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Long-term targets for the Celtic Sea mixed-species multi-métiers fisheries

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Abstract

A deterministic, forecasting, equilibrium study has been conducted of the multispecies and multi-métier fisheries of the Celtic Sea, ICES divisions VIIf and g. Calculations have been made of the optimal fleet sizes and mesh sizes required to maximize objectives of joint relative sustainable yields, gross revenue and net revenue. The species modelled are the resident populations of cod *(Gadus morhua)*, whiting *(Merlangius merlangus)*, sole *(Solea solea)*, plaice *(Pleuronectes platessa)* and Norway lobster *(Nephrops norvegicus)*, with additional consideration given to catches of hake *(Merluccius merluccius)*, monkfish *(Lophius* sp.*)* and megrim *(Lepidorhombus whiffiagonis)*. The fleet métiers modelled are the beam trawls, *Nephrops* otter trawls and non-*Nephrops* otter trawls. If mesh sizes can be calculated independently for each métier, then the yields and the gross revenue are maximized by increased effort and mesh sizes, especially in the non-*Nephrops* fleet. If a common mesh size is required for all fleets, then the yields and the gross revenue are maximized when (i) this mesh size is of 114 mm, (ii) the fishing effort in beam and *Nephrops* fleets is significantly increased, (iii) the non-*Nephrops* fleet is almost eliminated. Maximization of net revenue requires a mesh size similar to the current mesh of 80 mm, but with significant reductions of fishing effort in all fleets. Average profitability is increased by 50 millions EUROs per year for the Celtic Sea fishery. The model provides a basic structure for examining the management with a more realistic dynamic and stochastic description of the Celtic Sea fisheries.

Keywords: Celtic Sea, modelling, groundfish resources, fisheries management, yields, gross revenue, net revenue, mesh size, exploitation rate.

Objectifs à long terme pour les pêcheries multi-spécifiques et multi-métiers de mer Celtique.

Résumé

Une étude déterministe prévisionnelle a été menée, à l'équilibre, sur les pêcheries multispécifiques et multi-métiers de mer Celtique, divisions CIEM VIIf et g. Les efforts de pêche et les maillages optimaux ont été calculés, pour chaque métier, afin de maximiser, soit le poids des captures, soit la valeur des captures, ou bien la marge bénéficiaire. Les espèces étudiées sont les populations résidentes de morue *(Gadus morhua)*, merlan *(Merlangius merlangus)*, sole *(Solea solea)*, plie *(Pleuronectes platessa)* et langoustine *(Nephrops norvegicus)*, une attention complémentaire a également été portée sur les captures de merlu *(Merluccius merluccius)*, baudroie *(Lophius* sp.*)* et cardine *(Lepidorhombus whiffiagonis)*. Les chalutiers à perche, les chalutiers langoustiniers et les chalutiers non-langoustiniers sont les métiers modélisés. Si les maillages sont calculés indépendamment pour chacun des métiers, le poids et la valeur des captures sont les plus élevés lorsque les efforts de pêche et les maillages sont accrus, particulièrement pour les chalutiers non-langoustiniers. Si un maillage commun est requis pour tous les métiers, le poids et la valeur des captures sont les plus élevés lorsque (i) ce maillage est de 114 mm, (ii) l'effort de pêche des flottilles de chalutiers à perche et de chalutiers langoustiniers augmente significativement, (iii) l'activité de pêche des flottilles de chalutiers non-langoustiniers est réduite à zéro. La plus grande marge bénéficiaire est obtenue avec un maillage proche du maillage actuel de 80 mm, mais avec une réduction significative de l'effort de pêche pour tous les métiers. Le profit moyen est accru de 50 millions EUROs par an, pour la pêcherie de mer Celtique. Le modèle propose un cadre à l'examen de stratégies de gestion prenant en compte les composantes dynamiques et stochastiques des pêcheries de mer Celtique.

Mots-clés : mer Celtique, modélisation, ressources démersales, gestion des pêches, captures, marge bénéficiaire, maillage, taux d'exploitation.

INTRODUCTION

Most harvested species interact biologically, through predation or competition, and technically, as several species are likely to be caught by the same métier if they live in the same fishing area (Mercer, 1982). The enforcement of TACs (Total Allowable Catches), set independently for these species, is likely to lead to discards of species whose quota has been reached, but which are caught as by-catch with other target species. However, advice on TACs and technical measures by the ICES ACFM (International Council for Exploitation of the Sea Advisory Committee for Fishery Management) has traditionally been based primarily on single-species assessments, although management based on multispecies assessment has been reviewed (Stokes, 1992) and recommended by the European Commission.

Technical interactions (*e.g.* Hilborn and Walters, 1987; Mesnil and Shepherd, 1990), involving several fleets and several species, exist in the groundfish fisheries of the Celtic Sea. The Celtic Sea is made up of the ICES statistical divisions VIIf-j, and is mainly fished by France, Ireland, the United Kingdom, Spain and Belgium in order of size of catches. In fact, the relatively low degree of complexity of their technical interactions and the probable lack of significant biological interactions (DuBuit, 1982) make the Celtic Sea groundfish fisheries (*fig. 1*) a good example for modelling technical interactions. The French Celtic Sea fisheries have been described in detail (Biseau and Gondeaux, 1988; Biseau and Charuau, 1989; Pérodou, 1988). More generally, several main fisheries units, or métiers, targeting particular species, are considered by ICES in the Celtic Sea (*e.g.* Anon., 1992). This allows simulation of the impact of various multi-fleet technical measures on the different stocks. All vessels within a métier, characterised by one gear, one set of target species and one depth range, are assumed to have the same fishing pattern (*table 1*). The present study will be limited to ICES divisions VIIf and g. This restriction simplifies the fishery system as fewer métiers and species are involved. The borders of divisions VIIf and g also are, approximately, the natural boundaries of several important stocks. Divisions VIIf and g are harvested mainly by France and the United Kingdom.

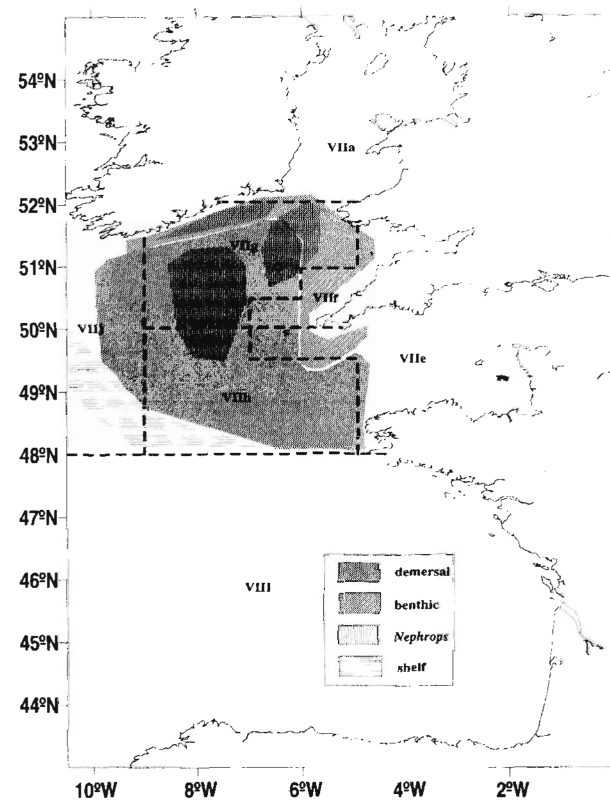

Figure 1. – Localisation of the main groundfish fisheries in the Celtic Sea (adapted from Biseau and Charuau, 1989).

