ELSEVIER

Fisheries Research 58 (2002) 379–401

FISHERIES RESEARCH

www.elsevier.com/locate/fishres

A multi-species multi-fleet bioeconomic simulation model for the English Channel artisanal fisheries

Clara Ulrich[a,*], Bertrand Le Gallic[b], Matthew R. Dunn[c,1], Didier Gascuel[a]

[a]Laboratoire Halieutique, ENSAR, 65 Rue de St Brieuc, CS 84215, 35042 Rennes Cedex, France
[b]CEDEM, UBO, 12 Rue de Kergoat, BP 816, 29285 Brest Cedex, France
[c]CEMARE, University of Portsmouth, Locksway Road, Southsea PO4 8JF, UK

Received 5 October 2000; received in revised form 12 July 2001; accepted 20 August 2001

Abstract

Considering the large number of technical interactions between various fishing activities, the English Channel (ICES divisions VIId and VIIe) fisheries may be regarded as one large and diverse multi-country, multi-gear and multi-species artisanal fishery, although rarely studied as such. A whole-scale bioeconomic model has been constructed. It does not take into account biological interactions, but focuses on competition among fleets. A large amount of biological and economic data have been preliminarily gathered, leading to a substantial increase of the quantitative knowledge available. The main purpose of the model is to study the long-term consequences of various management alternatives on the economic situation of the English and French fleets fishing in the area and on exploited resources. The model describes this feature through the links between three entities on the one hand (stocks, fleets and ‘‘métiers’’, i.e. gear $\times$ target species $\times$ fishing area), and three modules on the other hand (activity, biological production and economics). The model is described and some simulation results are presented. An example simulating a decrease of one fleet segment effort illustrates these technical interactions among fleets and underlines the interest of a large-scale approach for these fisheries.

Keywords: Bioeconomic modelling; English Channel fisheries; Multi-species; Multi-fleet; Technical interactions; Simulation

1. Introduction

Although most fisheries involve many species, the biological advice is often provided on a single species basis. It is clear now that such single species assessments cannot provide relevant medium-term scientific advice in composite fisheries (Pope, 1991). In addition, most ICES stock assessments cover only managed stocks, which are not necessarily all of the important stocks in a region, and particularly in coastal fisheries. However, during the last decade, new trends in fisheries sciences focused on integrating various intrinsic relationships within and between the different components of the fishery, i.e. the resources and the fishers. These relationships may be biological, economic or social. Interactions may be of two types (Mesnil and Shepherd, 1990): the inter- and intra-specific biological interactions, such as predator–prey and competition relationships, and the technical, or technological, interactions. The main technical interactions are either ground interactions, where the presence of one fishing

* Corresponding author. Present address: Danish Institute of Fisheries Research, Charlottenlund Castle, 2920 Charlottenlund, Denmark. Tel.: +45-33-96-33-95; fax: +45-33-96-33-33.
E-mail address: clu@dfu.min.dk (C. Ulrich).
[1] Current address: CEFAS, Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK.

0165-7836/02/$ – see front matter
PII: S0165-7836(01)00393-9

unit displaces or interferes with another fishing unit's operation (e.g. Rijnsdorp et al., 2000), or resource interactions, where different fishing units are exploiting the same stock. In the latter case, where all fishing units are targeting the same stock, then their individual revenues are linked. However, if some units target a stock taken as a negligible bycatch, or even discarded by others, then the fishery may suffer a potentially important economic loss (Pascoe, 1997).

Considering the operational needs of fisheries management, the measurement of the technical interactions is of key importance (Mesnil and Shepherd, 1990; Laurec et al., 1991). It allows estimation of the positive or negative impacts of any management policy applied to one given part of the fishery (e.g. effort reduction of one single fleet, quota on one single species) on other related species and fleets, both in terms of catches and revenues. But these interactions are sometimes poorly understood, especially in some small-scale fisheries. Whilst a qualitative description in such fisheries may be available (e.g. Tétard et al., 1995), the interactions cannot be accurately quantified without an exhaustive study of all species and fishing activities involved in the whole fishery. Examples of the quantification of technical interactions are found in studies of monospecific sequential fisheries (Charles and Reed, 1985; Ye and Beddington, 1996), or in some rather complex industrial fisheries such as those in the Celtic Sea (Laurec et al., 1991). Such quantification may also be made using a versatile multi-fleet bioeconomic model (e.g. BEAM IV, Sparre and Willmann, 1993a,b). They all rely on a preliminary precise description and delineation of fishing activities. As such, the concept of the *métier* was advocated by EEC workshops in order to categorise the activities of the fishing fleets. A métier is usually defined by the use of a given fishing gear in a given area, in order to target a single species or group of species: e.g. inshore shrimp trawling, offshore flatfish trammel netting, etc. (Mesnil and Shepherd, 1990; Laurec et al., 1991). This concept brings more accurate description of the fishing activity than the single *gear* term. It is commonly used to describe the fishing effort in European waters (e.g. Marchal and Horwood, 1996; Biseau, 1998; Jabeur et al., 2000), although it is sometimes referred to as *trip type* or *fishing tactic* (Laloë and Samba, 1991). Definition and description of métiers are variable, depending on the fishery of interest, but in all cases, it is necessary to respect the rule of homogeneity assuming rigid interactions within a métier, and implying that two métier fishing units developed simultaneously induce the same fishing mortalities (Laurec et al., 1991). This often leads to the identification of a larger number of métiers than fishers usually do.

