Aquat. Living Resour. 19, 15–29 (2006)
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DOI: 10.1051/alr:2006002
www.edpsciences.org/alr

Aquatic
Living
Resources

Assessing the impact of different management options using ISIS-Fish[⋆]: the French *Merluccius merluccius* – *Nephrops norvegicus* mixed fishery of the Bay of Biscay

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Received 19 May 2005; Accepted 30 November 2005

Abstract – In this paper, we present an approach to compare the impact of different management options on the dynamics of a mixed fishery. We used ISIS-Fish, a simulation tool aimed at evaluating the impact of spatial and seasonal management measures on the dynamics of mixed fisheries. The French *Nephrops norvegicus* (Norway lobster) – *Merluccius merluccius* (hake) mixed fishery of the Bay of Biscay was chosen as a study case. First, we parameterised the population and exploitation models. We then selected several management measures, including marine protected areas (MPAs) and total allowable catches (TAC), and parameterised fishermen's reaction to each measure. Then, a sensitivity analysis was performed according to a fractional factorial experimental design. Management scenarios were assessed and compared using a statistical simulation design. The sensitivity analysis showed the large influence of some parameters, such as natural mortality, *N. norvegicus* fecundity, and catchability on both abundance and catches. Given model parameters, an improvement of trawl selectivity and several MPA designs (differing in size, seasonality and location) were found to result in a significant increase in abundance over 10 years, especially for *N. norvegicus*. This study illustrates the need for a pluri-specific approach to fisheries assessment and management.

Key words: Fisheries dynamics / Spatial model / Management measures / Sensitivity analysis / Simulation design

Résumé – Évaluation de l'effet de différents scénarios de gestion à l'aide du simulateur « ISIS-Fish » : la pêcherie mixte merlu-langoustine française du golfe de Gascogne. Dans cet article, nous présentons des méthodes destinées à comparer l'impact de différentes alternatives de gestion sur la dynamique d'une pêcherie mixte. Pour cela, nous avons utilisé un outil de simulation, « ISIS-Fish », conçu pour évaluer les effets de mesures de gestion spatiales et saisonnières. Nous avons choisi la pêcherie mixte de merlu – langoustine (*Merluccius merluccius* – *Nephrops norvegicus*) française du golfe de Gascogne comme exemple d'étude. Dans un premier temps, un paramétrage des modèles de population et d'exploitation a été réalisé. La réaction des pêcheurs face aux mesures de gestion sélectionnées, notamment aux aires marines protégées et aux captures totales admissibles (TAC), a ensuite été programmée. Dans un second temps, une analyse de sensibilité a été réalisée à l'aide d'un plan d'expériences factoriel fractionnaire. Enfin, un second plan de simulation a permis d'évaluer l'effet des différents scénarios de gestion. L'analyse de sensibilité a permis de mettre en évidence l'influence importante de certains paramètres, notamment la mortalité naturelle, la fécondité de la langoustine et la capturabilité sur les captures et les abondances. Une amélioration de la sélectivité des chaluts et certaines aires marines protégées ont permis d'obtenir une augmentation significative des abondances sur une période de 10 ans, en particulier pour la langoustine. Cette étude a aussi mis en évidence la nécessité d'une gestion pluri-spécifique dans l'évaluation et la gestion des pêcheries.

1 Introduction

Many exploited stocks subject to total allowable catch (TAC) regulations still suffer from over-exploitation (Safina 1995; Botsford et al. 1997). Facing the relative failure of TAC as the main tool for fisheries regulation, there is an increasing interest in alternative management measures. Selective gears are considered in many fisheries to reduce technical interactions (Murawski and Stewart 1996; Commission of the European Communities 2001c). Marine protected areas (MPAs) are also more and more used to protect particular population stages and/or to preserve habitat and food webs (Botsford et al. 1997; Holland 2000). The effectiveness of MPAs is known to depend on the design of the closure (localisation, size, timing) (Sumaila et al. 2000; Jamieson and Levings 2001) and on interactions with other management

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measures (Holland 2003). Evaluating the impact of such alternative management options is essential for fisheries management (Gulland 1983; Hilborn and Walters 1992).

Although, this situation may be explained by a lack of control over policy implementation, it is also related to the description of fisheries and resources in stock assessment models. First, the monospecific approach which ignores dependencies between species induced by trophic relationships and by technical interactions in mixed fisheries (Botsford et al. 1997; Sumaila et al. 2000). Secondly, the lack of consideration of spatial and seasonal heterogeneities in models of populations and fishing activity dynamics (Pet et al. 1996; Maury and Gascuel 1999; Holland 2000). On the one hand, large-scale migrations of populations related to species life cycle involve seasonal concentrations (Pelletier and Magal 1996), on the other hand fishermen adapt their spatial allocation of fishing effort to their target species distribution, as well as management regulations and economic conditions. This is particularly critical in a mixed fisheries context where the diversity of resources and fishing activities make it difficult to estimate resulting fishing mortality (Murawski and Stewart 1996). Given the complexity of mixed fisheries dynamics, simulation models are necessary to evaluate the efficiency of alternative management measures.

Few tools are available to assess the impact of spatial and seasonal management measures on fisheries dynamics. ISIS-Fish (Pelletier et al. 2001; Mahévas and Pelletier 2004) is a generic simulation tool aimed at assessing quantitatively the impact of management measures on multi-species multi-fleet fisheries. The underlying fishery model takes into account the spatial and seasonal dynamics of each population and each fishing activity as well as fishermen's behaviour in response to management measures.

In general, a number of fishery parameters are imprecise or poorly estimated, and it is important to carry out sensitivity analyses of the model to the parameters while assessing the impact of management measures. Sensitivity analysis has two main goals: to evaluate the impact of uncertainty of input variables and/ or parameters (de Castro et al. 2001; Matsushita et al. 2004); and/or to calibrate and optimise a model (Guyon and Rahni 1997; Ruget et al. 2002). In fisheries-related papers, each parameter is generally considered individually. This approach, classically called elasticity analysis, consists of changing parameters one at time with comparison to a control experiment, and does not allow for assessing the impact of combinations of factors. This assessment may be achieved through experimental design, which consists in testing various combinations of values for the different input parameters and variables or through stochastic simulations based on probability distributions of parameters. Stochastic simulations were used by Pelletier (Pelletier 1990; Pelletier and Gros 1991; Pelletier and Laurec 1992) to study the sensitivity of stock assessment models and TAC policies to uncertainties ion input parameters. To our knowledge, experimental design has been used in industry (Ivanova et al. 1999) and agronomy (Henderson-Sellers and Henderson-Sellers 1996) but not in fisheries sciences.

Few studies consider the evaluation of management measures using simulations so that no standard methodology has been developed to assess the effect of management scenarios. We considered statistical experimental design to evaluate both management measures and combination of individual management measures.

The French *Nephrops norvegicus* – *Merluccius merluccius* mixed fishery of the Northern Bay of Biscay (ICES Div. VIIIa) was chosen to illustrate the methods described in this paper. This mixed-fishery was chosen because of its economic and social importance as well as the difficulty encountered in its management.

As a first step, we briefly present the model, and the fishery parameterisation used to carry out simulations. We then describe the methods used to practise the sensitivity analysis and the procedure that serves to estimate the effects of the management measures considered. Results are detailed and discussed in a final part.

2 Model

ISIS-Fish (Pelletier et al. 2001; Mahévas and Pelletier 2004) is a model of fisheries dynamics based on three sub-models: a population model, a fishing activity model and a management model. Models are spatially and seasonally explicit with a monthly time step. They are defined independently but interact in time and space through the relationship between fishing effort and fishing mortality and the response of fishermen to management. Fishing effort, abundance and catch are assumed to be uniformly distributed within each zone, and each season.