Optimization of mixed-species fisheries, controlled by both mesh size and fishing effort, was first explored by Beverton and Holt (1957). They drew eumetric curves for an aggregate of species belonging to the North Sea while pointing out the antagonism between eumetric fishing (maximizing yields) and optimal fishing (*e.g.* maximizing profit). Murawski (1984) and Murawski and Finn (1986) extended the approach to multi-métiers, mixed-species fisheries, but did not extensively explore the optimal allocation of fishing effort and mesh size by métiers. Pikitch (1987) used both mesh size and fishing effort as controls to achieve three alternate objectives: maximizing total yield, gross revenues or net revenues. However, the approach

Table 1. – Locations and characteristics of each Celtic Sea métier.

ICES divisions	Métier No.	Métier characteristics	Target species	By-catch
VII f and g	1	Non-*Nephrops* otter-trawlers	*Gadus morhua* *Merlangius merlangus*	*Solea solea* *Pleuronectes platessa* *Lepidorhombus whiffiagonis* *Lophius* sp.
	2	Beam-trawlers	*Solea solea*	*Pleuronectes platessa* *Lepidorhombus whiffiagonis*
	3	*Nephrops* otter-trawlers	*Nephrops norvegicus*	*Gadus morhua* *Merlangius merlangus* *Merluccius merluccius* *Lophius* sp. *Lepidorhombus whiffiagonis*
	4	Longliners	*Gadus morhua* *Merlangius merlangus*	
	5	Fixed nets	*Merluccius merluccius* *Lophius* sp. *Gadus morhua*	
outside VIIf and g	6	Other fleets	*Merluccius merluccius* *Lophius* sp. *Lepidorhombus whiffiagonis* Catches taken from stocks distributed exclusively outside VIIf and g	

was based upon a single-métier model. Laurec *et al.* (1991) dynamically modelled the technical interactions of the Celtic Sea fisheries, but the study did not take into account possible changes in mesh size.

After a short presentation of the stocks and the métiers in the Celtic Sea, divisions VIIf and g, the present paper aims to evaluate the potential long-term equilibrium outcomes for the fishery, under the objectives of maximizing yields, gross revenues and net revenues. The optimal allocation of potential control factors, *i.e.* fishing effort and mesh size, amongst the métiers, will be sought in relation to these long-term objectives, taking into account the multi-species character of the métiers.

METHODS

Stocks and fisheries métiers in divisions VIIf and g

Figure 2 shows the French and UK landings, averaged between 1991 and 1993, of the important eight demersal species caught in area VII (excluding the Irish Sea and the English Channel) by gear and by ICES division. These eight species are of cod *(Gadus morhua)*, whiting *(Merlangius merlangus)*, sole *(Solea solea)*, plaice *(Pleuronectes platessa)*, Norway lobster *(Nephrops norvegicus)*, hake *(Merluccius merluccius)*, monkfish *(Lophius* sp.*)* and megrim *(Lepidorhombus whiffiagonis)*. Due to the burying behaviour of the female *Nephrops* during the winter season, the two sexes of *Nephrops* have different biological parameters and exploitation patterns, and they are usually assessed separately as two pseudo-species. The monkfish also comprises two species, *Lophius piscatorius* and *Lophius budegassa*, which are assessed independently.

From divisions VIIb,c,h-k some 70–95 % of the catches of each species of cod, whiting, sole, plaice and *Nephrops* are from divisions VIIf and g. These species will be termed the "resident" species. Conversely, Celtic Sea hake, monkfish and megrim belong to stocks, which are more extensively distributed within and beyond the area VII, and only 3-13 % of the total TAC is taken in divisions VIIf and g. These species will be called the "ubiquitous" species.

The métiers fishing for the eight species are presented in *table 1*. The divisions VIIf and g are harvested by the métiers 1-5. These métiers will be termed the "resident" métiers. The resident species are caught almost exclusively by the resident métiers. Otter-trawlers can there target *Nephrops* (métier 3) or other species (métier 1). *Figure 2* shows that cod, whiting and *Nephrops* are caught almost exclusively by otter-trawlers (métiers 1 and 3), whereas catches of sole and plaice are shared between beam- and otter-trawlers (métiers 2 and 1). The ubiquitous species are mainly caught by the métiers fishing outside VIIf and g (métier 6). However, the amount of

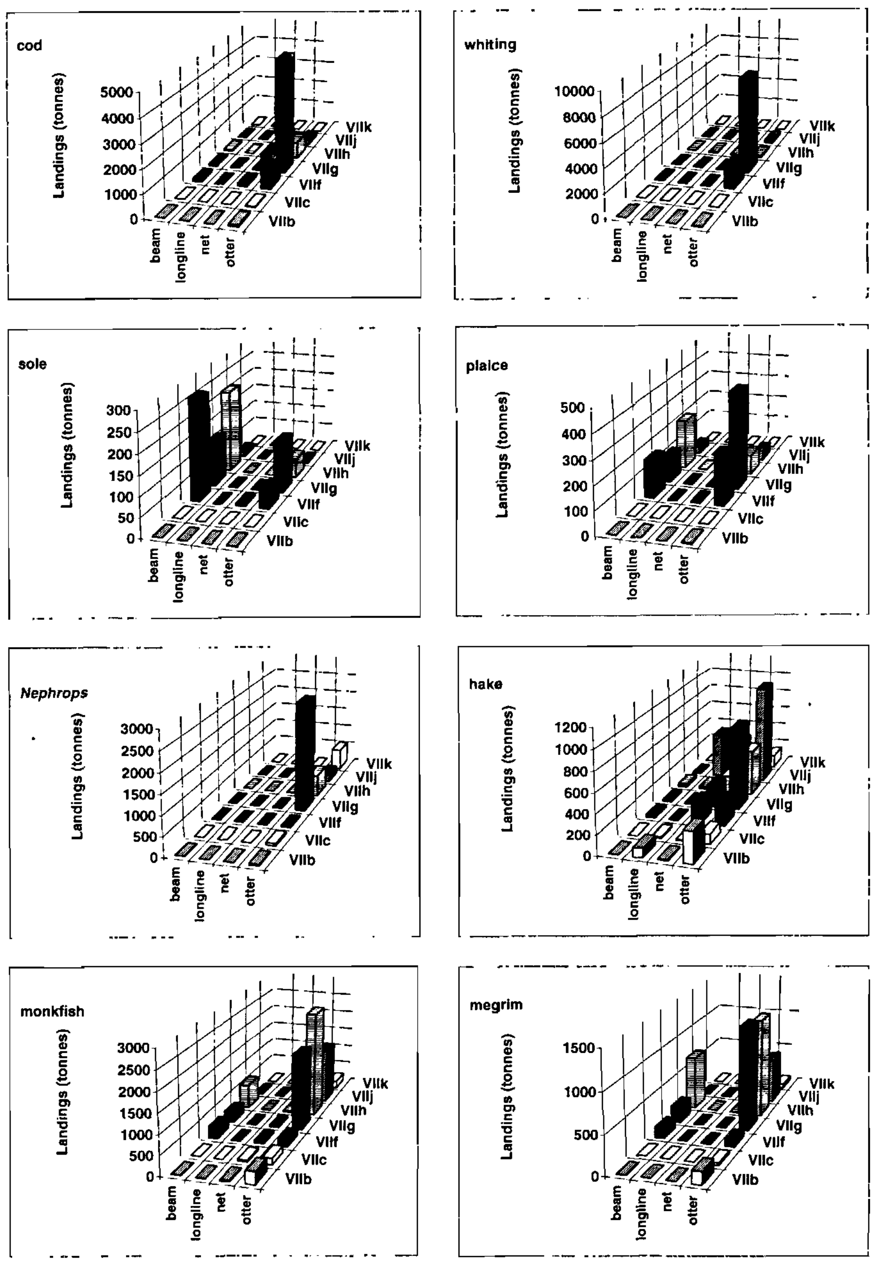

Figure 2. – French and UK landings (tonnes) of eight groundfish species from area VII (excluding the Irish Sea and the English Channel), averaged between 1991 and 1993, by ICES division and by gear.

ubiquitous species caught by the resident métiers represent a non-negligible value (35 %) for these métiers *(fig. 3)*. Netters and longliners (métiers 5 and 4) catch relatively little of the eight species.