The problem of technical interactions advocated above is particularly important in the English Channel fisheries. From a biological, physical and human point of view, this area (ICES divisions VIId and VIIe, Fig. 1) may be considered as an open ecosystem for

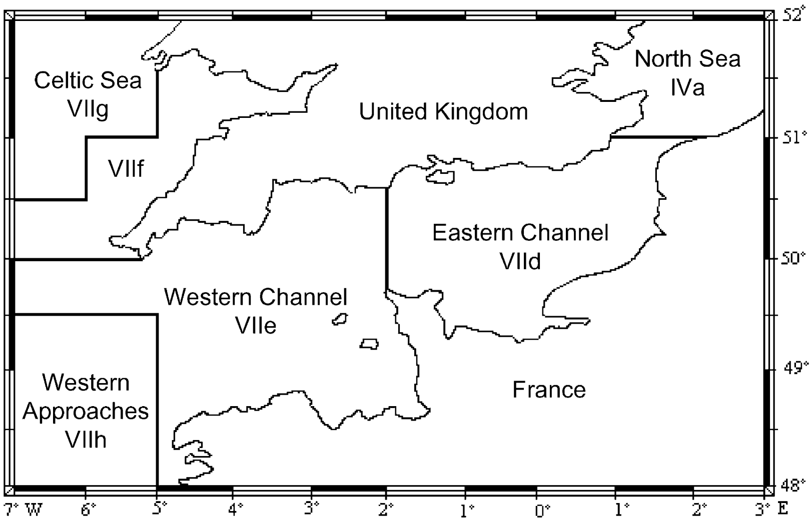

Fig. 1. The English Channel and adjacent seas.

exploited marine resources. A large number of species, mostly not managed by EU regulations, are either resident or seasonal visitors to the Channel, where they are opportunistically exploited by around 4000 boats from French and English fleets. The majority of these boats are small and work primarily inshore, where they engage in a variety of different activities and gears throughout the year. There is a high level of technical interaction between activities, which can be complementary or competitive. Because of this, the whole Channel can be regarded as a single multi-country, multi-activity and multi-species fishery, rather than a number of separate fisheries geographically co-located (with provision for some local activities targeting sedentary or semi-sedentary species). Whilst this makes intuitive sense, many previous studies have dealt with only a single species and/or fleet. A global approach is most often absent because it presents significant practical problems due to the collection, collation and common storage of a great deal of varied data, with the collaboration of biologists and economists usually from several nations.

A 3-year multi-disciplinary European-funded project has been conducted on the bioeconomic modelling of this fishery. A large amount of data has thus been gathered, representing an improvement without precedent of the current available data, and allowing identification of the major gaps existing in the knowledge of this fishery. Apart from their use in estimating the model input parameter values during reference years, these data are also useful to output relevant quantitative description of the current allocation of effort, production, revenue and costs among the various fleets, métiers and stocks. A bioeconomic simulation model has been developed. It focuses on the modelling of fleets activity and economic profitability in relation to technical interactions. Due to the low level of previously available and reliable data, the model, the first to be developed on this fishery, relies on rather simple assumptions and algorithms. However, its complexity arises from the large number and diversity of integrated resources and fleets. The model is not spatially explicit at this step of implementation so that the competition for fishing grounds is not investigated here, and only the competition on the resource has been taken into account. However, most métiers and many stocks are defined in relation to an area smaller than the whole Channel, allowing a more precise approach.

The model is designed to estimate and compare the long-term consequences of various effort management measures. This paper aims first to present the improvements made on the English Channel fisheries data and an updated description of these fisheries, and second, to present the modelling step and the model's usage, illustrated by some examples of effort management scenarios.

2. English Channel fisheries data

Available English, French and Belgian basic data, respectively, provided by CEFAS, IFREMER and FRS,[2] were the following: biological data by species (e.g. landings sampling), activity by boat, métier and month (from logbooks and surveys data), and effort and production (weight and value) by boat trip and species (from logbooks and auction files data). The allocation of each trip to a métier is based on aggregation thresholds initially proposed by Dintheer et al. (unpublished)[3] and revised to fit to newer data.

Definition of métiers within the English Channel fisheries were initiated by Tétard et al. (1995). When a métier is practised only within a part of the Channel, it is identified in relation to three geographical criteria (Eastern Channel/Western Channel; inshore/offshore; French coast/English coast), exception made to the particular area of Bay of St Brieuc (Western French coast), in which a specific dredging gear is used. In many cases, several groups of target species have been identified within a single combination of gear used and fishing area, and the métiers so defined are therefore fully named (e.g. UK west gadoids netting, French east shrimp trawling, etc.). In other cases, only one targeting strategy is identified in a given area using a given gear, or the métier is practised in the whole Channel. Métiers names are then shortened to their main characteristics (e.g. French offshore longlining, UK west inshore beam trawling, etc.) (Table 1).

[2] CEFAS: Centre for Environment, Fisheries and Aquatic Science, UK; IFREMER: Institut Français de Recherche pour l'Exploitation de la Mer, France; FRS: Fisheries Research Station, Belgium.

[3] Dintheer, C., Smith, M.T., De Clerck, R., Coppin, F., 1995. Base de données internationales en vue de l'évaluation biologique et économique des stocks de la Manche. BAHAMAS: Base Halieutique pour une Manche Stratifiée. Final Report of European Project BIOECO 93.018. IFREMER, France/MAFF-DFR, UK/RVZ, Belgium, 164 pp.

Table 1
Métiers definition: code, boats nationality, fishing area (ICES division: offshore and inshore refers to the 12 nm limit), gear and main target species