The population dynamic sub-model describes the biology of the different species considered (Tables 1 to 4, Fig. 1). Trophic relationships are not taken into account. The populations are age- or length-structured and are distributed over population zones. Zone-specific catchability may depend on seasons (Table 2). Seasonal migrations are allowed between "population zones" (Table 3). At each time step, the model computes the abundance of each population per class and zone.

The exploitation model calculates the standardised effort per fishing activity affecting each population in each zone at each month. In ISIS-Fish, fishing units are not individually identified but grouped into fleets according to trip duration. A more detailed fleet description is implemented in further versions of the software. Fishing activity is described through métiers and strategies, respectively at the fishing operation scale and at the month and year scale. Métiers are characterized by combining a gear, a set of target species with corresponding target factors which quantifies the strength with which the species is sought for by the métier, and fishing zones and seasons (Table 5). Gears are characterised by a standardisation factor, used to standardise fishing effort between gears, a selectivity model for each species, and a parameter which can be modified through management measures, e.g. mesh size (Table 6). A "strategy" is a set of vessels, possibly from different fleets (Table 7) that practise a similar sequence of métiers during the year. It is characterised by the monthly allocation of fishing effort between metiers (Table 8).

The management model describes the management scenario and its impact on the fishing activity. Each management measure is characterised by parameters (for instance, targeted species, zone, period, gear, etc.), and by the way fishing effort

Table 1. Parameters of the hake and Nephrops populations considered in the example. SSB: spawning stock biomass, R: Recruitment.

		Hake	Nephrops
General parameters	Number of age groups	9 (ICES 2003c)	10 (ICES 2003b)
	Stock recruitment relationship	If SSB < 71 660 t then $R = \Sigma_{\text{age}}$ number$_{\text{age}}$ × fecundity$_{\text{age}}$ else $R = 1.88 \times 10^8$ ind. (Murua and Lucio 1998; ICES 2003a)	$R = \Sigma_{\text{age}}$ number$_{\text{age}}$ × fecundity$_{\text{age}}$ (Morizur et al. 1981)
	Growth	von Bertalanffy model: $K = 0.09$ y^{-1} Linf = 114 cm $t_0 = -1.16$ y (Guichet 1996)	Carapace length (mm) at age: 0, 19, 23.5, 27.5, 31.1, 34.7, 39.1, 43.7, 49.5, 56.7 (Verdoit et al. 1999)
Age-specific parameters	Natural mortality (y^{-1})	0.20 for all age groups (ICES 2003c)	0.30 for age 1 0.25 for other age groups (ICES 2003b)
	Fecundity coefficients (ind^{-1})	0, 0, 0, 0.17, 0.81, 2.04, 3.11, 3.89, 5.58 (Murua and Lucio 1998)	0, 0.09, 0.36, 0.60, 0.88, 1.25, 1.83, 2.62, 3.88, 6.01 (Morizur et al. 1981)
	Mean weight at age (g)	26, 62, 174, 308, 571, 962, 1321, 1652, 2 371 (ICES 2003c)	0, 4.6, 9.0, 15.0, 22.0, 31.7, 47.3, 71.0, 114, 194 (ICES 2003b)

Table 2. Hake and Nephrops seasonal catchability coefficients (×10^{-6}) per season (Drouineau 2004).

Age	Hake				Nephrops		
	Jan. Mar.	Apr. Jun.	Jul. Sep.	Oct. Dec.	Jan. Mar.	Apr. Jul.	Aug. Dec.
0	0	0	9.14	6.94	0	0	0
1	3.34	6.90	3.81	3.14	22.0	17.5	10.3
2	0.339	3.60	4.41	1.73	66.0	234	117
3	0.0972	1.84	3.81	1.89	40.4	240	143
4	0.349	0.505	0.478	0.697	22.4	206	71.6
5	0.345	0.483	0.446	0.446	9.53	171	43.8
6	0.631	1.01	1.41	0.755	6.71	118	28.3
7	1.44	1.93	3.30	1.26	3.53	78.4	16.9
8	1.77	2.84	3.43	8.97	2.03	62.5	11.6
9					1.02	40.1	8.36

Table 3. Migrations and emigrations of hake (Quéro and Vayne 1997) between the different population zones (Fig. 1).

Season	Demographic process	Age group	Departure zone	Arrival zone	Migration rate
Jan.-Mar.	Spawning	3	Nursery	Spawning	1
	Change age	4	Presence	Spawning	1
		5	Presence	Spawning	1
		8	Presence	Spawning	1
Apr.-Jun.	Spawning	3	Spawning	Inshore	0.6
		4	Spawning	Inshore	0.6
Jul.-Sep.		3	Inshore	Presence	1
		3	Spawning	Presence	1
		4	Inshore	Presence	1
		4	Spawning	Presence	1
		7	Spawning	Presence	1
		8	Spawning	Presence	1
Oct.-Dec.		7	Presence	Leave the region	0.4
		8	Presence	Leave the region	0.4

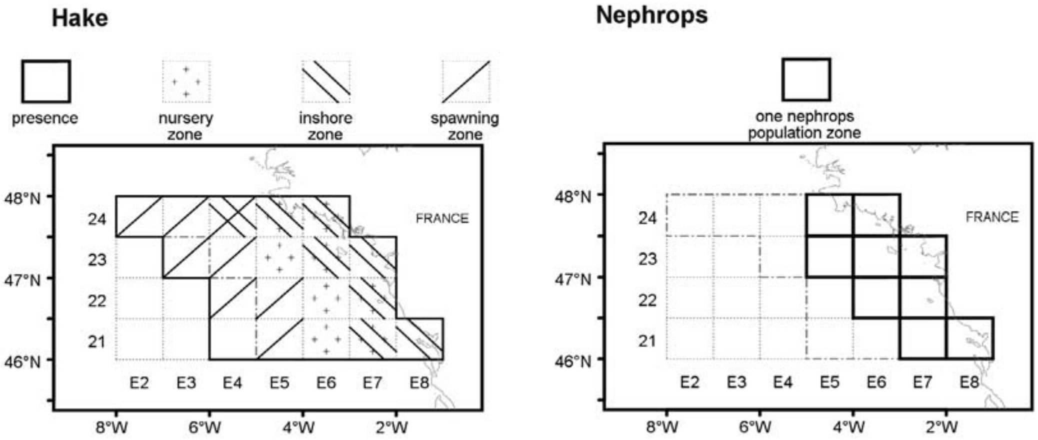

Fig. 1. Population zones considered in the model for Nephrops (right) and hake (left). ICES subdivision VIIIa is delineated by the grey dashed line. The name of the ICES statistical rectangle are obtained by merging codes reported on the left and below the grid. For Nephrops, each rectangle is a population zones. For hake, “presence” zone corresponds to the maximum extension.

Table 4. Initial abundances (millions) per age and population zones. The total abundance is equally divided among population zones for Nephrops.

Age	Hake				Nephrops
	Inshore zone	Presence zone	Nursery zone	Spawning zone	
0	0	0	0	0	0
1	0	0	79.5	0	538
2	0	0	47.2	0	4.48
3	0	0	0	44.1	2.65
4	0	0	0	27.0	1.06
5	0	0	0	14.8	0.415
6	0	0	0	8.25	0.176
7	0	0	0	4.21	0.0863
8	0	0	0	3.98	0.0473
9	-	-	-	-	0.0528

Table 5. Métier parameters. A métier is a combination of one gear, a set of target species areas and seasons. The seasonality of the métier was directly defined by the monthly allocation of effort within each strategy. Eight métiers were defined: a métier non activity, a métier using gillnet, 3 métiers using simple trawl and three similar métiers but using twin trawl.