Métiers 1, 2 and 3 are the most important for the fishery in divisions VIIf and g, and the optimal allocation of effort and mesh size will be determined with respect to them. The current minimum mesh size for métiers 1 and 2, which target finfish, is of 80 mm. The minimum mesh size for vessels targeting *Nephrops* is 70 mm. However, the vessels fishing for métier 3, especially the French ones, could not survive without by-catches of gadoids, which would be controlled and restricted if 70 mm mesh size was used. Consequently, almost all vessels belonging to métier 3 use an 80 mm mesh size (Anon., 1992). The effort and mesh size (if applicable) of métiers 4 and 5, which take only small quantities of the species

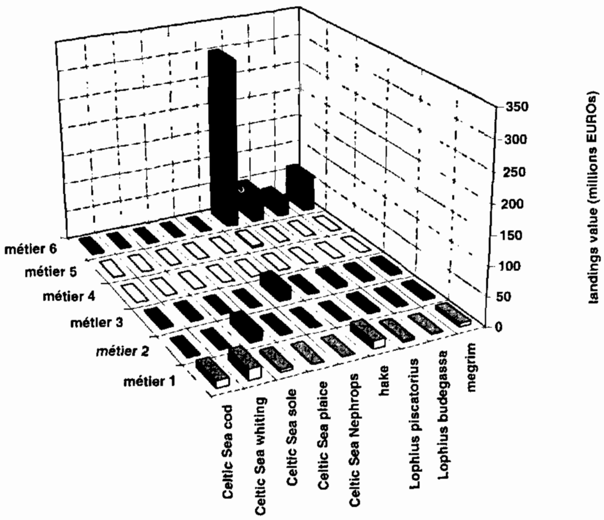

Figure 3. – Total international landings value (millions EUROs) in 1990 of Celtic Sea species, by métier. The resident stocks of cod, whiting, sole, plaice and *Nephrops* are confined to the Celtic Sea, divisions VIIf and g, whereas the ubiquitous stocks of hake, *Lophius* sp. and megrim are distributed within and beyond divisions VIIf and g. The resident métiers 1-5 fish only within divisions VIIf and g, whereas métier 6 fish only outside divisions VIIf and g.

selected, and of the "other" métiers (métier 6) fishing beyond VIIf and g, will be held constant at their value in the reference year of 1991.

Approaches to static optimal exploitation

Optimal allocation of fishing effort and mesh size amongst métiers in the mixed-species fisheries has been calculated based on deterministic dynamics, assuming constant average recruitment, in relation to specific long-term objectives and policies.

Long-term objectives

It would be desirable to maximize both fishery yields and profitability. Unfortunately, these two objectives are not compatible (Beverton and Holt, 1957) and consequently three possibly conflicting objectives have been explored:

– maximization of the sustainable yield in weight for the resident species (MSY),

– maximization of the sustainable gross revenues in EUROs, from the resident species (MSGR),

– maximization of the sustainable net revenues in EUROs, for the resident métiers (MSNR).

In a monospecific assessment and neglecting price elasticity, MSY and MSGR objectives would be both achieved by maximizing the catches of one species. However, in a multispecific assessment, there are several ways to achieve maximal catches for several species simultaneously. Thus, MSY which maximizes catches of all resident species without discrimination, would not necessarily correspond to MSGR, which gives a priority to high value species. To avoid the outcome of maximized yields being dominated by the large stocks of gadoids, we have chosen to maximize a joint relative yield, where the yield of each species is normalised to its maximum. The details about the normalisation are given later.

The MSNR objective requires costs of exploitation per resident métier, which are unknown. However, as in Horwood (1987), these parameters were calculated assuming that the international fleet has operated near to zero profit in the reference year (1991). This assumption is not unreasonable as the lack of expansion of the fleets suggests that current profits are low. Calculated costs of exploitation at 1991 levels of effort, based on French and English unpublished data, are presented in *table 2.*

Control factors and policies

Two control factors can be identified: mesh size and fishing effort. The policies will be determined by the value given to these two control factors for métiers 1, 2 and 3. Hence, at the most, six independent variables can potentially be used to manage the fishery and achieve any objective. However, optimizing the fishery could lead to extreme results of two kinds, if (i) both optimal control factors are very different from current values, and if (ii) the changes, related to the *statu quo*, in each optimal control factor are very different from one métier to another. Such impractical results can be reduced by imposing specific constraints on the variables.

In relation to (i), each control factor (fishing effort or mesh size) could either be optimized to achieve an objective (active), or be set to a given value (fixed). Hence, three cases related to (i) could potentially be explored:

– active fishing effort and active mesh size,

– active fishing effort and fixed mesh size,

– fixed fishing effort and active mesh size.

In relation to (ii), a control factor is said to be uniform if, whether it is fixed or active, it is required to be the same for the three métiers. Conversely, a control factor is said to be compound if, whether it is fixed or active, it can vary amongst the three métiers. Hence, three cases related to (ii) could potentially be explored:

– compound fishing effort and compound mesh size,

– compound fishing effort and uniform mesh size,

– uniform fishing effort and compound mesh size.

The different potential status of the control factors (active/fixed and compound/uniform) can be combined, resulting in nine policies, as displayed in *table 3.* Each policy identifies the number of variables to be optimized to achieve an objective. Policy P1, which identifies six independent variables, acts as a reference, as it represents the best theoretical achievement for any long-term objective. Not all

Table 2. – Main biological and economic parameters, for each species. SF and δ are the two parameters of the logistic curve of selectivity of a métier using a given mesh size. SF is a proportional factor between the L50 of the logistic curve and the mesh size. δ is a proportional factor between the L50 and the selectivity range (L75-L25) of the curve. R, M and π are respectively the recruitment, the natural mortality and the market price for each species. Reference fishing mortalities calculated from Anon. (1992) have been averaged between ages: 2-5 (cod and whiting), 4-8 (sole), 3-6 (plaice), 2-6 *(Nephrops)*, 1-4 (hake), 3-7 *(Lophius piscatorius)*, 4-8 *(Lophius budegassa)*, 3-6 (megrim). Reference fishing mortalities for métiers 4-6 are close to zero for the resident species, and are not reported. χ_0^m represents the estimated exploitation costs.