Code	Country operating	Fishing area	Gear	Target species
F1.1	France	VIIe offshore	Otter trawl	Groundfish, cuttle
F1.2	France	VIId offshore	Otter trawl	Groundfish, cuttle
F1.3	France	VIIe inshore	Otter trawl	Benthicfish, cuttle
F1.4	France	VIId inshore	Otter trawl	Flatfish, cuttle
F1.5	France	VIId	Otter trawl	Shrimp
F2.1	France	VIId + e	Beam trawl	Flatfish
F3.1	France	VIIe	Midwater trawl	Pelagic fish
F3.2	France	VIId	Midwater trawl	Pelagic fish
F4.0	France	Bay of St Brieuc	Dredge	Scallop
F4.1	France	VIIe (excl. St Brieuc)	Dredge	Scallop
F4.2	France	VIId	Dredge	Scallop
F4.3	France	VIIe	Dredge	Clams
F4.4	France	VIId	Dredge	Flatfish
F4.5	France	VIId	Dredge	Mussels
F5.1	France	VIIe offshore	Nets	Gadoids
F5.2	France	VIIe	Small mesh nets	Bass, pollack
F5.3	France	VIId + e	Large mesh nets	Benthicfish
F5.4	France	VIId inshore	Nets	Sole
F5.5	France	VIId inshore	Nets	Cod
F5.6	France	VIIe	Nets	Spider crab
F6.2	France	VIId + e	Pots	Large crustaceans
F6.3	France	VIId + e	Pots	Small crustaceans
F6.4	France	VIId + e	Pots	Whelk
F6.5	France	VIId + e	Pots	Cuttlefish
F7.1	France	VIId + e offshore	Long lines	Dogfish, conger
F7.2	France	VIId + e inshore	Long lines	Bass, conger, ling
F8.1	France	VIId + e	Hand lines	Bass, pollack
F9.1	France	VIId + e	Aquaculture	Miscellaneous
F9.3	France	VIIe	"Scoubidou" line	Seaweeds
U1.1	UK	VIIe	Otter trawl	Ground/flatfish
U1.2	UK	VIId	Otter trawl	Ground/flatfish
U2.1	UK	VIId offshore	Beam trawl	Benthicfish, cuttle
U2.2	UK	VIIe offshore	Beam trawl	Benthicfish, cuttle
U2.3	UK	VIId inshore	Beam trawl	Benthicfish, cuttle
U3.1	UK	VIIe	Midwater trawl	Pelagic fish
U3.2	UK	VIId	Midwater trawl	Pelagic fish
U4.1	UK	VIIe	Dredge	Scallop
U4.2	UK	VIId	Dredge	Scallop
U4.3	UK	VIId	Dredge	Oyster
U4.4	UK	VIId	Dredge	Clams
U5.1	UK	VIIe	Nets	Gadoids
U5.2	UK	VIIe	Nets	Bass
U5.3	UK	VIId	Nets	Bass
U5.4	UK	VIId	Trammel nets	Sole
U5.5	UK	VIId	Gillnets	Cod
U5.6	UK	VIIe	Nets	Hake
U5.7	UK	VIId + e	Large mesh nets	Groundfish
U5.8	UK	VIId + e	Dift nets	Bass
U5.9	UK	VIId	Gillnets	Flatfish
U6.1	UK	VIId + e offshore	Pots	Large crustaceans
U6.2	UK	VIId + e inshore	Pots	Large crustaceans
U6.3	UK	VIId + e	Pots	Whelk

Table 1 (*Continued*)

Code	Country operating	Fishing area	Gear	Target species
U7.1	UK	VIId	Longlines	Cod, dogfish
U7.2	UK	VIIe	Longlines	Ling, conger
U8.1	UK	VIId + e	Hand lines	Bass, mackerel
F_others	France	VIId + e	Miscellaneous	Miscellaneous
U_others	UK	VIId + e	Miscellaneous	Miscellaneous
B_others	Belgium	VIId + e	Miscellaneous	Miscellaneous

Individual boats have been gathered into fleets (Table 2). Each boat can only exist in a single fleet, but within the fleet it may engage in several métiers. All boats registered in French and English Channel maritime districts (not including Channel Islands boats) are included. The fleet definition was based on observed monthly patterns of activity for individual boats, recorded through exhaustive interviews on the French side, and through logbooks on the English side. For example, offshore beam trawlers often changed to scallop dredging, but did not engage in inshore netting or potting. Fleet definition was therefore largely a function of vessel design. Six theoretical external fleets (one per boat length class), describing the fishing time temporarily spent by non-Channel boats within Channel waters have also been defined.

Forty important commercial species, divided into 53 stocks and representing more than 85% of the recorded landings coming from the Channel (not including Channel Islands and Scottish fleets landings), have been recorded (Table 3). Similarly to métiers, stocks are defined either in the whole Channel area or in relation to a smaller distribution area (Eastern Channel/Western Channel; French coast/English coast; particular bays in the case of scallops stocks). Data for landings made by non-Channel fleets but within the Channel were also gathered, as well as landings and costs for the part of activity made by Channel fleets outside of the Channel. All data are aggregated by month, métier, stock, boat size, landing harbour, fishing area and boat maritime district. They are gathered into a single database, BAHAMAS (Dintheer et al., unpublished (see footnote 3); Ulrich, 2000),[4] which contains more than 800 000 records over the period 1993–1995. All métiers are recorded, but some are very little practised and have therefore only few records in the database (e.g. U5.6, U6.3, U7.1).

Almost no economic data on costs and revenues were previously available. Two economic surveys based on personal interviews, and with harmonised methodologies, have been worked out on both sides of the Channel to collect costs data by fleet and boat size class on an annual basis. Questionnaires dealt with information on the fishing level and behaviour of the fleet, as well as economic and financial information such as costs and earnings. A sample of 264 boat owners were interviewed on a stratified sampling basis, representing 7% of the whole Channel fleet. All fleets and size classes could be sampled, but practical difficulties led to some under-representation of the smallest boats (Boncoeur et al., 2000a).

One of the most characteristic features of English Channel fisheries is the heterogeneous amount of available data, and the low reliability of some of them, in particular for effort and production data. Most vessels (60%) are less than 10 m long, and are therefore not obligated to fill European logbooks. Thus all English boats <10 m were aggregated into two fleets (east and west), as their individual identities and activities could not be sufficiently determined from logbook data, and so the resulting mean activity pattern is not representative for individual boats. Most boats engage in several métiers within a month, and even often within a trip, and a relevant and reliable fishing effort unit cannot be easily defined. In many cases, landings are not sold through auctions and are consequently not recorded in official statistics. Some métiers have therefore very poor landings data. Le Pape and Vigneau (1998) developed a method for estimating monthly effort and landings by métier from interviews data, which could be used for four métiers (F1.2, F1.4, F4.2, F5.4), harvesting 15% of

[4] Channel data are available on the Internet at the URL: http://hal11.roazhon.inra.fr/projet. Username and password access may be requested from D. Gascuel (dgascuel@roazhon.inra.fr).