Métier	Hake target factor	Nephrops target factor
Nephrops (simple and twin trawl)	0.14	0.74 *
Benthic (simple and twin trawl)	0.09	0.07
Hake and cuttlefish (simple and twin trawl)	0.60 *	0.14
Gillnet	0.87 *	-
Non activity	-	-

* Main target

is reallocated after implementation of fishermen’ s reaction to the measure (Table 9). At each time step, this model calculates changes in the distribution of fishing effort among the métiers of the strategies affected by the scenario.

At each time step and in each zone, the model computes catch per métier and population class and corresponding in weight or number per population class.

3 The fishery and model parameters

3.1 The fishery

The hake-Nephrops mixed fishery has a major economic importance both at the regional and national scale. Hake was the second most important species landed in value in 2002 in France (*Direction des Pêches maritimes* / OFIMER 2003). There were about 230 French trawlers fishing for Nephrops in ICES division VIII, producing a total turnover of about 75 M€; 64% of the direct employment and 68% of the fleet are localised in South Brittany (A. Biseau unpubl. data).

The Bay of Biscay hosts one of the two major nurseries areas of the Northern stock of hake (ICES 2003c). In recent assessments, estimated fishing mortality was just above the fishing mortality level corresponding to the precautionary approach (F_{pa}) and the spawning stock biomass (SSB) which declined during the 1980s, is stabilized at a low level since the early 1990s (ICES 2004), raising serious doubts about the fishery’s sustainability. A recovery plan was enforced in April 2004 (Commission of the European Communities 2001a,b, 2002, 2004). In the Northern Bay of Biscay, hake constitutes an important by-catch in the Nephrops fishery. In this area, the biomass of Nephrops is considered to be at a low level (ICES 2003b), and a decrease in catch per unit of effort is observed. The state of these two stocks makes it urgent to find new regulation measures in order to achieve sustainability.

The two stocks are presently regulated through TAC, with minimum landing sizes and mesh size legislation. From 1970 to 1973, a marine protected area was introduced in the Bay of Biscay to protect hake juveniles but it was inefficient because of an inappropriate location (A. Forest unpubl. data). In 1996-1997, MPAs in the Northern Bay of Biscay were proposed again by the European Commission to preserve hake juveniles, but no MPA was implemented (A. Forest unpubl. data). In 2001, hake “boxes” were set (Commission of the European Communities 2001b) in the Bay of Biscay and in the

Table 6. Gear parameters. A gear is defined by a parameter which can be modified through a management measure, a selectivity factor to standardize nominal effort and a selectivity function for each species. Fish length (L, cm), SF Selectivity factor (SF), Selectivity range (SR), Mesh size (m, mm).

The trawl selectivity function:

$$s(L) = \frac{\exp\left[\frac{1}{m \times SF \times SR} \times 2 \times \ln(3) \times (L - m \times SR)\right]}{1 + \exp\left[\frac{1}{m \times SF \times SR} \times 2 \times \ln(3) \times (L - m \times SR)\right]}$$

The gillnet selectivity function:

$$s(L) = A(L) \times \exp\left[-\frac{1}{2} \times \left(\frac{L - \alpha}{\beta}\right)^2\right] + \kappa(L)$$

Gear	Parameter	Range (mm)	Standard factor	Selectivity function
Trawl	Mesh size	70–100	1	Hake $SF = 4.32$, $SR = 0.325$ Nephrops $SF = 0.5$, $SR = 0.43$
Twin trawl	Mesh size	70–100	1.39	
Gillnet	-	-	0.37	Hake: 1 if $64.4 \leq L \leq 70.3$ cm else $\alpha = 6.442$, $\beta = 0.707$ if $L < 64.4$ cm, $A = 0.985$, $\kappa = 0.015$ if $L > 70.3$ cm, $A = 0.65$, $\kappa = 0.538$ Nephrops: 0

Table 7. Number of fishing units per fleet practising each strategy (Drouineau 2004).

Strategy	Fleet: One-day fishing trip	Fleet: Five-day fishing trips
Benthic	101	55
Gillnet	89	27
Nephrops	106	14
Hake	47	13
Occasional	84	106

south west of Ireland to protect juveniles. Increased minimum mesh size is currently enforced in these "boxes".

3.2 Model parameters

Most parameters of the population sub-model were gathered from the literature (Table 1). The hake population is structured in nine age groups following standard ICES assessment (ICES 2003c). Growth follows a von Bertalanffy curve (Guichet 1996). A segmented stock-recruitment relationship was built combining two previous studies (Murua and Lucio 1998; ICES 2003a): we assumed a linear relationship between recruitment and the spawning biomass present in the reproduction zone during the spawning, and a constant recruitment when SSB is above a threshold. The mature fish outside the zone were assumed to reproduce in other spawning zones (especially in Celtic Sea) and corresponding recruitment occurs outside the zone (especially on the Celtic Sea shelf). Assuming a linear relationship in a first part of the relation has a very limited impact because the recruitment generally remains on the plateau. Age and season-specific catchability coefficients (Table 2) were estimated, based on a statistical analysis of log-books data and catch-at-length information (Drouineau 2004). The population was distributed in 4 different population zones, identifying presence, inshore, nursery and spawning zones (Abbes 1991) (Fig. 1). Age-specific seasonal migrations for reproduction, and emigration of older individuals (Table 3) were considered between these zones (Quéro and Vayne 1997). Emigration of old individuals towards the Celtic Sea was considered following Quéro and Vayne (1997) (Table 3), no immigration considered.

The Nephrops population is structured in nine age groups following standard ICES assessment (ICES 2003b). A tenth age group is added to store pre-recruits because of the software conception. Growth follows the model of Verdoit et al. (1999). A linear stock-recruitment relationship was built based on an existing length-egg relationship (Morizur et al. 1981). Catchability coefficients (Table 2) were estimated from a linear model of catches (Drouineau 2004). Nephrops population is a sedentary species (Quéro and Vayne 1998) and the Bay of Biscay population is distributed over several ICES statistical rectangles. We defined nine population zones, i.e. one per statistical rectangle where the species is found. This was necessary to ensure that Nephrops did not disperse over large zones, as a result of the assumption of uniform distribution of abundance within a population zone. Each zone contributes to reproduction and consequently to recruitment, which is equally distributed among the nine population zones, assuming a larval dispersion.

Initial population abundances (Table 4) were taken from ICES stock assessment results (ICES 2003c; ICES 2003b). The hake stock considered in ICES stock assessment has a larger extension than the studied area, and abundance indices of French surveys were used to estimate the proportion of total abundance present in the studied area. The Nephrops stock assessment considers the entire Bay of Biscay, but a large majority of the stock is located on its northern part so that estimated abundances were used directly, and assigned equally to rectangles.

Regarding fishing activity, several sources of information were used to parameterise the model: logbook data (catch, duration, gear per statistical rectangle and per trip), fishermen interviews (gear used and statistical rectangles visited per month and vessel), and technical characteristics of vessels (gear, fleet).

Table 8. Monthly allocation of effort between métiers in each strategy considered. Métier 1: Benthic simple, Métier 2: Benthic twin trawl, Métier 3: Gillnet, Métier 4: Nephrops simple, Métier 5: Nephrops twin trawl, Métier 6: Hake simple, Métier 7: Hake twin trawl, Métier 8: non activity (Drouineau 2004).

