regression coefficient and u is the number of years over which past profits affect fleet capacity changes in equation (11), minus one year. δ was estimated as the slope of the regression between interannual change in fleet size and past profits ($y = 7.283 \times 10^{-8} \times x$; $R^2 = 0.87$). Different u_f values were explored, and the best goodness of fit was achieved with $u_f = 1$. Finally, we assumed that δ fluctuates randomly, following a uniform distribution, between 0 (no change in fleet capacity) and 7.283×10^{-8} (fully economically-driven fleet capacity). These two boundaries reflect that, although economic theory predicts that variations in fleet capacity are driven by past profits, fleet capacity may also be maintained despite low fishing profits by subsidies, or decreased through decommission schemes.

Allocation of fishing effort

Similar to Marchal *et al.* (2011), we considered here that a fleet might operate different métiers, the choice of which is a combination of economic opportunities and traditions. The proportion of effort allocated to a métier then depends dynamically on two quantities. The first quantity represents anticipated economic opportunities, and it is hereby derived from the actual monthly profit per unit of effort observed in the previous year. The second quantity is the traditional effort allocation for the fleet, which is here derived from the effort actually observed during the same month in the previous year. The relative weight given to anticipated profit and traditions is defined by a parameter α, the fishing behaviour weighting coefficient. The proportion of fishing effort (θ) of fleet f allocated to métier m may then be formulated as:

$$\theta_{y,k,f1,m} = \alpha_y \left[\frac{\exp\left(\dfrac{\Pi_{y-1,k,f1,m} - \sum_s \lambda_{s,y,k,m} Y_{s,y-1,k,f1,m}}{E_{y-1,k,f1,m}} \right)}{\sum_m \exp\left(\dfrac{\Pi_{y-1,k,f1,m} - \sum_s \lambda_{s,y,k,m} Y_{s,y-1,k,f1,m}}{E_{y-1,k,f1,m}} \right)} \right] + (1-\alpha_y)\left[\frac{E_{y-1,k,f1,m}}{\sum_m E_{y-1,k,f1,m}} \right], \tag{12}$$

where $\lambda_{s,y,k,m} = 0$ if the quota of species s in year y, month k, and in the fishing area operated by métier m is not exceeded, and $\lambda_{s,y,k,m} = p_{s,y}$ otherwise. When the quota of a given species is reached, the fleets do not expect an economic return from selling it, and therefore are incentivized to operate métiers with reduced bycatch for this species. Fully static and fully profit-driven effort allocations are then characterized by values of α of 0 and 1, respectively. Based on (Marchal *et al.*, 2013), α was here varied randomly, following a uniform distribution, between 0.1 and 0.3.

Stock assessment

A stock assessment module has been coupled to our bioeconomic model to mimic the ICES advisory process. For blue ling, an XSA (Shepherd, 1999) was run at the beginning of every simulated year to estimate current biomass ($\hat{B}_y$) and fishing mortality ($\hat{F}_y$) in year y, by calling the FLXSA Fisheries Library in R (Kell *et al.*, 2007). Inputs to the XSA included total catches-at-age, weights-at-age, and catch rates (CPUE) at age of the large French trawlers. The CPUE abundance index used to tune the XSA was calculated by averaging CPUE over all métiers catching blue ling. Note that all input time-series started in 2004, five years before the first simulated year (2009), to enable the XSA to be run from 2009 onwards. The 2004–2008 inputs were historical data, while all inputs posterior to 2009 were simulated by our model.

Another approach had to be considered to mimic the saithe stock assessment, since we could simulate neither the Norwegian and German CPUE series nor the scientific surveys that are normally used to tune the assessment. Instead, we assumed that:

$$\hat{B}_y = B_y(1 + cv_a \times \xi_y), \tag{13}$$

where ξ is an uncorrelated random noise distributed as $N(0,1)$ depicting variability, and cv_a is the coefficient of variation characterizing the uncertainty around the saithe stock assessment. The random numbers used to simulate stock assessment uncertainty were constrained to the $[-1/cv_a, 1/cv_a]$ interval, where cv_a was set to 20%. The estimated fishing mortality $\hat{F}_y$ was then derived by solving numerically the Baranov catch equation.

No stock assessment was simulated for roundnose grenadier, black scabbardfish or deepwater sharks.