Table 2
Characteristics of Channel fleets, code, name, nationality, geographical origin, and nominal effort (number of boats and mean days at sea) by length class

Fleet code	Name	Country	Area	No. of boats by length class							Mean annual number of days at sea by length class						
				<7 m	7–10 m	10–12 m	12–16 m	16–20 m	>20 m	Total	<7 m	7–10 m	10–12 m	12–16 m	16–20 m	>20 m	Mean
FE_Ot	Otter trawlers	France	VIId		24	31	11	19	71	156		140	210	215	260	242	220
FW_Ot	Otter trawlers	France	VIIe	1		2	4	10	34	51	180		210	215	290	280	272
UC_Ot	Otter trawlers	UK	VIId + e			76	46	12	4	138			173	212	200	200	189
FE_Bt	Beam trawlers	France	VIId	4	38	35	8	1		86	180	167	200	215	250		186
UC_Bt	Beam trawlers	UK	VIId + e			21	10	3	108	142			130	174	205	236	215
FE_Ot_Dr	Trawlers–dredgers	France	VIId		11	42	80	30	5	168		167	200	210	230	280	210
FW_Ot_Dr	Trawlers–dredgers	France	VIIe		27	45	53	7		132		167	200	223	240		205
FE_Dr	Dredgers	France	VIId		8	6	14	8		36		167	190	190	140		174
FW_Dr	Dredgers	France	VIIe	20	121	58	16	2		217	180	193	203	210	215		196
UC_Dr	Dredgers	UK	VIId + e			14	21	3	7	45			224	230	234	251	232
FC_Pt	Potters	France	VIId + e	60	72	9	2	12	4	159	180	195	205	207	207	210	191
UC_Pt	Potters	UK	VIId + e			9	5	3	1	18			200	200	240	240	209
FE_Nt	Netters	France	VIId	6	45	41	19	4		115	180	200	220	230	240		212
FW_Nt	Netters	France	VIIe	11	11	9	19	7	0	57	110	120	130	145	160		133
FC_Ln	Liners–longliners	France	VIId + e	19	20			4	1	44	155	183			200	200	173
UE_Nt_Ln	Netters–liners	UK	VIId			19	3			22			147	258			162
UW_Nt_Ln	Netters–liners	UK	VIIe			55	18	23	8	104			157	228	170	180	174
FC_Wk	Whelkers	France	VIId + e	3	35	13				51	180	223	230				222
FC_Ms	Miscellaneous	France	VIId + e	74	32	7	8	5	1	127	155	183	197	200	204	220	170
FC_Sw	Seaweeders	France	VIId + e	2	37	17	3			59	136	136	136	136			136
FC_Fx	Other fixed gears	France	VIId + e	72	100	19	13	9	3	216	180	185	200	205	160	200	185
UE_under10 m	Under 10 m	UK	VIId	491	532					1023	82	129					106
UW_under10 m	Under 10 m	UK	VIIe	546	399					945	91	126					106
Total channel				1309	1512	528	353	162	247	4111	104	149	188	210	212	242	153
Ex_less7 m	External <7 m	France + UK	VIId + e	10						10	10						10
Ex_7–10 m	External 7–10 m	France + UK	VIId + e		34					34		34					34
Ex_10–12 m	External 10–12 m	France + UK	VIId + e			33				33			33				33
Ex_12–16 m	External 12–16 m	France + UK	VIId + e				25			25				25			25
Ex_16–20 m	External 16–20 m	France + UK	VIId + e					41		41					41		41
Ex_more20 m	External >20 m	France + UK	VIId + e						67	67						67	67

Table 3
Qualitative description of availability and reliability of biological data used in stocks assessment, and consequences for the choice of assessment method (see text for explanation)

Name		Data availability/reliability				No. of stocks in the Channel		Assessment method
English	Latin	Length samples	Age samples	Landings	Param. bio/age	Supposed	Evaluated	
Black bream	*Spondyliosoma cantharus*	x[a]	x	xx[b]	x	1	1	1
Pout	*Trisopterus luscus*	x	0[c]	xx	0	1	1	1
Brill	*Scophthalmus rhombus*	x	x	xx	x	1+	1	1
Bass	*Dicentrarchus labrax*	x	x	x	x	2	1	1
Cod	*Gadus morhua*	x	xx	xx	xx	2	2	2
Conger eel	*Conger conger*			xx			1	3
Pink shrimp	*Palaemon serratus*			0			1	3
Edible crab	*Cancer pagurus*	x		x			2	3
Brown	*Crangon crangon*			0			1	3
Crawfish	*Palinurus elephas*	0		x			1	3
Cuttlefish	*Sepia officinalis*	x		xx		1	1	3
Dab	*Limanda limanda*	x	x	xx	0	1	1	1
Dogfishes	*Scyliorhinus*, *Squalus*, etc.			xx			1	3
Spurdog	*Squalus acanthias*	0		xx		1	1	3
Red gurnard	*Aspitrigla cuculus*	x	x	x	x		1	1
Herring	*Clupea harengus*	xx	xx	xx	xx	2	2	1–2
Hake	*Merluccius merluccius*	x	0	xx	xx	1	1	2
Scad	*Trachrurus trachurus*			xx			1	3
John dory	*Zeus faber*	x		xx		1	1	3
Seaweed	*Laminaria* spp.			xx		1	1	3
Lobster	*Homarus gammarus*	x		x			2	3
Lemon sole	*Microstomus kitt*	xx	x	xx	0	1+	1	1
Ling	*Molva molva*	0	0	xx	0	1	1	1
Mackerel	*Scomber scombrus*	xx	xx	xx	xx	1	1	2
Megrim	*Lepidorhombus whiffiagoni*	xx	xx	xx	xx	1	1	2
Monkfish	*Lophuis piscatorius*	x		x	x	2	1	1
Red mullet	*Mullus surmuletus*	x		xx			1	3
Pilchard	*Sardina pilchardus*			xx			1	3
Plaice	*Pleuronectes platessa*	xx	xx	x	xx	2	2	2
Pollack	*Pollachius pollachius*	0	0	xx	0		1	1
Queens	*Chlamys* spp.			x			1	3
Scallop	*Pecten maximus*		xx	x	xx	6	6	1–3
Spider crab	*Maja squinado*	x		0			2	3
Skates	*Raja* spp.			xx		1	1	3
Sole	*Solea solea*	xx	xx	x	xx	2	2	2
Squid	*Loligo* spp.			xx			1	3
Turbot	*S. maximus*	x	x	xx	x	1+	1	1
Whelk	*Buccinum undatum*		0	0	0	1+	1	1
Whiting	*Merlangius merlangus*	x	x	xx	xx	2	2	2