		Monthly % of Total Effort Allocated											
Strategy	Métier	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Benthic	1	33	36	38	38	39	38	37	40	43	44	45	40
	2	33	36	38	38	39	38	37	40	43	44	45	40
	3	1	0	1	1	2	1	1	1	0	1	0	0
	4	0	1	1	3	5	6	4	2	1	0	0	0
	5	0	1	1	3	5	6	4	2	1	0	0	0
	6	1	0	2	1	0	1	2	1	2	1	1	2
	7	1	0	2	1	0	1	2	1	2	1	1	2
	8	31	26	17	15	10	9	13	13	8	9	8	16
Gillnet	3	83	86	90	95	94	89	89	85	89	92	90	84
	8	17	14	10	5	6	11	11	15	11	8	10	16
Nephrops	1	14	6	3	1	0	0	0	1	3	9	13	13
	2	14	6	3	1	0	0	0	1	3	9	13	13
	4	27	36	46	48	48	49	48	45	41	34	33	32
	5	27	36	46	48	48	49	48	45	41	34	33	32
	6	3	1	0	0	1	1	1	4	3	5	2	3
	7	3	1	0	0	1	1	1	4	3	5	2	3
	8	12	14	2	2	2	0	2	0	6	4	4	4
Hake	1	9	12	7	10	9	8	7	6	7	8	7	9
	2	9	12	7	10	9	8	7	6	7	8	7	9
	3	1	1	4	2	0	0	0	0	0	1	1	1
	4	0	2	7	11	13	12	9	7	3	3	2	1
	5	0	2	7	11	13	12	9	7	3	3	2	1
	6	24	23	19	19	21	27	31	32	35	34	28	22
	7	24	23	19	19	21	27	31	32	35	34	28	22
	8	33	25	30	18	14	6	6	10	10	9	25	35
Occasional	1	9	7	6	4	4	4	3	3	5	7	7	8
	2	9	7	6	4	4	4	3	3	5	7	7	8
	3	18	22	17	9	5	5	4	6	4	13	16	15
	4	1	1	1	3	3	2	1	1	0	0	0	0
	5	1	1	1	3	3	2	1	1	0	0	0	0
	6	0	1	0	0	0	0	0	0	0	1	1	2
	7	0	1	0	0	0	0	0	0	0	1	1	2
	8	62	60	69	77	81	83	88	86	86	71	68	65

Fleets were defined from multivariate analysis and cluster analysis of vessels characteristics (age, power, length and tonnage) (Drouineau 2004). Two fleets were obtained, one practising daily trips and the other practising 5 day trips.

Three gears were considered: trawl, twin trawl and gillnet. Selectivity curves for each gear were found from previous studies (ICES 1992; Commission of the European Communities 2001c). Standardisation factors were estimated for each gear, using a linear model of log-book catch and effort data (Table 6).

Eight métiers (Table 5), and their corresponding zones were defined. Each métier was characterised by a gear and target species. Principal component analysis and cluster analysis were carried out on the catch profile of fishing trips to define and characterise the different métiers (Table 5, Fig. 3). The metier zones (Fig. 2) were designed by analysing the different clusters. No seasons were defined for the métiers, the seasonality was described by the monthly allocation of effort within the different strategies.

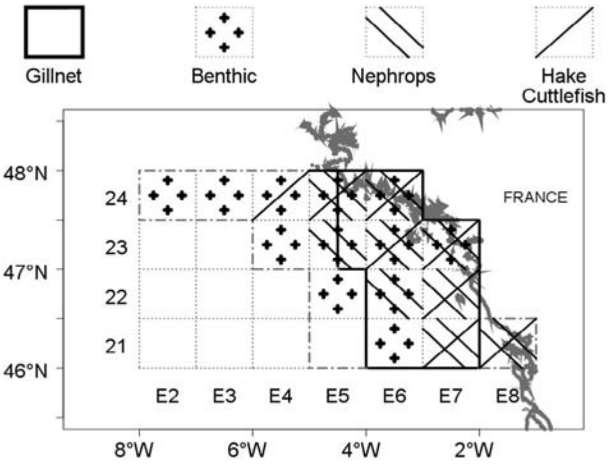

Fig. 2. Métier zones considered in the model. ICES subdivision VIIIa is delimited by the grey dashed line. The name of the ICES statistical rectangle are obtained by merging codes reported on the left and below the grid.

Table 9. Management measures explored. MPAs consist in the closure of one or two ICES rectangles, for all gears or just for twin trawl and during semester-1 and/or semester-2. The closed ICES statistical rectangles are 23E6 (when only one rectangle is closed) and 24E6 in the hake nursery zone, and 24E4 (when only one rectangle is closed) and 23E4 in the hake spawning zone. A fixed proportion of the biomass at the beginning of the year is allowed to be caught when a TAC is in force. The selectivity, for an undersized fish, is equal to 0.5 × normal selectivity when using the selective device. The mesh size increases from 70 mm to 100 mm when the mesh size management measure is applied.

	MPAs Nursery zone 23E6 23E6-24E6	MPAs Spawning zone 24E4 24E4-23E4	TAC	Gear change
Modalities explored	None	None	None	None
	AG S1 1R	AG S1 1R		
	TT S1 1R	TT S1 1R		
	AG S1 2R	AG S1 2R		
	TT S1 2R	TT S1 2R	Upper level: Hake 0.027 Nephrops 0.27	Mesh size
	AG S2 2R	AG S2 2R		
	TT S2 2R	TT S2 2R		
	AG Ye 1R	AG Ye 1R		
	TT Ye 1R	TT Ye 1R	Low level: Hake 0.015 Nephrops 0.15	Selective device
	AG Ye 2R	AG Ye 2R		
	TT Ye 2R	TT Ye 2R		
	AG S2 1R	AG S2 1R		
	TT S2 1R	TT S2 1R		
Fishermen' s reaction	Reduce their fishing zone if there is an intersection with the closed rectangle.		When a TAC is reached, fishermen who practised a metier targeting the corresponding species, seek for an alternative metier, if possible using the same gear. The effort is uniformly reported among all possible alternative metiers. They stop fishing (leave the fishery) if no alternative metier is found.	Apply the gear change

AG = all gears, TT = twin trawl, S1 = Jan.-Jun., S2 = Jul.–Dec. 2, Ye = year, 1R = one rectangle, 2R = 2 rectangles.

Finally five strategies, namely Nephrops, hake, benthic, gillnet and occasional were defined (Table 7). Fishers' interviews were used together with the log-book data to define the strategies through a multiple correspondence analysis (Tables 7 and 8). One métier predominates in each strategy, nevertheless the effort is distributed among at least two métiers (strategy gillnet).

Regarding management measures, two TAC levels were considered, a "low level" (very restrictive) and a "high level" (Table 9). The annual value of the TAC (either low or high) was set to a fixed proportion of the biomass in the region at the beginning of the year, for both species. The levels were chosen in order to ensure that at a same level, the TAC came into effect in the same period for both species. When a TAC is reached, it is assumed that the fishermen who practised a métier targeting the corresponding species stop fishing in that métier and seek for an alternative métier within the same strategy and if possible using the same gear. The effort is uniformly reallocated among possible métiers if several alternatives exist. They leave the fishery (i.e. they exit the region or they target species not described in the fishery) if no alternative métier exists. When a métier incidentally catches a species whose TAC is reached, species catch is discarded and the proportion of discards that survive is assumed to be 30% for Nephrops and 0% for hake (Charuau and Biseau 1989).

Changes in trawl selectivity were also tested. We considered an increase in mesh size from 70 mm to 100 mm, and the use of a selective device leading to a 50% reduction of selectivity for undersized catch (selectivity = 0.5 × normal selectivity for under sized fish). We assumed that fishermen comply with these regulations.

Finally, MPAs were tested for both the hake nursery zone and the hake spawning zone (Table 9). It should be noted that MPAs in the hake nursery zone designed to protect juveniles of hake, also protect Nephrops. MPA design was considered by timing (January-June, July-December, throughout year), by size (one or two rectangles) and by the gears concerned (twin trawl or all gears). In the simulations, when a métier is affected by a closure, fishermen redistribute their effort uniformly in the rest of the métier zone.