	Individual growth parameters			Selectivity parameters		Maximum eumetric catches	Population growth parameters		Reference fishing mortalities by métiers			Economic parameters			
	L_∞ (mm)	t_0 (y)	K (y^{-1})	SF	δ	C_*^* (10^3 tonnes)	R (10^6 fish)	M(y^{-1})	$\overline{f^1}$ (y^{-1})	$\overline{f^2}$ (y^{-1})	$\overline{f^3}$ (y^{-1})	π (10^6 EUROs/ 1000 tonnes)	χ_0^1 (10^6 EUROs)	χ_0^2 (10^6 EUROs)	χ_0^3 (10^6 EUROs)
Gadus morhua	1 090	-0.19	0.38	3.2	0.15	10.9	3.1	0.20	0.72	0.05	0.22	2.40	40.4	15.0	50.7
Merlangius merlangus	660	-2.19	0.18	3.8	0.15	11.3	29.0	0.20	1.13	0.01	0.16	1.65	40.4	15.0	50.7
Solea solea	450	-1.14	0.30	3.5	0.13	1.2	4.2	0.10	0.09	0.41	0.00	6.69	40.4	15.0	50.7
Pleuronectes platessa	600	-2.74	0.12	3.6	0.14	2.1	5.7	0.12	0.15	0.63	0.00	1.47	40.4	15.0	50.7
Nephrops norvegicus (male)	68	-0.60	0.12	0.5	0.43	4.9	409.0	0.30	0.00	0.00	0.30	6.23	40.4	15.0	50.7
Nephrops norvegicus (female)	49	-0.70	0.17	0.5	0.43	1.5	173.0	0.30	0.00	0.00	0.35	6.23	40.4	15.0	50.7
Merluccius merluccius	1 275	-1.13	0.07	3.7	0.40	-	250.0	0.20	0.01	0.00	0.01	3.50	40.4	15.0	50.7
Lophius piscatorius	1 400	-0.03	0.10	2.5	0.40	-	12.6	0.15	0.01	0.03	0.02	2.63	40.4	15.0	50.7
Lophius budegassa	940	0.78	0.09	2.5	0.40	-	15.1	0.15	0.00	0.01	0.02	2.55	40.4	15.0	50.7
Lepidorhombus whiffiagonis	690	0.11	0.12	3.1	0.15	-	310.2	0.20	0.07	0.01	0.03	2.79	40.4	15.0	50.7

of policies P2-P9 are realistic management options. Unlike other areas where some métiers have distinct and different mesh sizes (*e.g.* beam-trawlers in the North Sea or *Nephrops* trawlers in the Bay of Biscay), métiers 1, 2 and 3 currently have the same mesh size. Therefore, policies involving compound mesh sizes will not be considered further. Policy P6, where only one control factor is optimized, with the constraint to have the same value for each métier, provides a weak control with only one variable, and it will not be considered further. Consequently, only policies P1, P3, P9 will be examined.

Eventually, long-term equilibrium outputs provided by the three objectives (MSY, MSGR, MSNR), achieved with three policies (P1, P3 and P9), based on mesh size and/or exploitation rate controls, will be presented. All outputs will be compared with outputs

Table 3. – Definition of all potential policies, related to the varied status of each control factor (mesh size and fishing effort). Policies which have been used in the study are P1, P3 and P9. When a control factor (mesh size or fishing effort) is used in the optimization (*i.e.* active control factor), it is indexed with the sign "*". When a control factor is allocated to each métier 1, 2, 3 independently (*i.e.* compound control factor), the three métier-dependent elements of the control factor vector are set in brackets. The total number of independent variables used in the optimization is also quoted.

Mesh size			Fishing effort			Number of independent variables	Policy
active	compound	$(\mu_*^1, \mu_*^2, \mu_*^3)$	active	compound	(E_*^1, E_*^2, E_*^3)	3 + 3 = 6	P1
active	compound	$(\mu_*^1, \mu_*^2, \mu_*^3)$	active	uniform	$E_* = E_*^1 = E_*^2 = E_*^3$	3 + 1 = 4	P2
active	uniform	$\mu_* = \mu_*^1 = \mu_*^2 = \mu_*^3$	active	compound	(E_*^1, E_*^2, E_*^3)	1 + 3 = 4	P3
active	compound	$(\mu_*^1, \mu_*^2, \mu_*^3)$	fixed	compound	(E^1, E^2, E^3)	3 + 0 = 3	P4
active	compound	$(\mu_*^1, \mu_*^2, \mu_*^3)$	fixed	uniform	$E = E^1 = E^2 = E^3$	3 + 0 = 3	P5
active	uniform	$\mu_* = \mu_*^1 = \mu_*^2 = \mu_*^3$	fixed	compound	(E^1, E^2, E^3)	1 + 0 = 1	P6
fixed	compound	(μ^1, μ^2, μ^3)	active	compound	(E_*^1, E_*^2, E_*^3)	0 + 3 = 3	P7
fixed	compound	(μ^1, μ^2, μ^3)	active	uniform	$E_* = E_*^1 = E_*^2 = E_*^3$	0 + 1 = 1	P8
fixed	uniform	$\mu = \mu^1 = \mu^2 = \mu^3$	active	compound	(E_*^1, E_*^2, E_*^3)	0 + 3 = 3	P9

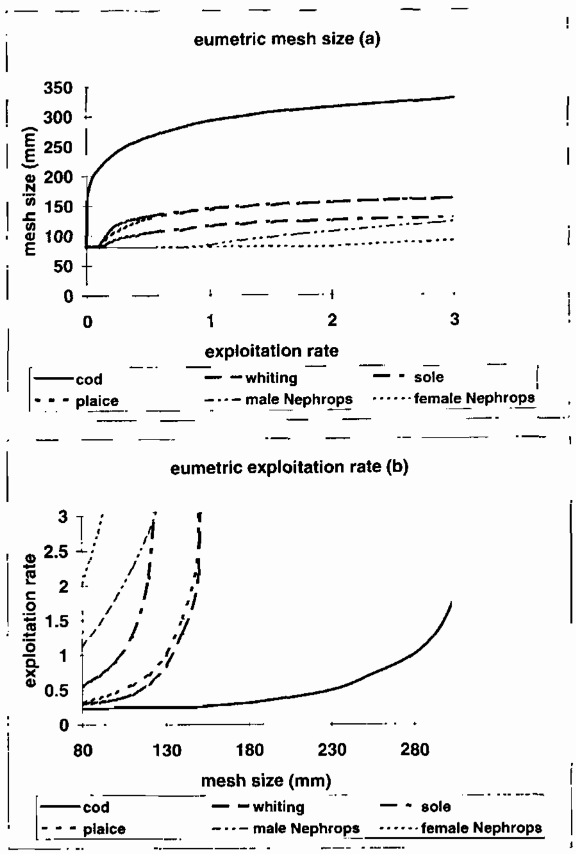

Figure 4. – Eumetric curves by species, as depicted in Beverton and Holt (1957). These curves plot the exploitation rate related to a given mesh size (a) and the mesh size related to a given exploitation rate (b), which provide the maximum yields.

produced by the long term *statu quo* option, where all exploitation rates and mesh sizes are held at the reference level of 1991. Note that P9 sets a common mesh size to a fixed level, which will be varied in the study.

Eumetric curves

In order to identify optimal levels of mesh size and exploitation rate for species confined in divisions VIIf and g, eumetric curves have been drawn, based on a basic one fleet – one species assessment. The eumetric curves, based on a classical age-structured model (Beverton and Holt, 1957), provide a rational basis for the mutual adjustment of the two factors which control the fishing activity: the exploitation rate and the mesh size. They represent the exploitation rate relative to a given mesh size *(fig. 4a)*, and the mesh size related to a given exploitation rate *(fig. 4b)*, which provide the maximum yields. Although eumetric curves shown in *figure 4a, b*, are not reciprocal, they have the same asymptotic values. The asymptotic mesh sizes depend on the species, and a single mesh size will not give high yields for all species. Thus, there are large differences among the eumetric asymptotic mesh sizes of cod (350 mm), plaice (180 mm), whiting (173 mm), sole (130 mm), male *Nephrops* (107 mm) and female *Nephrops* (< 80 mm).

Optimization

Define the following terms:

E^m : Exploitation rate for métier m (*i.e.* fishing effort at the equilibrium related to fishing effort in the reference year of 1991). In 1991, the value of exploitation rate for all the métiers is 1.0.