[a] Medium-scale samples; recently updated data.
[b] Large-scale samples; annually updated data.
[c] Sporadic samples; old data.

total landings. For the other métiers, an estimate has been set based on unpublished data and observations collected by IFREMER and CEFAS experts in the relevant fishery. This had to be made for French landings of crustaceans and molluscs, and for French and English landings of bass (i.e. 14% of total landings). Data heterogeneity occurs also for biological data (Table 3). Some stocks are studied and assessed by ICES working groups and/or are highly valuable, and improved biological data (growth, recruitment, maturity, etc.) are available (e.g. ICES, 1997a,b). Some stocks are less known, and little biological information is available, particularly on molluscs and crustaceans, which represent a major part of English Channel revenue (Pawson, 1995).

For all these reasons, data collection, collation, validation and sometimes re-estimation have been a significant part of the modelling process. No long relevant time series could have been made available for all stocks and métiers, thus restricting the fisheries modelling possibilities. At the time of modelling, validated biological, effort and production data (i.e. gathered, sorted, debugged, and checked by IFREMER and CEFAS biologists) covered the years 1993–1995 (Ulrich, 2000). The economic surveys, implemented between 1997 and 1998, estimated costs for the years 1996–1997 (Boncoeur et al., 2000a; Le Gallic, 2001).

3. Overview of the status of the English Channel fisheries

Along the Channel shore, 4111 boats have been estimated to be active (41% in France, 59% in the UK, Channel Islands excepted) and can be divided into six boat length classes and 23 French and English fleets. Fleets are engaging in 55 métiers. The main métiers, in terms of total yearly number of days fished, are métiers using fixed gears (potting and netting mostly) and inshore trawling (Fig. 2). These métiers are practised by a large number of small boats (69% of Channel boats are smaller than 10 m) throughout the year. In equivalent 12–16 m units, main métiers are almost only trawling and dredging métiers, practised by less numerous but much larger and more efficient boats. The fisheries produce around 230 000 t annually (71% by French boats, 28% by UK boats and 1% by Belgian boats), in value more than 300 MEuros. Boats catch either abundant but low-value species (e.g. seaweeds and small pelagics) or low-abundance but higher priced species (e.g. flatfishes and crustaceans, Fig. 3). Apart from the French seaweeders fleet (FC_Sw), which is a small and very specialised fleet of northern Brittany (north-western France) landing very large amounts of seaweeds (sold around 0.04 Euros/kg), the main landings (both in weight and in value) come from towing fleets (trawlers and dredgers, Fig. 4). The most important fleet is the French Eastern otter trawlers fleet (FE_Ot), which lands more than 16% of the total value, although it represents only 3.8% of the total number of boats. Non-Channel boats represent 12.7% of total production, which is landed both in Channel and non-Channel harbours.

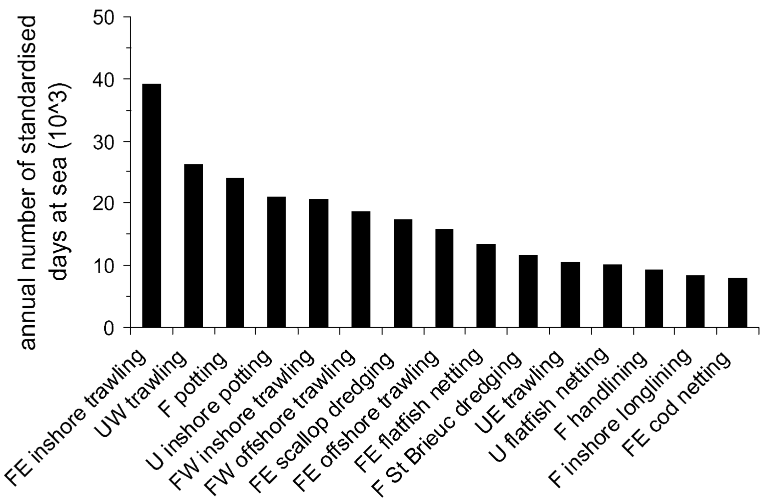

Fig. 2. Nominal annual effort by métier in the English Channel, in standardised days at sea (equivalent 12–16 m boat day unit) for the first 15 métiers (mean 1993–1995). F: French; U: English; E: Eastern Channel (VIId); W: Western Channel (VIIe).

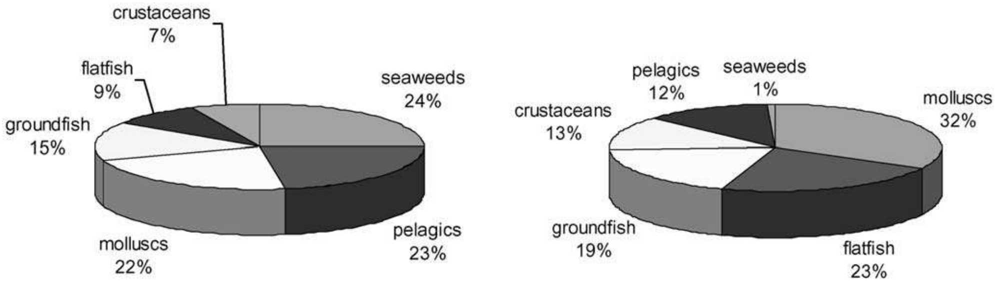

Fig. 3. Production by group of species in weight (left) and in value (right) (mean 1993–1995).