4 Simulation experimental design

Ten years simulations were performed and the following 3 output variables (Y) were analysed for both species: biomass at the end of the simulation, catch (landings + discards) in weight in the final year, and cumulative catch over the last 5 years. Two additional outputs were considered during the management scenarios exploration: nominal effort in the last year and cumulative nominal effort during the five last years. Biomass at the end of the simulation and last year catches are metrics of the final state and can be compared to the initial state. Five last years cumulative catches integrate results on a larger period and account for the evolution of the two populations during the simulations.

4.1 Sensitivity analysis

Model parameters were partitioned into two sets: i) parameters where values are consensual among experts of the fishery; and ii) parameters that are less well estimated. Sensitivity analysis of the model was carried out to estimate the impact of poorly estimated (group ii) parameters on simulation results.

Ninety nine uncertain parameters were identified and grouped into 7 types: “the hake fecundity coefficients and reproduction function”, “Nephrops fecundity coefficients and reproduction function”, “hake migration coefficients”, “hake growth curve”, “natural mortality” (hake and Nephrops), “gears standardisation factors” and “catchability coefficients”.

Uncertainty on parameters could not formally be estimated or quantified and therefore, we arbitrarily considered a 20% range of variation for parameters. This level of uncertainty is often used in sensitivity analysis (de Castro et al. 2001; Elkalay et al. 2003) and represents a reasonable value for parameters generally estimated from regression models. For each parameter, a low and a high value were set based on this variation range.

We used a group-screening methodology, combined with a fractional factorial design to evaluate model sensitivity to these parameters. Group-screening method (Kleijnen 1987) are appropriate for simulation design with a large number of factors: the parameters are grouped and each group is considered as a single factor. The major underlying assumption is that all parameters in a given group should affect each output variable in the same direction (Kleijnen 1987). The migration parameter group was split in 4 sub-groups to meet this assumption. A complete description of the methodology may be found in Kleijnen (1987), section 28 (pages 320-328). Fractional factorial designs are particularly appropriate to estimate sensitivity for factors (in our case, for parameter group) with two levels (Kleijnen 1987; Henderson-Sellers and Henderson-Sellers 1996). It consists in selecting a set of experiments among the 2^p possible sufficient to estimate. A fractional factorial design of resolution V was used (128 simulations) considering the 9 groups as single factors. A fractional factorial design is said to be of resolution V, if assuming that second and superior order interactions are not significant, it allows estimation of every main effect and first-order interactions of factors (Droesbeke et al. 1997). Estimating the impact of first order interactions is necessary to assess the combined effect of uncertainties on two groups, which may be different from the sum of the individual effects of the two groups.

A preliminary analysis of the simulations outputs was performed using principal components analysis (PCA) to graphically identify groups of simulations bearing similar impacts on outputs and the most sensitive groups of parameters. Each experiment (simulation) was considered as a statistical individual characterized by 6 outputs as active variables and the 9 groups of parameters (“the hake fecundity coefficients and reproduction function”, “Nephrops fecundity coefficients and reproduction function”, “hake growth curve”, “natural mortality” (hake and Nephrops), “gear standardisation factors” and “catchability coefficients” and the 4 sub-groups of hake migration coefficients) as supplementary variables. Simulations and the average location of the two modalities of each group were projected on the factorial plan defined by the two first components. Groups with most distant categories are the ones that yield the most important variations among simulations.

In a second step, a linear model was fitted for each output Y to estimate the impact of the 20% uncertainty of each group of parameters. The linear model included main effects and first-order interactions of parameter groups.

$$Y \sim \sum\nolimits_i \alpha(i;k) + \sum\nolimits_{i<j} \beta(i;k,j;k') + \varepsilon \qquad (1)$$

with:

$\alpha(i;k)$ the effect of the factor i with modality k,
$\beta(i;k,j;k')$ the effect of the interaction between factor i with modality k and factor j with modality k',
and $\varepsilon \sim N(0,\sigma^2)$.

A 15% significance level was chosen for the coefficients estimated in equation (1); this level is recommended when applying group-screening methodology (Ivanova et al. 1999). The coefficients should be interpreted as follows: the larger they are, the more sensitive is the model to the corresponding group.

A confidence interval can be constructed around each output of a simulation without management measure:

$$Y - 1.96\sigma^2 \leq Y \leq Y + 1.96\sigma^2 \qquad (2)$$

with σ, the estimated residual standard error of the corresponding linear model.

Relative sensitivity coefficients of each output to each group were calculated by dividing the estimated coefficients in Eq. (1) by the corresponding output value in each simulation (Kleijnen 1998), denoted as $\Delta Y/Y$ in the following. The mean values of these relative sensitivity coefficients described the average percent variation of the outputs induced by the 20% variation in model parameters, and they can be compared between groups and between outputs.

4.2 Simulation design for exploring management scenarios

Management scenarios include individual measures as well as combinations of measures. Consequently, estimating the impact of management scenarios requires quantification of the effect of each measure and of interactions between measures.

Four types of management measures were considered: TAC, gear changes and MPA either in the hake nursery zone or in the hake spawning zone. An experimental design was used to run simulations in a statistical frame to provide quantitative estimates of effects. A complete design would have taken too much time since it would involve 1521 simulations and the number of categories in this case makes it impossible to use a fractional factorial design. Regarding the number of factors and modalities, the most appropriate experimental design are D-optimal designs (NIST/SEMATECH 2004). In this type of design, the estimations of the effects are partially correlated i.e. that, contrary to factorial design, confusion between effects estimates may exist, but an algorithm is used to find the set of experiments, maximising the determinant of the information matrix (XX' with X, the matrix of the different combinations of modalities for each experiment) of the design, equivalent to maximising the efficiency of the estimation (Droesbeke et al. 1997). Finally, the resulting experimental design consisted of 320 simulations.

Effects were estimated through a linear model limited to main effects and first-order interactions:

$$\begin{aligned} Y \sim\ & \mathrm{TAC} + \mathrm{MPA}_{\mathrm{spawning}} + \mathrm{MPA}_{\mathrm{nursery}} + \mathrm{Gear} \\ & + \mathrm{TAC} : \mathrm{MPA}_{\mathrm{spawning}} + \mathrm{TAC} : \mathrm{MPA}_{\mathrm{nursery}} + \mathrm{TAC} : \mathrm{Gear} \\ & \quad + \mathrm{MPA}_{\mathrm{spawning}} : \mathrm{MPA}_{\mathrm{nursery}} \\ & \quad + \mathrm{MPA}_{\mathrm{spawning}} : \mathrm{Gear} + \mathrm{MPA}_{\mathrm{nursery}} : \mathrm{Gear} \end{aligned}$$

Y being one of the eight outputs, previously centred and normalized by their variance to allow for comparison between outputs, and each effect being denoted by the name of the measure.

For each factor, the modality "none" (i.e. without the management rule) was constrained to 0. A stepwise selection using Akaike Information Criterion (AIC) was run in order to select the most parsimonious model.

As for sensitivity analysis, PCA was performed on the simulations described by output variables in order to identify groups of simulations impacting the fishery in a similar way with respect to the considered outputs. The different factors (management measures) were considered as illustrative variables in order to project the average position of each management measure on the plan defined by the two first factorial axes. In this projection, scenarios impacting the outputs the same way are close.