μ^m : Mesh size for métier m. In 1991, the mesh size for all trawling métiers in divisions VIIf and g is of 80 mm.

$\mathcal{M}_1$: Total number of resident métiers, $\mathcal{M}_1$=5. Control factors for métiers 4 and 5 are held constant at their value in the reference year of 1991; control factors of métiers 1, 2 and 3 are optimized.

$\mathcal{M}_2$: Number of other métiers (métier 6), $\mathcal{M}_2$=1. Control factors for these métiers are held constant at their value in the reference year of 1991.

$\mathcal{M}$: Total number of métiers fishing for the harvested species, $\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2$.

$\mathcal{S}_1$: Number of resident species (cod, whiting, sole, plaice, *Nephrops* male and female), $\mathcal{S}_1$=6.

$\mathcal{S}_2$: Number of ubiquitous species (hake, *L. piscatorius, L. budegassa* and megrim), $\mathcal{S}_2$=4.

$\mathcal{S}$: Total number of harvested species, $\mathcal{S} = \mathcal{S}_1 + \mathcal{S}_2$.

$\underline{\mu}$: Column $\mathcal{M}$-vector, the m-th component of which is μ^m.

$C^{m,s}_{\mu^m}$: Long-term equilibrium catches in weight (tonnes) of species s with métier m when exploitation rate E^m and mesh size μ^m are enforced.

$C^s_{\underline{\mu}}$: Total long-term equilibrium catches in weight (tonnes) of species s.

C^s_* Maximal possible long-term catch at equilibrium (tonnes), which can theoretically be achieved for each species s, with asymptotic eumetric mesh size, and exploitation rate tending towards the infinity *(table 2)*.

π^s Price of species s (millions EUROs/1 000 tonnes).

$\mathcal{X}^m_0$: Cost of métier m in 1991 for métiers fishing in divisions VIIf and g (millions EUROs).

$\mathcal{X}$: Total cost of the international fleet fishing in divisions VIIf and g (millions EUROs).

Γ_{MSY} : Yield maximization function, for the resident species.

Γ_{MSGR} : Gross revenue maximization function, for the resident species.

Γ_{MSNR} : Net revenue (or profit) maximization function, for the resident métiers.

Optimizations have been achieved with programmes written in FORTRAN77, using NAG routines. Long-term objectives are to be optimized and as such, the underlying biological model presented in appendix A depicts the long-term equilibrium exploitation of age-structured populations. The constant parameter values have been taken from Anonymus (1992, 1994*a*, *b*). They are displayed in *table 2*. Individual growth, selectivity and economic parameters, related to plaice, have been calculated according to unpublished English data. Reference fishing mortalities have been estimated by assuming that the proportion of total fishing mortality awarded to a métier was equal to the fraction of total catches of a species derived from that métier (Murawski and Finn, 1986). The long-term equilibrium outcomes of the different optimizations are based on the assumption that parameters such as recruitment, catchabilities, market prices of species, costs of exploitation for métiers, are constant. The relevance of these assumptions will be debated in the discussion.

Exploitation rates and selectivity of métiers 4-6 are held at their current value, whatever the objective and the policy applied. If the policy P1 is applied, six independent variables ($E^1, E^2, E^3, \mu^1, \mu^2, \mu^3$) will be calculated. If policy P3 is applied, four independent variables ($E^1, E^2, E^3, \mu^1 = \mu^2 = \mu^3$) will be calculated. Eventually, if policy P9 is applied, three exploitation rates (E^1, E^2, E^3) will be generated, while the common mesh size $\mu = \mu^1 = \mu^2 = \mu^3$ is set to a given value, which will be varied between 80 (current mesh size) and 150 mm. The gear selectivities are calculated, from appendix B, with respect to mesh sizes (B.1). Given the gear selectivities and the exploitation rates, fishing mortalities (A.3), total mortalities (A.2), long-term equilibrium stocks number at age (A.1), catches (A.6) and spawning stock biomass, SSB (A.7) can be evaluated with the biological age-structured model defined in appendix A.

The maximization of joint yields (MSY) has been interpreted here as wishing to get as near as possible to the relative maximum for each resident species simultaneously as the joint fisheries will allow. Consequently, the objective function attached to MSY minimizes the discrepancy between the calculated catch of each species $\left(C^s_{\underline{u}}\right)$ and the maximum theoretical catch, with eumetric fishing, C^s_*, scaled by C^s_*. Hence, the objective function attached to MSY is:

$$\Gamma_{\mathrm{MSY}} = \sum_{s=1}^{\mathcal{S}_1} \left(\frac{C^s_{\underline{\mu}} - C^s_*}{C^s_*} \right)^2 \qquad (1)$$

The objective MSGR will be achieved when the function (2) is maximized with respect to E^m and/or μ^m.

$$\Gamma_{\mathrm{MSGR}} = \sum_{s=1}^{\mathcal{S}_1} \left(\pi^s . C^s_{\underline{\mu}} \right) \qquad (2)$$

The objective MSNR aims to maximize profit for the resident métiers. Gains for the resident métiers are raised with catches of both resident and ubiquitous species. Losses are due to the costs of exploitation. MSNR will be achieved when the function (3) is maximized with respect to E^m and/or μ^m.

$$\Gamma_{\mathrm{MSNR}} = \sum_{m=1}^{\mathcal{M}_1} \left[\sum_{s=1}^{\mathcal{S}} \left(\pi^s . C^{m,s}_{\mu^m} \right) - \chi^m_0 E^m \right] \qquad (3)$$

Γ_{MSNR} can also be related to Γ_{MSGR}:

$$\Gamma_{\mathrm{MSNR}} = \Gamma_{\mathrm{MSGR}} - \chi' \qquad (3')$$

where: $\chi' = \sum_{m=1}^{\mathcal{M}_1} (\chi^m_0 E^m) - \sum_{s=\mathcal{S}_1+1}^{\mathcal{S}} \left(\pi^s . C^s_{\underline{\mu}} \right) = \chi - \sum_{s=\mathcal{S}_1+1}^{\mathcal{S}} \left(\pi^s . C^s_{\underline{\mu}} \right)$ represents the virtual costs of exploitation of the resident species, that is the total exploitation cost of the international fleet in divisions VIIf and g minus the gains raised by catches of ubiquitous species.

RESULTS

Simultaneous optimization of exploitation rate and mesh size

The results provided by policies P1 and P3 are given in *figure 5a-e*. Those with MSY and MSGR objectives are very similar for both management policies. Consequently, only one of those objectives, MSGR, will be considered below.