Harvest control rules

Blue ling

Blue ling is not subject to any explicit management plan. In this study we evaluated two HCRs for blue ling. The first (data-rich) HCR assumes that stock numbers and fishing mortality at age estimates are available every year through an analytical assessment. The shape of the blue ling data-rich HCR is typical of EU management strategies in place for e.g. North Sea gadoids (EC, 2008), and it may be formulated as:

$$\begin{cases} \tilde{F}_y = F_{target}, \text{ if } \hat{B}_y \geq B_{target} \\ \tilde{F}_y = F_{target} - (F_{target} - F_{min}) \left(\dfrac{B_{target} - \hat{B}_y}{B_{target} - B_{lim}} \right) \text{ if } B_{lim} < \hat{B}_y < B_{target} \\ \tilde{F}_y = F_{min}, \text{ if } \hat{B}_y < B_{lim} \end{cases}, \tag{14}$$

where $\tilde{F}_y$ is the desired fishing mortality level, used to calculate the TAC in year y, F_{min} is the minimum fishing mortality level corresponding to bycatches for the case that the targeted fishery was to cease, B_{target} and F_{target} are, respectively, the spawning stock biomass and fishing mortality levels targeted in the medium term. F_{target} and B_{target} were set at a level expected to sustainably maximize blue ling yield in the long term (MSY). Based on recommendations of ICES (2012a) and on preliminary simulations, F_{target} and B_{target} were then, respectively, calculated as 80% of natural mortality (M) and 35% of the unfished spawning stock biomass (B_0). B_{lim} has been set to 20% of B_0. (i.e. 57% of B_{target}). F_{min} has been set to 0. The different reference points are shown in Table 4.

The second (data-limited) HCR assumes that only total international landings and large French trawlers CPUE abundance indices are available. We then implemented the ICES HCR framework to derive an annual TAC for data-limited stock (ICES, 2012b):

$$TAC_{s,y} = 0.8 \times Y_{s,y} \times \left[\frac{\sum_{i=1}^{2} \sum_m \left(\dfrac{Y_{s,y-i,f1,m}}{E_{y-i,f1,m}} \right) / 2}{\sum_{i=3}^{5} \sum_m \left(\dfrac{Y_{s,y-i,f1,m}}{E_{y-i,f1,m}} \right) / 3} \right] \tag{15}$$

For both data-rich and data-limited HCRs, interannual variations in TAC are bounded to 15%.

Saithe

North Sea saithe has been managed by the EU and Norway through an explicit long-term management plan, since 2004 (Anonymous, 2004). This plan establishes a TAC for the year to come (y), mainly based on two elements. The first element is $\tilde{F}_y$, the mean fishing mortality (averaged over ages 3–6), the TAC should be consistent with in year y [as in equation (14) formulated for the data-rich blue ling HCR]. The second element is, as for blue ling, a set of boundaries set to constrain interannual variations in TAC.

Table 4. Biological reference points considered in this study: target and limit spawning stock biomass, target and minimum fishing mortality for blue ling (*Molva dypterygia*) and saithe (*Pollachius virens*); target biomass, target harvest rate for roundnose grenadier (*Coryphaenoides rupestris*), black scabbardfish (*Aphanopus carbo*) and deepwater sharks (*Centrophorus squamosus* and *Centroscymnus coelolepis*).

		Blue ling	Saithe	Roundnose grenadier	Black scabbardfish	Deepwater sharks
Target (spawning)	B_{target}	48 212	200 000	67 151	30 329	26 442
stock biomass (t)	B_{target}/B_0	0.35	0.15	0.50	0.50	0.50
Limit (spawning)	B_{lim}	27 550	106 000	–	–	–
stock biomass (t)	B_{lim}/B_0	0.20	0.07	–	–	–
	B_{lim}/B_{target}	0.57	0.53	–	–	–
Target fishing mortality (y^{-1})	F_{target}	0.12	0.30	–	–	–
Minimum fishing mortality (Y^{-1})	F_{lim}	0.00	0.10	–	–	–
Target harvest rate	H_{target}	–	–	0.08	0.22	0.00

Table 5. Blue ling. Summary performances of the management strategies building in data-rich or data-poor harvest control rules.

B_{2009}	66% B_{target}		29% B_{target}	
HCR type	**Data-rich**	**Data-poor**	**Data-rich**	**Data-poor**
Year where *Pr* (B_y > B_{target}) > 50%	–	–	–	–
Year where *Pr* (F_y < F_{target}) > 50%	2 013	2 014	2 011	2 014
Median (B_{2018} / B_{target})	0.97	0.95	0.56	0.55
Median (F_{2018} / F_{target})	0.65	0.70	0.57	0.71

The stock-at-age numbers in the initial simulation year (2009) correspond to either the actual 2009 spawning stock biomass estimate (66% B_{target}), or a lower value (29% B_{target}).

Roundnose grenadier and black scabbardfish

Roundnose grenadier and black scabbardfish are not subject to any explicit management plan. We applied to these species the same data-limited HCR as for blue ling [equation (15)], including the constraint on interannual variability in TAC. Although reference points were not required in these HCRs, we defined a target biomass (B_{target}) and harvest rate (H_{target}) for these stocks to evaluate their performances. B_{target} and H_{target} were here defined as the levels of biomass and harvest rate, respectively, which maximize long-term catches (Table 4).