5 Results

5.1 Sensitivity to parameters

5.1.1 Principal component analysis

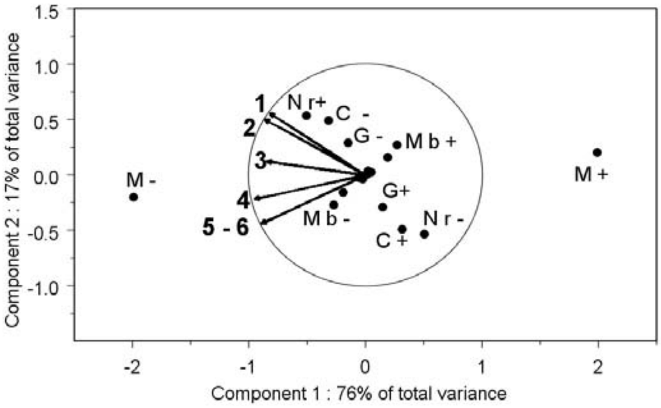

Fig. 3. Projection of the modalities (+, −) of parameter groups (circles) and of the output metrics (arrows) on the first factorial plane. Note that by construction, the average value of parameter is at the origin. The groups with most distant categories are the ones with the most important impacts on the simulations. Arrows- 1: Nephrops biomass at the end of the simulation, 2: Nephrops cumulative catch of the last five years, 3: Nephrops cumulative catch of the last year, 4: Hake biomass at the end of the simulation, 5: Hake cumulative catch of the last five years, 6: Hake cumulative catch of the last year. M: Natural mortality, G: Gear standardisation factor, Nr: Nephrops reproduction, C: Catchability, Mb: Migration B.

The first two factorial axes of the PCA accounted for 93% of the total variability (Fig. 3). All the outputs were strongly negatively correlated to the first component which distinguished simulations that are beneficial or not to catch and abundance. The second component was positively correlated with Nephrops biomass and to a lesser extent with Nephrops catch, and negatively correlated with hake catch. It tends to separates simulations that are beneficial to Nephrops catch and abundance from simulations beneficial to for hake catch and biomass.

Natural mortality was the group with the most important impact on the results, as illustrated by the distance between the average position of its two modalities (+, −) (Fig. 3). For both species, an increase of natural mortality produced a decrease in catch and abundance. Other groups also strongly influenced the results: a high Nephrops fecundity enhances Nephrops biomass. A decrease of both catchability and gear standardisation factors tends to increase the biomass for the two species and Nephrops catch, but on the other hand it increases hake catch.

The hake reproduction function is less influential than the Nephrops reproduction function because of the different stock-recruitment relationship: on the one hand, the Nephrops relationship is linear so that productivity is very sensitive to a change in fecundity with large cumulative effects (i.e. a better recruitment increases latter the SSB resulting in higher recruitment next year, etc.), and the two line model used for hake results in the recruitment being constant most of the time, so that the impact on population dynamics is more limited.

5.1.2 Linear models for each output variables

Each of the six models satisfied linear model assumptions and explained more than 90% of the total variability (Table 10).

Table 10. Significant coefficients estimated for the 6 linear models (empty cases correspond to non significant coefficients). The coefficients must be compared to 0: the more distant they are, the more impact they have on model results. Natural mortality is very sensitive. Nephrops metrics are largely influenced by all parameters, particularly natural mortality and reproduction function. B: Biomass at the end of the simulation, C5: cumulative catch of the last five years, C1: cumulative catch during the last year.

	Hake			Nephrops		
	B	C5	C1	B	C5	C1
R^2 coefficient	0.999	0.999	0.999	0.988	0.998	0.993
Catchability	9.5	−4.9	−1.2	0.0	0.6	0.1
Growth	18.0	−1.2	0.4			
Gear	6.1	−3.4	−0.9	0.0	0.3	0.0
MigrationA	5.8					
MigrationB	10.0	12.0	4.0			
MigrationC	−8.5	2.3	0.6			
Mortality	170.0	38.0	12.0	0.1	1.3	0.1
FecundityNephrops				−0.1	−0.8	−0.1
FecundityHake	−31.0	−5.7	−1.9			
Catchability:Growth	−1.3	−0.2	−0.1			
Catchability:Gear	−0.4			0.0	0.1	0.0
Catchability:MigrationB	1.6	−0.4	−0.1			
Catchability:Mortality	4.6	−2.6	−0.7	0.0	0.3	0.0
Catchability:FecundityNephrops				0.0	−0.1	0.0
Catchability:FecundityHake	−0.8	0.4	0.1			
Growth:Gear	−1.0		−0.1			
Growth:MigrationB	1.1	1.3	0.5			
Growth:MigrationC		0.2	0.1			
Growth:Mortality	7.9	0.9	0.7			
Growth:fecundityHake	−1.7	0.4				
Gear:MigrationB	1.1	−0.4	−0.1			
Gear:Mortality	3.0	−1.8	−0.5	0.0	0.2	0.0
Gear:FecundityNephrops				0.0	−0.1	0.0
Gear:FecundityHake	−0.4	0.3	0.1			
MigrationA:MigrationB	−0.6	−0.3	−0.1			
MigrationA:MigrationC	−0.7					
MigrationA:Mortality	2.4					
MigrationA:fecundityHake	−0.5					
MigrationB:MigrationC		−0.3	−0.1			
MigrationB:Mortality	14.0	8.6	3.0			
MigrationB:FecundityNephrops						
MigrationB:FecundityHake	−1.2	−0.8	−0.4			
MigrationC:Mortality	−4.0	1.5	0.4			

Results show that all the groups have at least one significant effect on one of the outputs and that the interactions generally have less effect on the results than the corresponding main effects. As found in the PCA, the most sensitive parameter is natural mortality for both stocks (Table 10). The output metrics are also sensitive to fecundity (for both stocks), growth and migration. Hake growth had a major influence on hake biomass, although it was less important in terms of catch. The group migration B mainly corresponds to emigration coefficients for age group 7 and 8, so it directly impacts the population size. Catchability and gear standardisation factors also have an important effect because they are linearly related to fishing mortality.

Analysing relative sensitivity coefficients ($\Delta Y/Y$), we saw that only 16 of them were larger than 20% variation, corresponding to the variation of the input parameters (Table 11). The largest one was the sensitivity of Nephrops biomass to natural mortality. The relative sensitivity was more important for Nephrops outputs than for hake outputs, in relation to the stock-recruitment relationships used (see above).

5.2 Impact of the management measures

5.2.1 Principal component analysis

The first two components account for 81.6% of total inertia (Fig. 4). Biomass and catches are quite well correlated for Nephrops whereas there are nearly opposite for hake. Simulations with high Nephrops biomass and catch and high hake biomass (on the right part of the factorial plan) are opposed

Table 11. Average relative sensitivity coefficients of the 6 outputs for the main groups. B: biomass at the end of the simulation, C5: cumulative catch of the last five years, C1: cumulative catch during the last year.