With the MSGR objective and policy P1, exploitation rates should be raised to 540, 146 and 140 % of current values for métiers 1, 2 and 3 respectively while mesh sizes should increase to 350, 119 and 91 mm, for the same métiers. This large difference in mesh sizes amongst métiers reflects the different species targeted by these métiers. Thus, optimal mesh sizes of métiers 1, 2 and 3 are closely related to asymptotic eumetric mesh sizes of cod, sole and *Nephrops* respectively. With the P3 policy of a common mesh size, fishing effort in métier 1 should be decreased to 0 %, and it should be raised to 126 and 232 % of current values for métiers 2 and 3, with a common mesh size increased to 114 mm, for all métiers. Optimal values of exploitation rates in métiers 1, 2 and 3, with the common mesh size of 114 mm are related to the

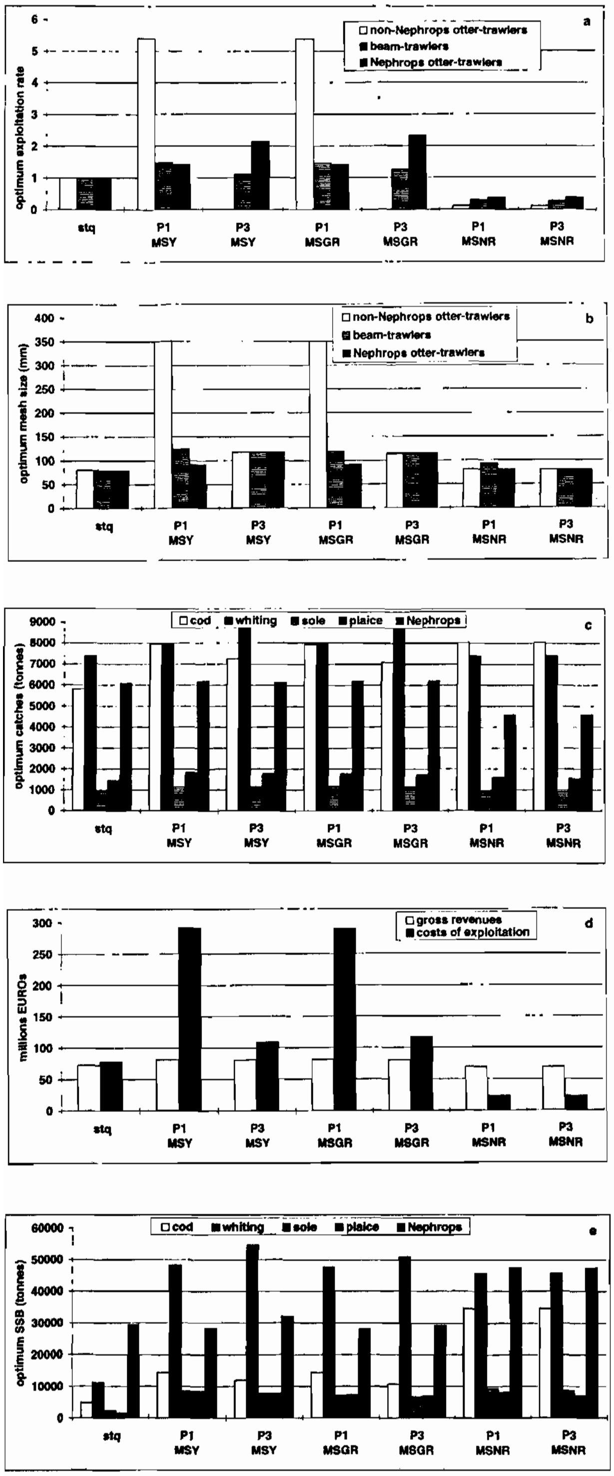

Figure 5. – Optimal results provided by three objectives (MSY: maximum sustainable yield, MSGR: maximum sustainable gross revenues and MSNR: maximum sustainable net revenues) and two policies (P1 and P3). Results provided by *statu quo* option are also quoted; a: allocation amongst métiers of exploitation rate relative to *statu quo*; b: mesh size allocated to each métier; c: catches by species in tonnes; d: gross revenues and virtual costs of exploitation in millions EUROs; e: spawning stock biomass by species in tonnes.

eumetric curves of cod, sole and *Nephrops (fig. 4b)*. Gross revenues are only slightly better with P1 than with P3, but net revenues are dramatically lower and for both significant economic losses are predicted. This last result arises from huge costs of exploitation under policy P1 and, to a lesser degree, under policy P3.

For the MSNR objective, the results for policies P1 or P3 are very similar. Under the P1 policy, optimal exploitation rates are only 11 – 38 % of current values, for métiers 1, 2 and 3, due to the introduction of exploitation costs. As optimal exploitation rates are low for each métier, mesh sizes are close to the current 80 mm, in order to approach eumetric catches for all species. Catches of all species are much lower than with the MSY or the MSGR objectives, except for cod, due to its particular eumetric curve. Gross revenues are even lower with the MSNR objective than with the *statu quo* option but net revenues are much higher and profitability of the fleets is about 46 millions EUROs per year.

Optimization of exploitation rate with fixed mesh size

The results with the MSGR objective, under policy P9 (fixed mesh size) are given in *figure 6a, b*. With the current 80 mm mesh size, exploitation rates in métiers 1 and 2 should be decreased to 7 and 56 % respectively, owing to the current situation of growth overfishing for targeted stocks of cod, whiting, sole and plaice. Conversely, as *Nephrops* stocks are currently slightly underexploited, the exploitation rate of métier 3 could be increased to 115 %. As a result, catches of all species, gross and net revenues are higher than with the *statu quo* option.

As the common mesh size is increased from 80 to 150 mm, the different curves of exploitation rate by métier follow different trends. When the mesh size increases from 80 to 140 mm, the global exploitation rate required to achieve eumetric yields (*i.e.* the eumetric exploitation rate) is increasing steadily for all species except cod *(fig. 4b)*. As a result, optimal exploitation rates of métiers 2 and 3 increase exponentially with mesh size. Eumetric exploitation rate of cod remains the same when mesh size is increased from 80 to 140 mm. Cod is harvested by métiers 1 and 3 and the steady increase in exploitation rate of métier 3 is balanced by the elimination of métier 1, when mesh size is increased from 80 to 140 mm. When mesh size is bigger than 140 mm, eumetric exploitation rate for cod increases, and so does the exploitation rate in métier 1. Eventually, all species, except cod, are exploited close to the eumetric levels. When mesh size is increased, catches of all species, except cod, increase until their particular eumetric asymptotic mesh size is exceeded. Hence, the variations of the yields with respect to mesh size are depending upon the species, and the gross revenues reaches a maximum of 81 millions EUROs when the mesh size is 114 mm. The huge increase

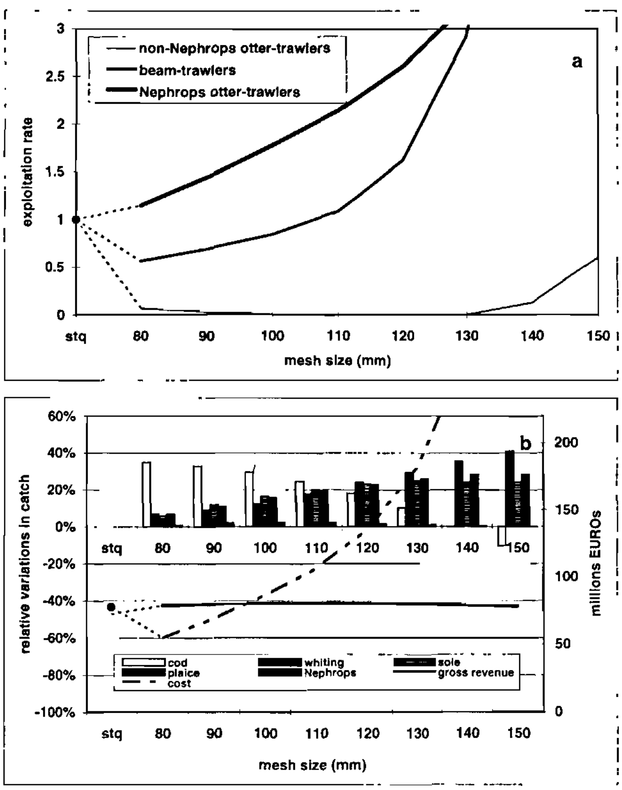

Figure 6. – a: Optimal exploitation rate by métier, relative to the *statu quo*, versus mesh size at MSGR (maximum sustainable gross revenue) with fixed mesh size (policy P9); b: Percentage variation in catches by species (relative to the *statu quo*), total gross revenues and virtual exploitation costs (millions EUROs), versus mesh size at MSGR (maximum sustainable gross revenue) with fixed mesh size (policy P9).