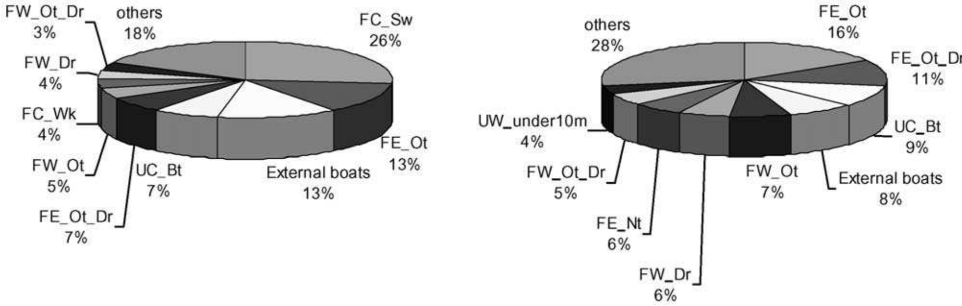

Fig. 4. Production by fleet in weight (left) and in value (right) (mean 1993–1995). Refer Table 2 for fleets name.

4. The English Channel bioeconomic model

The model used here is the model BECHAMEL (BioEconomic CHAnnel ModEL, Ulrich et al., 1999; Ulrich, 2000; Pascoe, unpublished[5]).[6] It is a static multi-species multi-fleet equilibrium model, composed of three main components: a fishing effort component, a biological component and an economic component. The cornerstone of the model is the métier, which is both linked to the fleet through an activity pattern matrix (expressing the percentage of total annual effort spent by each fleet in each métier) and to the stocks through an exploitation pattern matrix. The activity matrix is estimated from the French monthly surveys and English logbook data provided by IFREMER and CEFAS. It is the same within one fleet across all the boat length classes. The exploitation pattern matrix is expressed through the stock (or age class of a stock)-specific catchability coefficients for each métier. It is derived from the biological and effort model results.

The fishing effort component estimates the level of fishing effort by fleet, métier and boat length class, expressed in days at sea per year, and calculated from the number of boats, the mean number of days at sea per boat, and the activity matrix. Mean number of days at sea by fleet and length class is estimated from the outcomes of the economic surveys, for consistency purposes. The fishing effort is used in its nominal form by length class for the purposes of calculating variable costs and is standardised across length classes within a fleet using fishing powers (derived from observed differences in total catch per unit of nominal effort by métier between each length class and the standard length class). The standardised effort applied by a fleet is hence the sum across length classes of their nominal effort times their relative fishing power.

The biological component of the model calculates the expected yield for the given level of standardised effort, using model parameters derived from reference year data (1993–1995). Each stock caught in the

[5] Pascoe, S. (Ed.), 2000. Bioeconomic Modelling of the Fisheries of the English Channel. FAIR CT 96-1993, Final Report. CEMARE Research Report No. 53.

[6] URL model address is http://hal11.roazhon.inra.fr/projet/MODELE. Restricted access, see footnote 4.

Channel has a separate production–effort relationship. The 53 stocks (33 fish, 10 molluscs, 9 crustaceans, and seaweed) are included in the model. Four types of catch–effort relationships were developed in the model, depending on available data and on how production–effort functions were fitted (Tables 3 and 4). Twenty-seven stocks have been assessed using age-structured methods. Among these, 15 are distributed only within the Channel, and a usual cohort analysis has been used (Method 1). The 12 other stocks are spatially distributed both inside and outside of the Channel, and a specific assessment method, the In/Out method (Method 2) has been developed (Ulrich et al., 1998, 2000). Production functions for the age-structured stocks are calculated with the Thompson and Bell equation (1934). No such methods could be used for other 26 stocks (mostly molluscs and crustaceans), for which the biological knowledge is often poor and little production and effort data are available and reliable. For these stocks, an empirical surplus production model curve has thus been set (Method 3), based on estimated landings and an a priori hypothesis on the shape of the curve (either a Fox (1970) or a Scheafer (1954) curve equation). Given the large number of commercial stocks involved in Channel fisheries, details of stock assessments and parameters estimation are not fully presented here, but in Dunn (1999), Ulrich (2000), Le Gallic (2001), and Pascoe (unpublished).[5] Only a qualitative description of the availability and reliability of data usable in assessment (length and age samples, biological parameters at age, quality of landings data) and leading to the choice of the method used is summarised in Table 3.

The production by stock is allocated to each fleet and length class, proportionally to their own level of effort by métier. By using both age-structured and

Table 4
Classification of Channel stocks, regarding the assessment method used, and estimated mean landings (in tonnes) over the reference period (1993–1995)

Age-structured model stocks				Empirical surplus production model stocks (Method 3)			
Method 1, Channel stocks (15)		Method 2, In/Out stocks (12)		Fox model (23)		Schaefer model (3)	
Bass	1095	Cod VIId	2375	Brown shrimp	340	Crawfish	25
Brill	379	Cod VIIe	812	Conger eel	976	Queens	1510
Black bream	2218	Hake	436	Cuttlefish	10567	Skates spp.	3112
Dab	1031	Herring VIId	6650	Dogfish spp.	3199		
Herring VIIe	542	Mackerel	26260	Edible crab France	3622		
Lemon sole	1464	Megrim	446	Edible crab UK	4959		
Ling	1337	Plaice VIId	5270	John Dory	370		
Monkfish	2007	Plaice VIIe	1292	Lobster France	228		
Pollack	1935	Sole VIId	4515	Lobster UK	223		
Pout	4566	Sole VIIe	797	Other gurnards	1825		
Red gurnard	3417	Whiting VIId	5485	Pilchard	5588		
Scallop bay of Seine	5629	Whiting VIIe	2107	Pink shrimp	152		
Scallop bay of St Brieuc	4434			Red mullet	1005		
Turbot	423			Scad	11406		
Whelk	10260			Scallop bay of Brest	116		
				Scallop bay of Morlaix	125		
				Scallop other VIId	6672		
				Scallop other VIIe	9286		
				Seaweeds	58228		
				Spider crab France	5460		
				Spider crab UK	844		
				Spurdog	578		
				Squid	4063		
Total	40737		56445		129832		4647
%	17.6		24.4		56.0		2.0

surplus production methods, any commercial stocks participating in fishers revenue may be integrated in the general framework, whatever the level of knowledge is available. Similar methodology has been used previously for other multi-species bioeconomic modelling, e.g. in the Celtic Sea (Laurec et al., 1991). This model then estimates each stock production regarding each fleet and boat length class effort. Simulations are generally conducted under a constant activity pattern hypothesis, but changes in this pattern might be introduced also.