Groups	Hake			Nephrops		
	B	C5	C1	B	C5	C1
Catchability	0.05	−0.10	−0.10	0.67	0.25	0.48
Growth	0.09	−0.02	0.03	0.00	0.00	0.00
Gear	0.03	−0.07	−0.07	0.40	0.15	0.29
MigrationA	0.03	0.00	0.00	0.00	0.00	0.00
MigrationB	0.05	0.24	0.32	0.00	0.00	0.00
MigrationC	−0.04	0.04	0.05	0.00	0.00	0.00
Natural mortality	0.80	0.75	0.92	1.11	0.55	0.97
Nephrops fecundity	0.00	0.00	0.00	−0.79	−0.34	−0.65
Hake fecundity	−0.15	−0.11	−0.15	0.00	0.00	0.00

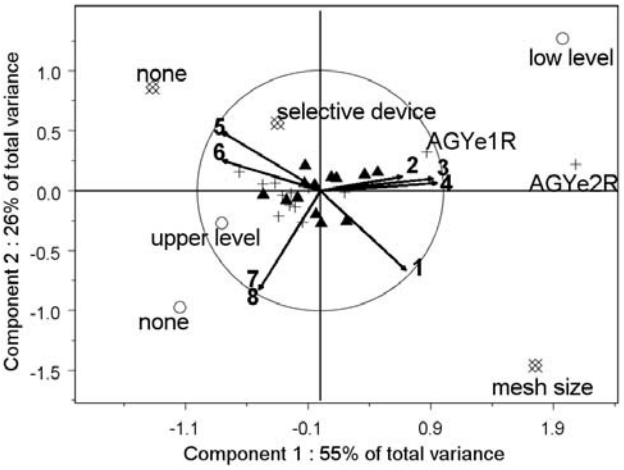

Fig. 4. Projection of the variables and of the management measures on the first factorial plane. Arrows- 1: Nephrops biomass at the end of the simulation, 2: Nephrops cumulative catch of the last five years, 3: Nephrops cumulative catch of the last year, 4: Hake biomass at the end of the simulation, 5: Hake cumulative catch of the last five years, 6: Hake cumulative catch of the last year. O: MPAspawning, +: Gear change, Triangles: MPAnursery, xx: TAC.

to simulations with high hake catches (on the left part). Nominal effort is negatively correlated with the second component. Hence, there is an opposition between measures which benefit to hake catches and measures which benefit to Nephrops catch, illustrating the trade-off between the species in this example.

The two permanent closures for all gears in the hake nursery zone largely impacted Nephrops biomass and catches (Fig. 4). It caused a biomass accumulation in the unfished area which explained an increase in total spawning biomass and subsequently in recruitment. As recruitment is uniformly distributed over all population zones, the whole population benefited from the measures. Seasonal MPAs and/or closures for some particular gears had limited effects. An MPA in the hake spawning zone, aimed at protecting hake spawning biomass, had limited effects, probably because they were small compared to the population zone, where abundance is considered as homogeneous (Fig. 4).

Both mesh size and catch limitation (Fig. 4) significantly increased the biomass of both species. TAC was the only management measure linked to a decrease of the nominal effort which can be explained by the fishermen's reaction we selected, because as soon as the hake TAC was reached, fishermen practising the gillnet strategy could not find an alternative metier within their strategy and leave the fishery. No other management measures impacted so drastically fishing activity.

5.2.2 Linear models

The eight fitted linear models resulting from stepwise selection conformed to linear model assumptions and explained a large part of total variability (Table 12). The stepwise selection removed interactions of management measures from the proposed model. Overall, the results confirmed the results obtained with the PCA.

Permanent closures in the hake nursery zone for all gears implied an important increase in Nephrops biomass and catch (Table 13). The closure of two statistical rectangles implied an increase in biomass more than twice that of the closure of one rectangle. On the contrary, catch was not multiplied by two. As observed from the PCA, other forms of MPAs had limited effects.

A change in mesh size impacted both hake and Nephrops populations (Table 13). It provided an increase in Nephrops catch, that was more limited than with MPAs, and a decrease of hake catch. It should be noticed that the change is mesh size is the measure which resulted in the largest increase of hake biomass.

TAC at a low level had effects on both species and on nominal effort. TAC, either low or high level, was the only single management measure which had a significant effect on nominal effort as observed with the PCA. It is interesting to notice that all the significant interaction terms between low TAC and gear mesh size or MPAspawning have negative effects on biomass of both species but especially hake.

Several interactions of management measures were significant, especially for hake (Table 13). Some are opposite to the main effects (for example TAC low and Gear mesh size), i.e. that the effect of the combination may be inferior to the sum of the effects of the individual measures.

Table 12. Linear models fitted on the eight outputs resulting from a stepwise selection. The models are of the form: $Y \sim \Sigma$(factors), with Y one output variable. B: Biomass at the end of the simulation, C5: cumulative catch of the last five years, C1: cumulative catch during the last year, E5: cumulative nominal effort (days fishing) during the last 5 years, E1: cumulative nominal effort (days fishing) during the last year.

		Output Metrics							
		Hake			Nephrops			Effort	
		B	C5	C1	B	C5	C1	E5	E1
	R^2	0.99	0.95	0.93	0.99	0.997	0.996	0.99	0.99
Remaining factors	TAC	*	*	*	*	*	*	*	*
	MPAspawning	*	*	*	*	*	*	*	*
	MPAnursery	*		*	*	*	*	*	*
	Gear	*	*	*	*	*	*	*	*
	TAC: MPAspawning	*	*	*	*	*	*	*	*
	TAC: MPAnursery				*	*	*		
	TAC: Gear	*	*	*	*	*	*	*	*
	MPAspawning: Gear	*	*	*	*	*	*	*	*
	MPAnursery: Gear					*	*	*	*

Five selected management scenarios were then studied. Their output values (Fig. 5) were then compared to the corresponding output values for simulation without management measures. Confidence intervals were constructed for the simulation without management measure using Eq. (2) (Fig. 5). We could not construct any confidence intervals for simulations with management measures since the sensitivity was practiced without any measures. Uncertainty on input parameters was too large to discriminate outputs from simulations with management from those obtained from simulations without management measure for hake with assurance. However, if the confidence intervals are of similar magnitude, a combination of a low TAC and a change in gear mesh size resulted in a significant increase in biomass. On the contrary, the impacts were largely discriminated for Nephrops population (confidence intervals were very tight compared to the discrepancy in metrics), the stock-recruitment relationship may partly explained the tightness of the intervals.

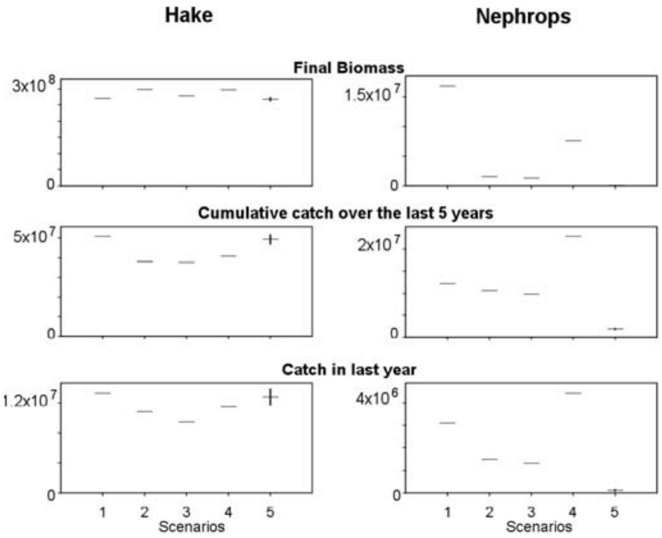

Fig. 5. Output values for five management scenarios. The represented confidence interval for the simulation without management measure is calculated using the equation (2). Scenario 1: MPA nursery AGYE2R; Scenario 2: change gear mesh size; Scenario 3: low TAC; Scenario 4: low TAC + change gear mesh size; Scenario 5: no management measure.

6 Discussion

This study was the first application of ISIS-Fish (version 1.5) to a real case study. The large number of parameters extracted or estimated from many sources of information and the conducted sensitivity analysis confirmed the potential of ISIS-Fish to integrate the available knowledge about the studied fishery, and to utilize it for exploring management scenarios.

According to the current parameterization of the French hake-Nephrops mixed fishery of the Bay of Biscay, hake was not overexploited. The lack of knowledge on hake migrations and the fact that only a small portion of the entire distribution area was studied may explain this counter intuitive diagnostic. It is also explained by the absence of Spanish fleets in the description of fishing activity. Exploitation by Spanish fleets accounted for about 38% of the total catch in ICES subdivision VIIIa in 2002 according to catch data extracted from the ICES database using *FishstatPlus* software (FAO 2000), but Spanish data were not available for this study. Regarding Nephrops, data are more complete since Nephrops in the Bay of Biscay are mainly exploited by French trawlers. The parameterization of stock-recruitment relationship and catchability is more uncertain, but theses parameters are integrated in the sensitivity analysis. Consequently, results of this study regarding the impact of management measures should be taken with caution, overall uncertainty is less for Nephrops than for hake.