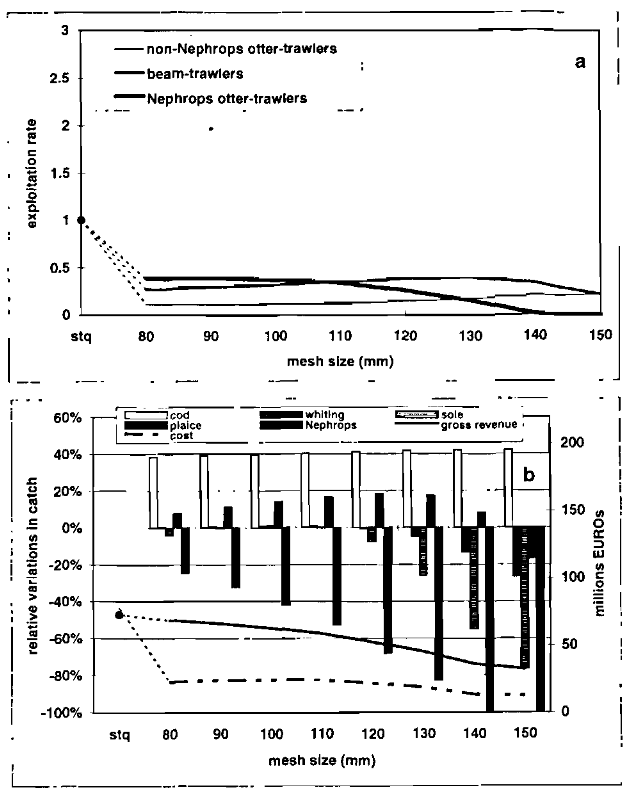

Figure 7. – a: Optimal exploitation rate by métier, relative to the *statu quo*, versus mesh size at MSNR (maximum sustainable net revenue) with fixed mesh size (policy P9). b: Percentage variation in catches by species (relative to the *statu quo*), total gross revenues and virtual exploitation costs (millions EUROs), versus mesh size at MSNR (maximum sustainable net revenue) with fixed mesh size (policy P9).

of global exploitation rate makes the net revenues steadily decrease when mesh size grows; zero-profit is reached when mesh size is 100 mm.

Figure 7a, b gives the optimal exploitation rates by métiers and catches in weight by species, relative to the *statu quo* option, for the MSNR option. Net revenues are maximized with the current 80 mm mesh size, but exploitation rates in métiers 1, 2 and 3 have to be decreased to 11, 27 and 39 % respectively. This level of exploitation enhances catches of severely overexploited species, such as cod (+ 38 %) but reduces catches of other species such as *Nephrops* (– 25 %). Gross revenues are lower with the MSNR objective (69 millions EUROs) than with the MSGR objective and the *statu quo* option but profitability (+ 46 millions EUROs) is much higher.

As mesh size is increased from 80 to 150 mm, the different curves of exploitation rate by métier follow different trends but they are always less than half of the current level. The pattern of exploitation is far away from the eumetric levels. As a result, catches of all species decrease when mesh size increases, except for cod, due to its particular eumetric curve. When mesh size increases from 80 to 150 mm, gross revenues drop dramatically from 69 to 32 millions EUROs, whereas total profit also decreases steadily from + 46 to + 20 millions EUROs.

DISCUSSION

This study provides several combinations of long-term objectives and management policies, expressed in terms of fishing effort and mesh size, that could be attained by the métiers fishing in the Celtic Sea, divisions VIIf and g. Managers and fishermen are likely to question, (i) whether the combination of policies and long-term objectives is practically relevant, (ii) how valid are the results, and (iii) how could the calculated long-term targets be reached.

Optimized gross revenues achieved with total flexibility in choosing exploitation rates and mesh sizes for each métier require unrealistic increases in fishing efforts and mesh sizes, compared with the *statu quo*. If a common optimal mesh size is required, it has to be increased to 114 mm, but whereas fishing effort is significantly increased in the *Nephrops* and flatfish métiers, the gadoid métier is almost eliminated. Similar results are found for maximizing relative MSY levels. Optimizing net revenues needs mesh sizes similar to those in current use but with exploitation rates of all métiers very reduced.

A common mesh size is an attractive option for managers and fishermen. If a common mesh size is imposed then maximizing gross or net revenues requires a mesh size close to that in current use. The European Council has already agreed to increase the minimum mesh size in the North Sea from 70 to 100 mm over 12 years (between 1980 and 1992) (Holden, 1994). Therefore, increasing mesh size from 80 to 114 mm (with the objective of maximizing gross revenues), or, *a fortiori*, holding it close to the current level (with the objective of maximizing net revenues) represent a realistic long-term target for the Celtic Sea fisheries. The different policies demand different changes in fishing effort, but in both policies, a dramatic reduction in effort for the gadoid fleet is required. To maximize profit, all fishing rates have to be significantly reduced, giving an estimated increase in profitability of about 50 millions EUROs per year.

The differences in results provided by the various policies and mesh selections emphasize the difficulties of extrapolation from the *statu quo*. Thus, it is assumed that the métiers will behave in a similar way to the present, so that the fishing strategies and the fleets selectivity will be constant over the years. In fact, as one species becomes relatively more abundant (*e.g.* whiting in *figure 5e*), fishing effort may shift towards areas where this species is predominant, or possibly from one métier to another. Thus, a gadoid fisherman would probably be reluctant in optimizing global gross revenues across all species and fleets, if this results in the elimination of his own métier. Such a fisherman would rather target *Nephrops* than being unemployed. Changes in fleets selectivity would also be brought about by more general use of square-mesh panels in the *Nephrops* fleet and separator trawls in the gadoid fleet.

Prices by weight of species have also been held constant. Due to sensitivity of prices to supply, this assumption is unlikely to be true. It has also been assumed that cost of exploitation is a function of fishing effort only. Costs of exploitation are dependent on many parameters such as vessel nationality, vessel sizes, distance to fishing grounds, size and remuneration of crew, the value of landings etc. so the modelling of costs with a function of fishing effort is only a very first approximation. A key assumption about the calculation of costs of exploitation was to assume that fisheries operate currently at about a zero-profit level. This is not unreasonable as the lack of expansion of the fleets suggests that current profits are low. However, if the current profits are much lower than zero, then the real costs of exploitation are likely to be much higher than the ones computed in this study. Hence, results dealing with the objective of maximizing net revenues may be affected. With the assumption of current zero-profit, net revenues are maximized when exploitation rates are low and mesh sizes are close to the current 80 mm level. Increasing costs of exploitation would drive optimal exploitation rates even closer to zero whereas optimal mesh sizes will still be 80 mm, since we assumed that mesh sizes will not be less than the current size. As a result, apart from the value of profit which is directly linked to the costs of exploitation, the results stemmed from the objective of maximizing net revenues will not be significantly affected by any increase in costs of exploitation. In particular, optimal exploitation rates and mesh sizes will remain low.

The enhancement of biomasses, in different proportions, may bring some unpredictable effects. Thus, increasing biomass of piscivorous species, may lead to more significant biological interactions. In particular, cod are known to prey on *Nephrops* in the Irish Sea (Brander and Bennett, 1986). Recent studies (DuBuit, 1995) have also shown some predation by cod on *Nephrops* in the Celtic Sea, although it is thought to be overestimated.