The economic component of the model is largely driven by the outputs from the effort and biological components. Just as the biological component transforms fishing effort into landings, the economic component transforms these landings into revenue, and fishing effort into costs. This requires estimates of prices and costs. For many species, landings from the English Channel fisheries have no noticeable influence on prices. Channel landings of these species generally represent only a small part of a well-integrated national or international market, and prices are thus treated as exogenous. This was the case for all UK species. However, there were a small number of French stocks (spider crab, scallops, brill, sole) whose prices show a significant flexibility to landings from the Channel (coefficient $(\partial P/\partial Y)\cdot(Y/P)$ significantly different from zero, CEDEM, unpublished), and which were thus considered sufficiently dependent on Channel landings to warrant an explicit equilibrium price–quantity relationship in the model. For these species, landings from the Channel represent a major part of the market and the prices are thus treated as endogenous variables, through a log–linear regression to landings. This neglects the cross-effects of price elasticity to demand. Such effects could be observed for some seafood products, but at a much larger-scale (Jaffry et al., 1997). In the Channel, the species with endogenous prices represent only 20% of the total value landed in the Channel between 1993 and 1995. This low percentage reflects the wide current internationalisation of seafood market (e.g. Ioannides and Whitmarsh, 1987; Gordon and Hannesson, 1996).

All cost parameters were calculated by fleet and boat length class from the results of economic surveys. Four types of costs were distinguished: (i) fixed costs, depending on the characteristics of the boat, irrespective of its level of activity and distribution of total activity between various métiers (cash costs—insurance, licences, boat maintenance—and non cash costs—depreciation and opportunity costs); (ii) métier variable costs, depending on boat activity (number of days at sea) in each métier (e.g. fuel, ice, bait, gear maintenance); (iii) landing taxes and other marketing costs, depending on revenue (gross sales); (iv) labour costs. In much of the English Channel, as in most small-scale or artisanal fisheries, crew members are rewarded through a share system. Crew members get a share of the balance from deducting the common costs (the costs of both the owner and the crew, although obviously the division may not be uniform) from the value of net sales (revenue minus landing taxes). The share system encourages and rewards harvesting efficiency and cost effectiveness, which makes the crew share somewhat different from a standard wage cost.

Once the costs are deducted from the revenue, it is then possible to measure various economic indicators describing profit and income (Boncoeur et al., 2000a). Mathematical specifications of the model are described in Appendix A.

5. Effort variation simulations

Various levels of total effort E are simulated in order to output long-term diagnostics under constant activity and exploitation patterns assumption. Effort is expressed in relation to the mean observed effort over the period 1993–1995, as a multiplicator of effort mf ($\mathrm{mf} = E/E_{93-95}$). As catchability is assumed constant, mf is similarly used to estimate the level of simulated fishing mortality coefficient by age F_a ($F_a = \mathrm{mf}\, F_{a,93-95}$). This classical approach (e.g. Gascuel and Ménard, 1997) shows the long-term trends of outputs of interest at the whole Channel scale, when the total effort level varies. Fully external stocks (stocks mainly distributed outside of the Channel, such as whiting or hake for instance) are not included in this diagnosis, as their total fishing mortality relies little on Channel effort. For these stocks, production is almost proportional to Channel effort.

Effort reductions are also simulated. In the fishing effort component, total effort reduction might be simulated by decreasing either the number of boats by fleet or the number of days fished annually, as can be expected from the Multi-annual Guidance Programs of the CFP (COM, 2000). Changes in effort allocation (decrease of the effort in a particular métier, or of the effort exerted on a particular stock) might be simulated by changing activity coefficients. Simulations are conducted with constant catchability coefficients. A variation in fishing effort then modifies the fishing mortality coefficients by the same proportion. It modifies also the effort costs (fixed and/or variable). Results presented here compare the variation of the total production, gross revenue (production × price) by fleet, gross margin (gross revenue minus landing taxes, variable costs, fixed cash costs and wage costs) by fleet (which can be considered as a fleet profitability indicator), and mean skipper–owner net revenue. This indicator has been chosen preferentially to the rate of return to capital, commonly used in economic studies (ratio of full equity profit, i.e. net margin, to the level of capital invested in the fishery), as an individual profit indicator. Because of the share-wage system particularities traditionally used in artisanal fisheries, the rate of return has not been considered as a relevant indicator, when comparing the relative rates of profit by size class and the fleet dynamics during the last decade (Boncoeur et al., 2000a). The skipper–owner net revenue has therefore been considered as a more relevant indicator. It is equal to the full equity profit plus his own wage as a crew share, and minus the opportunity costs of capital (measuring the fact that the money invested in the boat could have been invested elsewhere).