The impact of the assumed stock-recruitment relationships has been analysed. Additional simulations considering a constant recruitment for both two species were conducted and the results were qualitatively similar (Drouineau 2004).

The methodology developed to analyze and compare various management scenarios will be easily applied to the hake-Nephrops Bay of Biscay case study completed with the Spanish fleet data in order to improve the reliability of the

Table 13. Significant coefficients (0.1‰) estimated by the linear models of output variables (the confidence level was chosen to limit the size of the table). Empty cases correspond to non significant coefficients. B: Biomass at the end of the simulation, C5: Cumulative catch of the last 5 years, C1: Cumulative catch of the last year, E5: Total nominal effort (days fishing) of the last five years, E1: Total nominal effort (days fishing) of the last year.

		Hake			Nephrops			Effort	
	Management measures	*B*	*C5*	*C1*	*B*	*C5*	*C1*	*E5*	*E1*
Main effects	Gear mesh size	2.1	−1.6	−1.2		1.4	1.0		
	Selective device	0.3				0.6	0.4		
	MPAnursery TTYe2R	0.2							
	MPAnursery AGS12R	0.1				0.2			
	MPAnursery AGYe1R				1.2	0.9	1.1		
	MPAnursery AGYe2R	0.2			2.7	1.6	2.1		
	TAC low	0.6	−1.9		0.3	1.3	0.9	−2.7	−2.7
	MPAspawning AGYe2R		−0.7	−1.0					
First-order interactions	MPAspawning TTYe2R X Gear mesh size	0.3	−0.7						
	MPAspawning AGS11R X Gear mesh size	0.4	−0.9	−1.2					
	MPAspawning AGS12R X Gear mesh size	0.3	−0.7	−0.9					
	MPAspawning AGYe1R X Gear mesh size	0.5	−0.9	−1.1					
	MPAspawning AGYe2R X Gear mesh size	0.4							
	MPAspawning TTS12R X Gear mesh size	0.3	−0.7	−0.9					
	MPAnursery TTYe2R X Gear mesh size				0.3	0.2	0.4		
	MPAnursery AGYe1R X Gear mesh size				0.3	−0.4			
	MPAnursery AGYe2R X Gear mesh size				0.5	−0.7	−0.4		
	MPAnursery AGYe2R X Gear selective device				0.4				
	TAC low X Gear mesh size	−0.3	1.5	2.1	0.8	0.7	1.0	0.7	0.7
	TAC low X Gear selective device				0.4	0.6	0.7		
	TAC low X MPAnursery AGS11R				0.4		0.3		
	TAC low X MPAnursery AGS12R				1.0	0.4	0.7		
	TAC low X MPAnursery AGYe1R					−0.3			
	TAC low X MPAnursery AGYe2R				0.4	−0.6	−0.4		
	TAC low X MPAspawning AGS11R	−0.6	1.2	1.4		−0.3	−0.3	0.5	0.5
	TAC low X MPAspawning TTYe1R	−0.6	1.4	1.6	−0.4	−0.3	−0.4	0.6	0.6
	TAC low X MPAspawning TTYe2R	−0.6	1.3	1.6		−0.3	−0.3	0.5	0.5
	TAC low X MPAspawning AGS12R	−0.6	1.1	1.2	−0.3	−0.4	−0.4	0.5	0.5
	TAC low X MPAspawning AGYe1R	−0.6	1.1	1.3	−0.3	−0.4	−0.4	0.5	0.5
	TAC low X MPAspawning AGYe2R	−0.6	1.4	1.7	−0.3	−0.4	−0.5	0.6	0.6
	TAC low X MPAspawning TTS11R	−0.6	1.4	1.6		−0.3	−0.3	0.6	0.6
	TAC low X MPAspawning TTS12R	−0.6	1.3	1.5		−0.3	−0.3	0.5	0.5
	TAC upper X Gear mesh size		−0.4	−0.5		−0.2		1.2	1.2
	TAC upper X Gear selective device		−0.6	−0.8		−0.1		0.7	0.7

diagnostics. The outputs considered in this purpose were chosen because they describe the final state of the fishery, and to a lesser extent their evolution. Additional outputs focused on the dynamics of the fishery may be considered. Some further investigations are also necessary to provide methods to construct confidence intervals for the outputs of all simulations (with or without management measures).

Uncertainty of the results due to uncertainty of the input parameters was quantified by the sensitivity analysis of the model to parameters. For hake, uncertainty was often too large to really discriminate the impact of different management measure. In the range of variation considered, few groups of parameters have large effects on outputs, natural mortality being not surprisingly the most influential parameter. Other parameters, especially reproduction, growth, emigration and catchability, significantly influenced the results. The level of uncertainty for parameters was chosen in reference to previous sensitivity analyses (de Castro et al. 2001; Elkalay et al. 2003), but some of parameters, especially catchability or emigration coefficients, might be more uncertain. It is necessary to improve the estimation of theses parameters through new methods and new data collection. Current studies intending to provide direct population density estimates using visual transects (Trenkel et al. 2004) could be used to calibrate catchability coefficients. Tagging survey of hake (de Pontual et al. 2003) should improve knowledge of migration, natural mortality and growth.

This study introduces the use of experimental designs with the group screening method which allows estimating efficiently the main effects and possible interactions between parameters. It should be underlined that some interactions might be underestimated because of group-screening, since possible compensations between the parameters of a group could occur.

Simulations with various hypotheses of uncertainty function, either deterministic or stochastic may be performed to improve the sensitivity analysis in further studies regarding parameters for which the uncertainty level of 20% is not appropriate. In this paper, a linear response to the variation of the parameters has been assumed, but surface response methodology might be considered to evaluate other types of responses to uncertainty.

Few studies have assessed the effect of management scenarios (individual management measure or combination of management measures) on a multi-specific fishery. This is thought to be very important since management measures can have negative effect on species not targeted by the measures and combined management measures can interact. This kind of analysis requires an experimental design, based in this paper on general linear modelling with further possible developments including generalized and mixed models.

PCA is a useful and synthetic tool to carry out preliminary explorations the impacts of these measures and to group them with respect to the consequences on both catches and biomasses. The impact of each management measure and their interactions have been estimated and compared using linear models. Impacts were difficult to anticipate, mainly because of the complexity of fishing activity in mixed fisheries and more specifically of fishermen adaptation to management measures. It should be underlined that the results observed are totally dependent on the assumed fishermen' s reaction to the different management measures. Additional reactions should be explored to provide a more complete picture of consequences of management scenarios.

Some catch limitation, a change in mesh size and permanent marine protected areas on the hake nursery zone for all gears seemed to be relevant with the current parameterisation and assumed fishermen' s reaction. Gear change and TAC impact both species (TAC also impacted the total nominal effort) whereas MPA had significant effect especially on the Nephrops population. The assumed larval dispersion may have an important impact on these results, other dispersion patterns should be tested in further studies.

Few measures had a positive impact on hake, probably because of its healthy situation derived from the current parameterisation of the fishing activity, and because of the selected stock-recruitment relationship. A tool like ISIS-Fish may therefore be very useful to pre-evaluate management measures and to avoid implementing inefficient measure.

Acknowledgements. This study was made possible through the European project TECTAC (Technological developments and tactical adaptations of important EU fleets – Contract number: QLK5-2001-01291). We would like also to acknowledge the two anonymous referees for their relevant comments that have improved the paper.

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