Deepwater sharks

Deepwater shark fishing has been prohibited in EU waters since 2009, and a zero TAC has been implemented in our simulations for these species. The target harvest rate (H_{target}) has hence been set to zero. All deepwater shark catches simulated in our model are then considered as discards. Consistent with roundnose grenadier and black scabbardfish, we also defined a target biomass (B_{target}) for deepwater sharks as biomass maximizing long-term catches (Table 4).

Simulation design

Four sets of 200 simulations have been run over the period 2009–2018 on the ISIS-Fish platform, to evaluate the respective merits of data-rich and data-poor HCRs for blue ling, and their sensitivity to initial blue ling abundance. Each set of simulation evaluates the effects of one type of blue ling HCR (data-rich or data-limited), in combination with two vectors of stock-at-age numbers in the initial simulation year (2009). These abundance vectors correspond to either the actual 2009 spawning stock biomass estimate (23% B_0, or 66% B_{target}), i.e. above the B_{aggreg} (the spawning biomass level below which stock contraction occurs), or a value lower than B_{aggreg} (10% B_0, or 29% B_{target}).

A set of 28 200 independent random numbers was generated to reflect the interannual variability and/or uncertainty around blue ling and saithe weights-at-age [4000 draws for ς in equation (1)], blue ling and saithe stock-recruitment relationships [4000 draws for ε and ζ in equations (2) and (3), respectively], blue ling density-dependence (200 draws for B_{aggreg}), all species' prices [10 000 draws for η in equation (10)], proportion of other species in landing value [2000 draws for μ in equation (10)], operating costs [2000 draws for χ in equation (10)], fleet capacity [2000 draws for δ in equation (11)], fishing effort allocation [2000 draws for α in equation (12)], and saithe stock assessment [2000 draws for ξ in equation (13)]. The same set was used to simulate the effects of both blue ling HCRs, to make the comparison between management scenarios more tractable.

Results

Blue ling spawning-stock biomass (SSB) was slightly higher and closer to B_{target} with the data-rich HCR (Table 5, Figures 1a and b). The SSB increased over the period 2009–2018, but its median value remained below B_{target}. When B_{2009} was 66% of B_{target}, the blue ling SSB only dropped below B_{aggreg}, the level of biomass below which density-dependence occurs, on rare occasions. By contrast, the blue ling SSB was rarely above B_{aggreg}, when B_{2009} was 29% of B_{target}.

Blue ling fishing mortality was lower, with the data-rich HCR, compared with the data-limited HCR, especially when B_{2009} was 29% of B_{target} (Table 5, Figures 2a and b). When B_{2009} was 66% of B_{target}, blue ling fishing mortality decreased over 2009–2018, falling below F_{target} with a 50% probability in 2013 (data-rich HCR) or 2014 (data-limited HCR). When B_{2009} was 29% of B_{target}, blue ling fishing mortality increased over 2009–2010, and decreased over 2010–2018, falling below F_{target} with a 50% probability in 2011 (data-rich HCR) or 2014 (data-limited HCR).

Neither the type of HCR, nor the initial stock-at-age numbers chosen for blue ling, had a substantial impact on the SSB and fishing mortality (or harvest rate) trajectories of the other species caught in the mixed fishery. These are presented in Figures 3