The main results brought by this study should be interpreted cautiously as they are based on first approximations. Nevertheless, the results provided are still useful for comparing various management objectives and policies. Moreover, many other mechanisms could easily be added to the model. On the socio-economic side, area- or season-specific catchabilities, exploitation costs, prices and price elasticity functions could easily be incorporated. Similarly, biological interactions and stock-recruitment relations could also be incorporated as knowledge increases. Nevertheless, the study describes the essential features of the multispecies and multi-métier Celtic Sea fisheries and it gives insight for the long-term consequences of possible targets for the fisheries.

The conclusions of this study are based on long-term equilibrium results, for a constant recruitment. However, once a long-term target is agreed, two essential problems will arise. The first issue is dealing with the practical implementation of the optimal exploitation rates for each métier. Solutions could be to implement fishing efforts either directly for each métier (Total Allowable Fishing Efforts), or through a global multispecies TAC (Fukuda, 1976).

The second and the more important issue is of how to get from the *statu quo* to the long-term target, and how to best manage the fisheries in the region of the target once achieved. Such an approach should account for the variable context of the fisheries and should address the short-term effects raised by the achievement of any long-term objective. For instance, parameters known for their high variability such as recruitment, which have been held constant to its historical average value in this study, should be more realistically modelled. This is a complex problem for modelling such fisheries, requiring a dynamic and stochastic approach, which will be addressed in a companion study.

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APPENDIX A

Biological model used in the multispecies multimétiers assessment

s	Species.
a	Age of species s.
N_a^s	Stock number of species s on age group a.
R^s	Recruitment for species s.
m	Métier.
$\mathcal{S}$	Total number of species.
$\mathcal{A}$	Total number of age groups for species s.
$\mathcal{M}$	Total number of métiers.
μ^m	Mesh size of trawling métier m (in mm).
$\underline{\mu}$	Column $\mathcal{M}$-vector, the m-th component of which is μ^m.
E^m	Exploitation rate for métier m, that is the fishing effort at equilibrium relative to the fishing effort in the year of reference. Note that $E^m = 1.0$ for *statu quo* option.
Z_a^s	Total mortality (y^{-1}) generated on age group a of species s.
M_a^s	Natural mortality (y^{-1}) generated on age group a of species s.
$F_{\mu^m,a}^{m,s}$	Fishing mortality (y^{-1}) generated on age group a of species s by métier m when mesh size μ^m and exploitation rate E^m are enforced.
$f_a^{m,s}$	Reference fishing mortality for age group a of species s caught by métier m.
$C_{\mu^m,a}^{m,s}$	Long-term equilibrium catches in weight (tonnes) for age a of species s, due to métier m.
$C_{\mu^m}^{m,s}$	Long-term equilibrium catches in weight (tonnes) of species s, due to métier m.
$C_{\underline{\mu}}^s$	Long-term equilibrium catches in weight (tonnes) of species s when mesh size $\underline{\mu}$ is applied.
$wc_a^{m,s}$	Weight in catch, by fish belonging to species s (kg) for age group a.
SSB^s	Long-term equilibrium spawning stock biomass (tonnes) for species s.
ws_a^s	Weight in stock, by fish belonging to species s (kg) for age group a.
pm_a^s	Proportion of fish, belonging to species s, sexually mature, for age group a.
$GS_{\mu^m,a}^{m,s}$	Age-dependant gear selection of métier m using mesh size μ^m, harvesting age group a of species s relative to the selection by the reference mesh size (80 mm). In particular, GS = 1.0 if the mesh size is unchanged or if the gear is irrelevant (longline, gill net, etc.). The way GS has been calculated for trawling métiers is depicted in appendix B.

The underlying biological model used in the study is a long-term equilibrium age-structured model:

$$\left.\begin{aligned} N_0^s &= R^s \\ &\dots \\ N_a^s &= N_{a-1}^s.\exp\left[-Z_{a-1}^s\right] \\ &\dots \\ N_{\mathcal{A}-1}^s &= N_{\mathcal{A}-2}^s.\exp\left[-Z_{\mathcal{A}-2}^s\right] \\ N_{\mathcal{A}}^s &= \frac{N_{\mathcal{A}-1}^s.\exp\left[-Z_{\mathcal{A}-1}^s\right]}{1-\exp\left[-Z_{\mathcal{A}}^s\right]} \end{aligned}\right\} \quad \text{(A.1)}$$

where:

$$Z_a^s = M_a^s + \sum_{m=1}^{\mathcal{M}} F_{\mu^m,a}^{m,s} \quad \text{(A.2)}$$

and

$$F_{\mu^m,a}^{m,s} = f_a^{m,s}.E^m.GS_{\mu^m,a}^{m,s} \quad \text{(A.3)}$$

Long-term equilibrium catches are calculated with:

$$C_{\mu^m,a}^{m,s} = \frac{F_{\mu^m,a}^{m,s}}{Z_a^s}[1-\exp(-Z_a^s)]wc_a^{m,s}.N_a^s \quad \text{(A.4)}$$

and

$$C_{\mu^m}^{ms} = \sum_{a=1}^{\mathcal{A}} C_{\mu^m,a}^{m,s} \quad \text{(A.5)}$$

and

$$C_{\underline{\mu}}^s = \sum_{m=1}^{\mathcal{M}} C_{\mu^m}^{m,s} \quad \text{(A.6)}$$

Long-term equilibrium SSBs are calculated with:

$$SSB^s = \sum_{a=1}^{\mathcal{A}} pm_a^s.ws_a^s.N_a^s \quad \text{(A.7)}$$

APPENDIX B

Calculation of the age-dependent gear selection relative to the reference mesh size for the trawling métiers, *e.g.* Macer (1982)

$\overline{L_a^s}$ (mm)	Average length for species s, belonging to age group a. $\overline{L_a^s}$ is deducted from Von Bertalanffy growth function, the parameters (K^s, t_0^s, L_∞^s) of which are given in *table 2*.
$\varphi_{\mu^m,a}^{m,s}$	Logistic function, giving the probability for species s, belonging to age group a and sizing $\overline{L_a^s}$ mm, to be caught by a gear, the mesh size of which is μ^m.
μ_0^m	Reference mesh size (i.e. mesh size enforced within reference period) for métier m. Actually, its value is 80 mm whatever the trawling métier.
$L50_{\mu^m}^{m,s}$ (mm)	Length at which 50 % of fish belonging to species s, are caught by a gear, the mesh size of which is μ^m.
$L75_{\mu^m}^{m,s} - L25_{\mu^m}^{m,s}$ (mm)	Selection range.
$SF^{m,s}$	Conventional selection factor.
$\delta^{m,s}$	Ratio between the selection range and the L50.

The age-dependant gear selectivity has the form:

$$GS_{\mu^m,a}^{m,s} = \frac{\varphi_{\mu^m,a}^{m,s}}{\varphi_{\mu_0^{m,s},a}^{m,s}} \tag{B.1}$$

where:

$$\varphi_{\mu^m,a}^{m,s} = \frac{1}{1+\exp\left[-\beta_{\mu^m}^{m,s}\left(\overline{L_a^s} - L50_{\mu^m}^{m,s}\right)\right]} \tag{B.2}$$

with

$$\beta_{\mu^m}^{m,s} = \frac{\ln(9)}{L75_{\mu^m}^{m,s} - L25_{\mu^m}^{m,s}} \tag{B.3}$$

and

$$L50_{\mu^m}^{m,s} = SF^{m,s}.\mu^m \tag{B.4}$$

and

$$L75_{\mu^m}^{m,s} - L25_{\mu^m}^{m,s} = \delta^{m,s} L50_{\mu^m}^{m,s} \tag{B.5}$$