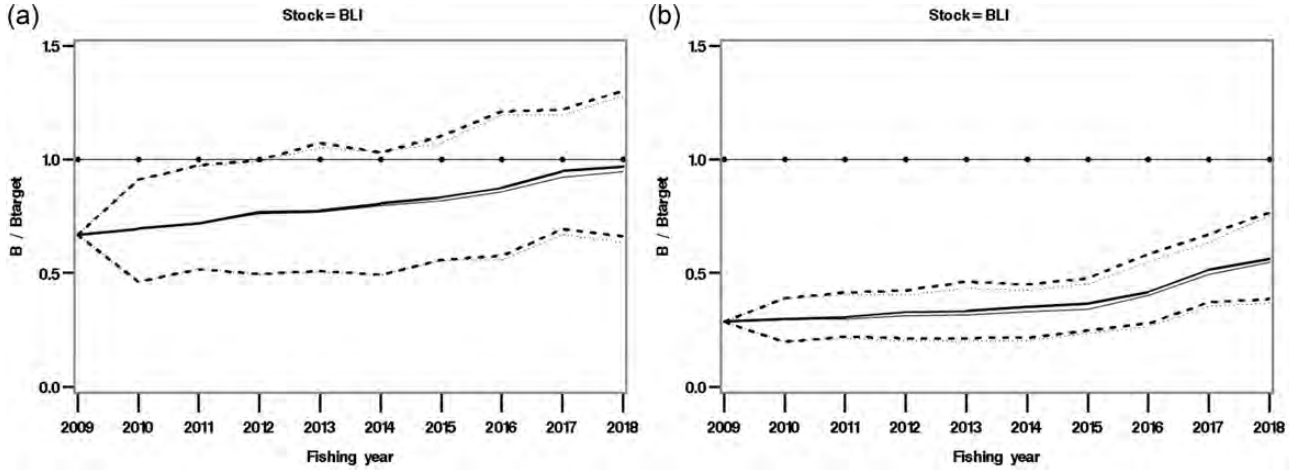

Figure 1. Blue ling. Annual spawning stock biomass relative to B_{target} resulting from 200 simulations run with either the data-rich (median: thick and plain line, 5th and 95th percentiles: thick and dotted lines) or the data-limited (median: thin and plain line, 5th and 95th percentiles: thin and dotted lines) blue ling harvest control rules. The initial blue ling stock-at-age numbers correspond to either (a) the actual 2009 spawning biomass or (b) 10% of the unfished spawning biomass. The plain dotted line represents the targeted level.

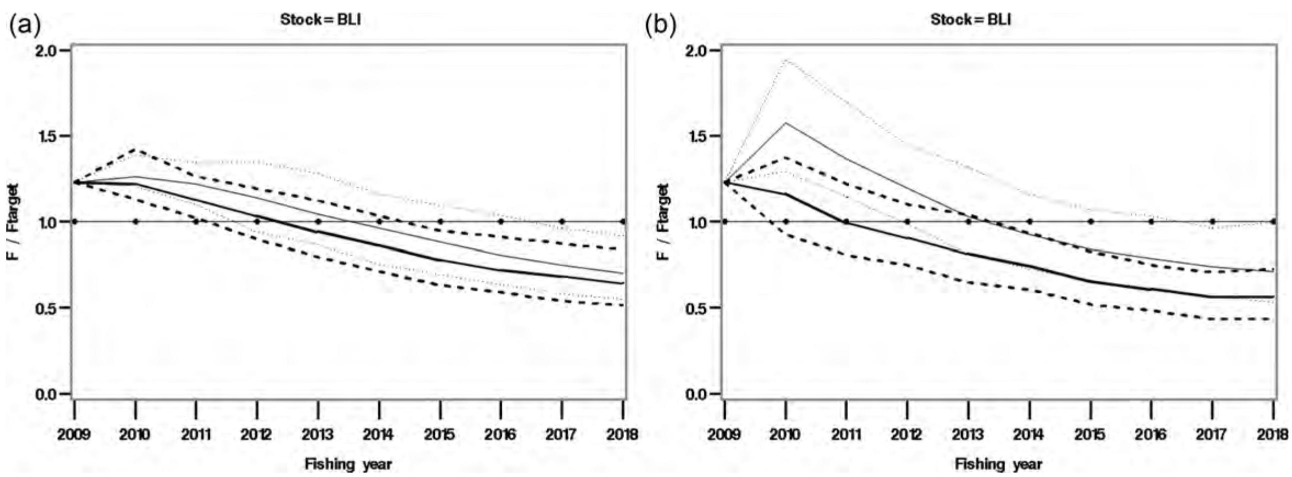

Figure 2. Blue ling. Annual fishing mortality relative to F_{target} resulting from 200 simulations run with either the data-rich (median: thick and plain line, 5th and 95th percentiles: thick and dotted lines) or the data-limited (median: thin and plain line, 5th and 95th percentiles: thin and dotted lines) blue ling harvest control rules. The initial blue ling stock-at-age numbers correspond to either (a) the actual 2009 spawning biomass, or (b) 10% of the unfished spawning biomass. The plain dotted line represents the targeted level.

and 4 with the data-rich blue ling HCR, and with blue ling B_{2009} set to 66% of B_{target}. The projected saithe SSB decreased below B_{target} over 2009–2014, and increased over 2015–2018, exceeding B_{target} with a 50% probability in 2017 (Figure 3a). The projected saithe fishing mortality decreased gradually over 2009–2018, dropping below F_{target} with a 50% probability from 2014 onwards (Figure 4a). The variability of saithe SSB increased dramatically over the period 2014–2018. The biomass of roundnose grenadier, black scabbardfish and deepwater sharks did not vary substantially over 2009–2018 (Figure 3b–d). Roundnose grenadier biomass remained below B_{target} (Figure 3b), while its harvest rate decreased slightly since 2010, falling below H_{target} with a 50% probability in 2012 (Figure 4b). The black scabbardfish SSB remained slightly above B_{target} (Figure 3c), while its harvest rate remained well below H_{target} (Figures 4c). Despite a very low harvest rate (< 0.01, not shown here), the deepwater shark biomass remains below B_{target} (Figure 3d).

The annual profit achieved by large French trawlers decreased on average over 2009–2011 and then increased over 2012–2018 (Figure 5). Profit is negative most of the time, including the 95th percentile value. The large French trawlers' profit is predicted to be around −10 million euros in 2018, with a 50% probability. Projected profits are almost not sensitive to the type of blue ling HCR selected. Profit was only slightly larger when the initial blue ling SSB was set to 66% of B_{target} compared to when it was set to 29% of B_{target}.

Finally, we compared the trends in blue ling SSB and CPUE relative to 2009, for each blue ling HCR type and starting biomass scenario (Figure 6). There was almost no influence of the type of HCR selected on the relative SSB or CPUE trends, and we show only the results obtained with the data-rich HCR. The SSB and CPUE trends were broadly consistent over 2009–2018 (Figure 6). Still, the blue ling CPUE slightly overestimated the SSB recovery over 2012–2018, when the initial 2009 blue ling SSB was assumed to be

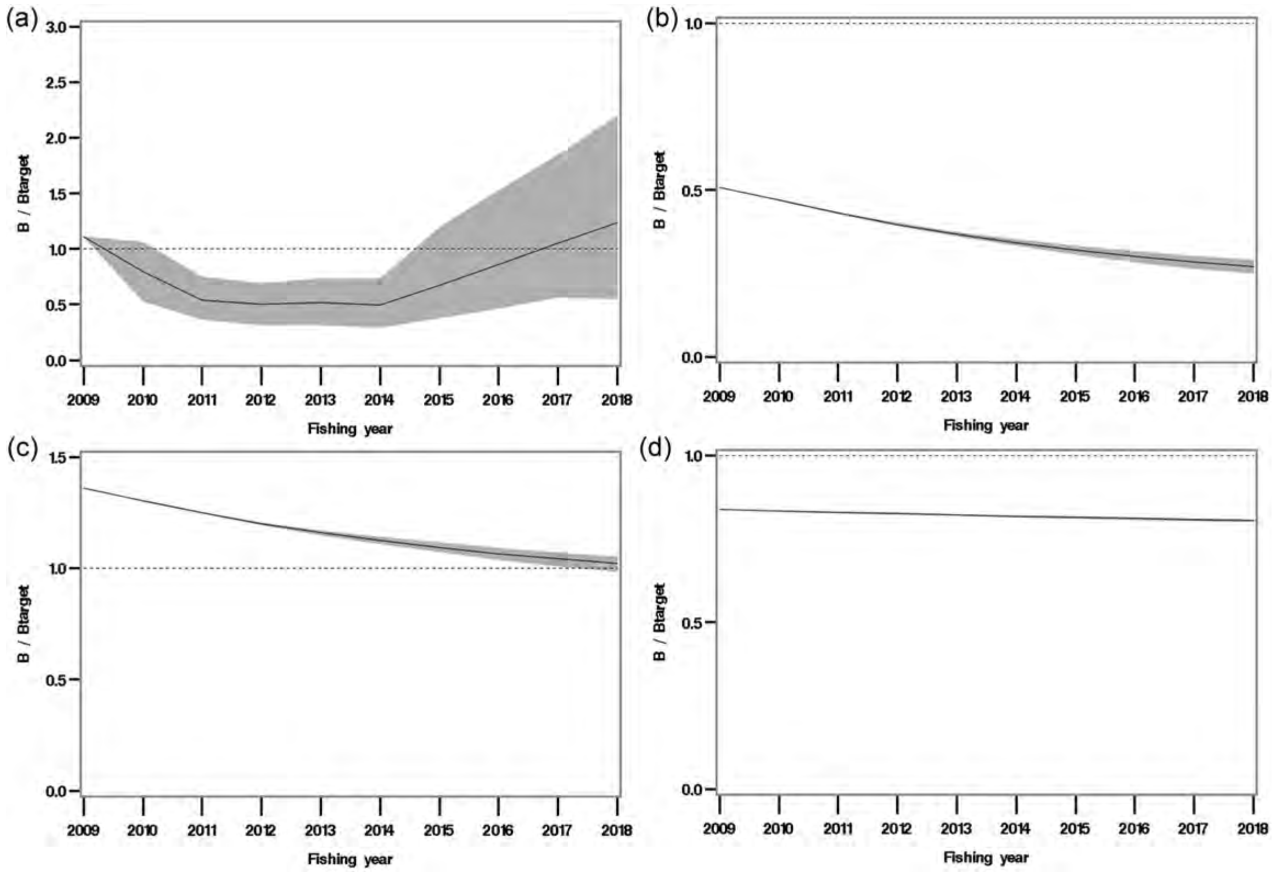

Figure 3. Annual spawning stock biomass (or total biomass) relative to B_{target} resulting from 200 simulations run with the data-rich blue ling harvest control rule; (a) saithe, (b) roundnose grenadier, (c) black scabbardfish, (d) deepwater sharks. The initial blue ling stock-at-age numbers correspond to the actual 2009 spawning biomass. The median (plain line) and the area between the 5th and the 95th percentiles (shaded in grey) are represented. The thin dotted line represents the targeted level.

above the level that triggers stock contraction (B_{aggreg}). In contrast, the blue ling CPUE underestimated the SSB recovery over 2010–2015, when B_{2009} was above B_{aggreg}.

Discussion

There were only limited differences between the trends in SSB and fishing mortality obtained for the two types of HCR, when the initial biomass was set at current levels, although blue ling spawning biomass recovered slightly quicker with the data-rich HCR. The differences between the conservation performances of both HCRs were more important when the initial SSB was lower. In particular, fishing mortality decreased below the targeted level after only two years with the data-rich HCR (compared with five years with the data-limited HCR). These results may inform management that the data-limited HCR prescribed by ICES (2012b) could be appropriate for calculating blue ling catch limits at current biomass levels. However, if blue ling SSB was to be more severely depleted, a management strategy building on a full analytical assessment would then be required.

The slow (or the lack of) recovery of the different stocks has four main origins. First, the system we modelled is a mixed, and not a single-species, fishery. Therefore, the expected fishing mortality derived from the HCRs for one species may not be achieved because the fishing fleets may exceed their quota allowance as bycatch effect. A tax applied to overquota shooting has been set to fish price to discourage fishing for species for which the quota has been exceeded (which reproduces conceptually discarding practices), but that has not been sufficient to prevent catching above quota allowance. Although this approach reproduces conceptually a situation in which fishers are allowed to discard fish (and thereby cannot expect to make a revenue out of catching them), setting the overquota landing tax to a higher level than fish price would have further discouraged fishing above quota, and thereby accelerated the stock recovery process (Holland and Herrera, 2006; Marchal *et al.*, 2009a). Second, interannual changes in TAC have been bounded by a buffer inspired from current EU fisheries management plans, which slows down the recovery of fish stocks towards target levels. Third, in the case of blue ling, CPUEs were used in both management strategies, either to tune the blue ling stock assessment, or to trigger a management action. Therefore, the mismatch observed between CPUE and SSB trends has adversely altered the performances of the HCRs under investigation. Finally, we assumed that vessels' entry–exit was decided on an annual basis. Within a year, vessels may only modulate their activity through métier shifts, so they stay in the fishery even when they achieve negative profits. This assumption is not unreasonable when one considers that skippers and vessel-owners have an annual, or possibly multi-annual, strategy. Also, there are social reasons why employment at sea should be maintained until the end of the fishing year despite low or negative profits. Still, one cannot exclude the possibility that some fishing vessels could

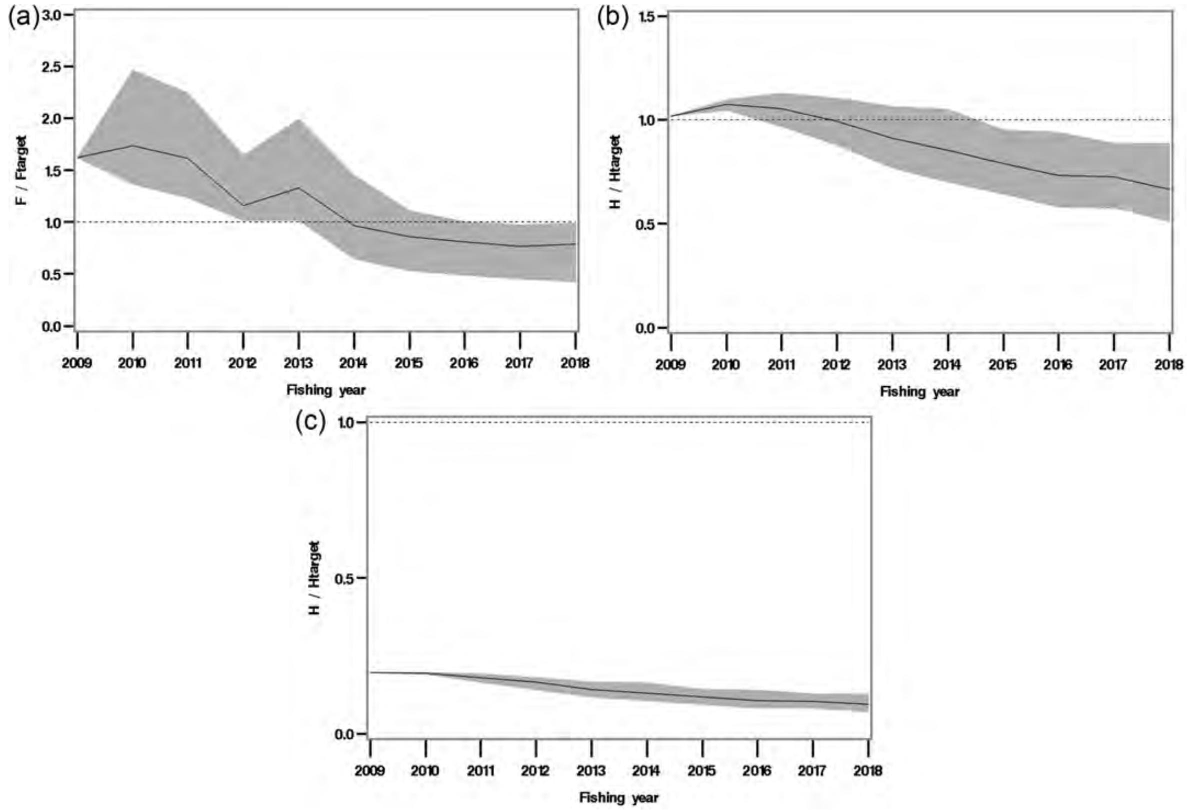

Figure 4. Annual fishing mortality (or harvest rate) relative to F_{target} (or H_{target}) resulting from 200 simulations run with the data-rich blue ling harvest control rule; (a) saithe, (b) roundnose grenadier, (c) black scabbardfish. The initial blue ling stock-at-age numbers correspond to the actual 2009 spawning biomass. The median (plain line) and the area between the 5th and the 95th percentiles (shaded in grey) are represented. The thin dotted line represents the targeted level.

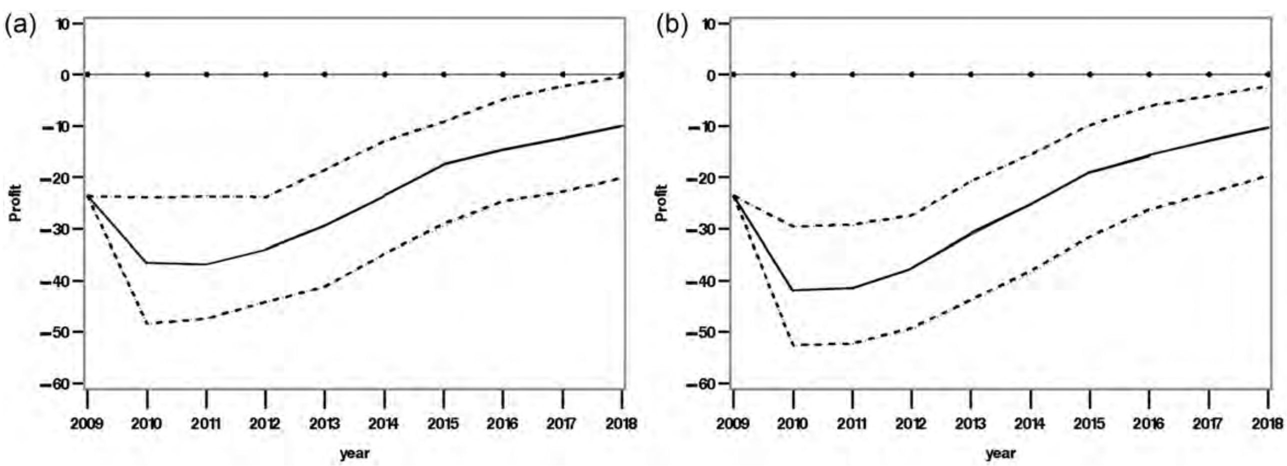

Figure 5. Annual profits (million €) of the large French trawlers, resulting from 200 simulations run with either the data-rich (median: thick and plain line, 5th and 95th percentiles: thick and dotted lines) or the data-limited (median: thin and plain line, 5th and 95th percentiles: thin and dotted lines) blue ling harvest control rules. The initial blue ling stock-at-age numbers correspond to either (a) the actual 2009 spawning biomass or (b) 10% of the unfished spawning biomass. The plain dotted line represents the zero-profit level.

retire in the middle of the year, in which case the decrease of fishing effort (and thereby the recovery of fish stocks) could be steeper than anticipated by our model.

Annual profit was only slightly affected by the type of blue ling HCR, and by the initial blue ling abundance level. This is because blue ling landings contribute relatively little to the profit achieved by large French trawlers. However, the general declining pattern in fishing mortality (or harvest rate) observed for blue ling, but also for the other species, results directly from a decline in fishing effort due to the negative profits recorded by this fleet.

When the initial blue ling biomass was set to current levels, CPUE trends overestimated the increase in SSB at the end of the simulated

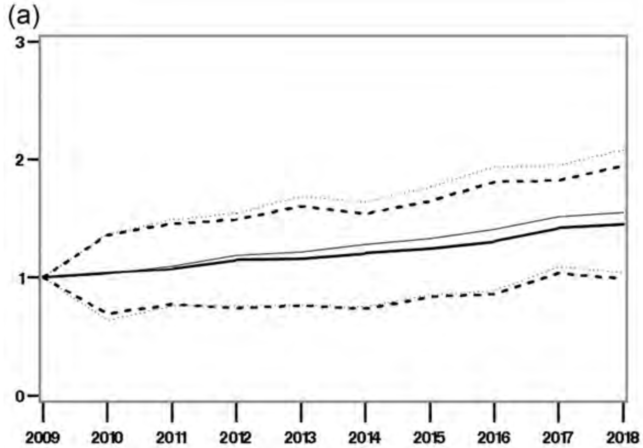

Figure 6. Blue ling. Annual catch per unit of effort (median: thin and plain line, 5th and 95th percentiles: thin and dotted lines) for large French trawlers, and spawning stock biomass (median: thick and plain line, 5th and 95th percentiles) relative to their respective 2009 value, resulting from 200 simulations run with the data-rich blue ling harvest control rule. The initial blue ling stock-at-age numbers correspond to either (a) the actual 2009 spawning biomass or (b) 10% of the unfished spawning biomass.

period. The spatial dynamics of the blue ling stock cannot explain this discrepancy, since density-dependence barely occurred when stock abundance was initialized at current levels. The increasing mismatch between CPUE and SSB trends resulted almost entirely from fleet dynamics. In the first years of the simulations, fishing behaviour was essentially driven by the second term of equation (12), i.e. past effort allocation, since $\alpha < 0.3$. The quasi-absence of spatial interannual stock dynamics throughout the time-series, combined with the limited fleet dynamics in the first simulated years, explains the consistency between blue ling CPUE and SSB trends at that time. However, after 5–10 years of simulations, the first term in equation (12), i.e. expected profit, becomes increasingly dominant over past effort allocation. Therefore, fishers increasingly favour the most profitable métiers, so the resulting CPUEs provide an overoptimistic picture of the actual biomass.

When the initial blue ling biomass was severely depleted, CPUE trends underestimated the increase in SSB at the start of the simulated period. This discrepancy resulted from combined stock and fleet spatial dynamics. Density-dependence occurred when initial stock abundance was severely depleted. At the start of the simulations, blue ling was concentrated in its most favourable habitats. As SSB gradually recovered above the density-dependence trigger level, blue ling slowly replenished in the whole stock area. Fishers, however, do not react instantaneously to the shift in blue ling spatial dynamics, because of (i) the lagged structure of the first term in equation (12), i.e. expected profit, (ii) the high weight assigned to the second term in equation (12), i.e. historical effort allocation, and (iii) their targeting species other than blue ling. As a result, the fleet distribution poorly overlaps that of blue ling, resulting in low CPUEs despite increasing SSB, during the first simulated years. After five years of simulation, fishers acquire better information on the distribution of the stock and also become increasingly opportunistic, so the trend in CPUE becomes more consistent with, and even slightly overestimates, the SSB trend.

The discrepancy between CPUE and SSB trends would have been even inflated, had we allowed the fishing behaviour coefficient (α) to be closer to 1 (fully opportunistic fishing behaviour). In several fisheries modelling studies, the discrepancy between CPUE trends and stock abundance fluctuations is simulated by an uncorrelated random noise in the relationship between CPUE and biomass (Butterworth *et al.*, 2010; Dichmont and Brown, 2010; Little *et al.*, 2011). While such a representation mimics variations of the CPUE index around a mean biomass value, it does not reflect the bias due to fishing efficiency increases over time and/or to the spatial structuring of fishing fleets and/or fish stocks. The impact of an annual trend in catchability on management strategies performance has been evaluated by Ulrich *et al.* (2002) for the North Sea flatfish fisheries. Our study contributed to evaluate some of the potential impact of spatial structuring in fisheries data on the relationship between CPUE and stock biomass.

Supplementary data

Supplementary materials presenting the stock assessments conducted for blue ling (S1), black scabbardfish (S2) and deepwater sharks (S3) are available at *ICES Journal of Marine Science* online.

Funding

This study was carried out with financial support from the Commission of the European Communities under the DEEPFISHMAN project (grant agreement No. 227390). This support is gratefully acknowledged.

Acknowledgements

We would first like to thank José De Oliveira (CEFAS, UK) for providing very helpful stock assessment advice. We are also indebted for the thorough and constructive comments from two anonymous referees.

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Handling editor: Jörn Schmidt