Two simulations are conducted here. They both measure changes of indicators when varying the effort of one single fleet. A typology of fleets based on their level of technical interactions with other fleets (Ulrich, 2000) showed that the most interacting fleet within the Channel is the French Western otter trawlers fleet (FW_Ot). Interactions occur both actively (the level of the mean revenue of all other fleets is strongly dependent on the level of effort of this fleet) and passively (its own level of revenue also depends on the mean level of effort of all other fleets). This fleet has therefore been chosen for the purpose of the simulation. It is comprised of 51 boats, 86% of them being longer than 16 m. Although its strength is low compared to the whole Channel fleet (1.2%), its fishing effort and landings are high (6.7% of the total Channel landings value, involving more than 40 valuable stocks). Simulations aim to compare externalities induced by two different effort measures. The first simulation (run 1) involves a decrease in the number of boats of the fleet. A reduction measure of 20% is applied to the FW_Ot largest boats class (i.e. boats longer than 20 m), which corresponds to a 13% decrease in the total fleet strength, and to 0.17% decrease of total Channel boats strength. The second simulation is a reduction in the number of days fished annually. Time at sea is similarly decreased by 20% in the fleet segment (run 2). From a biological point of view, both measures are equivalent, as only the total annual level of effort (number of boats × number of days at sea) is taken into account in the calculation of fishing effort, and therefore of production and revenue. Thus, only economic results are to be compared.

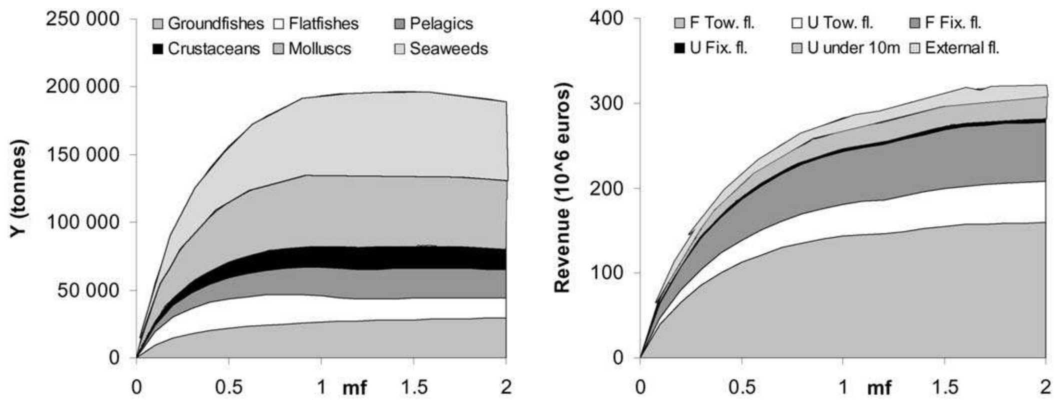

Fig. 5. Long-term results vs. level of effort, external stocks not included. Left: total production by biological group (tonnes). Right: gross revenue by fleet group (millions of Euros). F: French; U: English; Tow. fl.: towed gears fleets; fix. Fl.: fixed gears fleets.

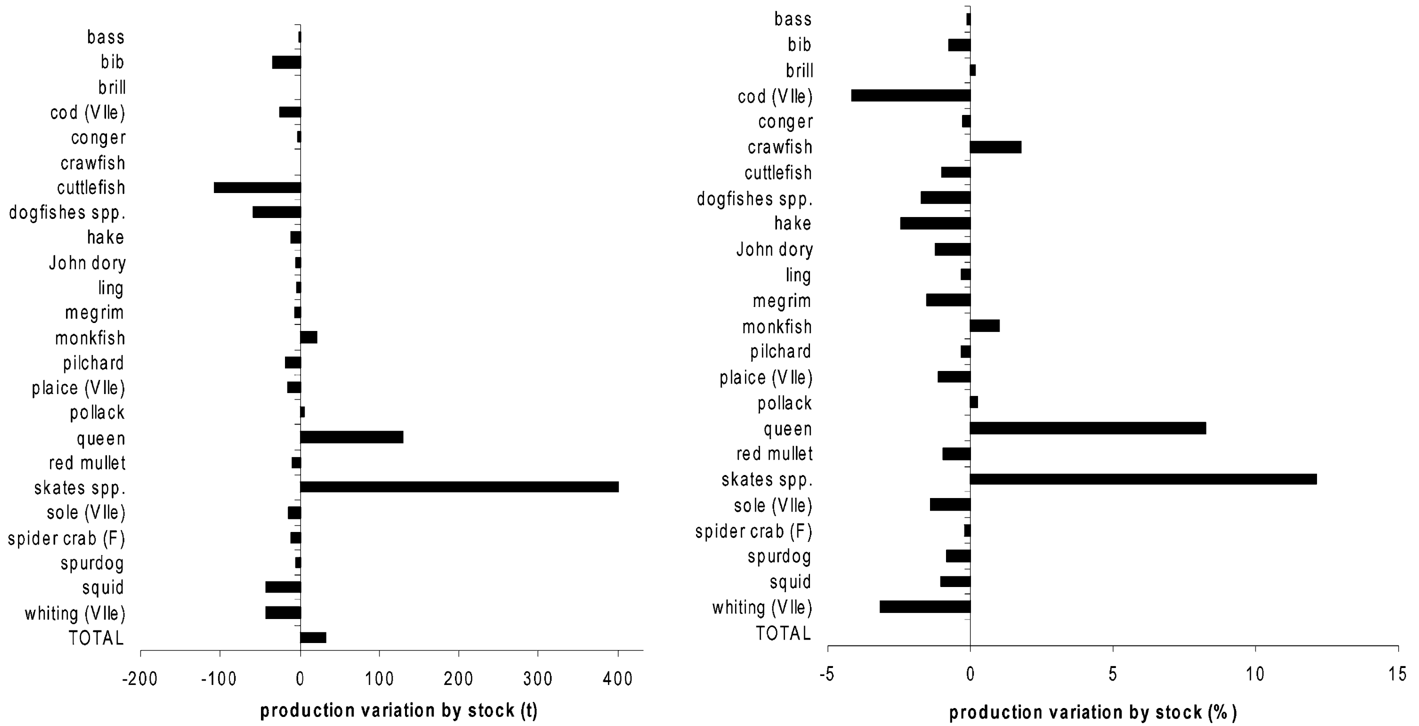

Fig. 6. Change in total annual long-term production for some stocks, following a 20% decrease of the French Western otter trawlers longer than 20 m nominal effort (days at sea reduction or number of boats reduction), in tons (left) and in percentage of the initial value (right).

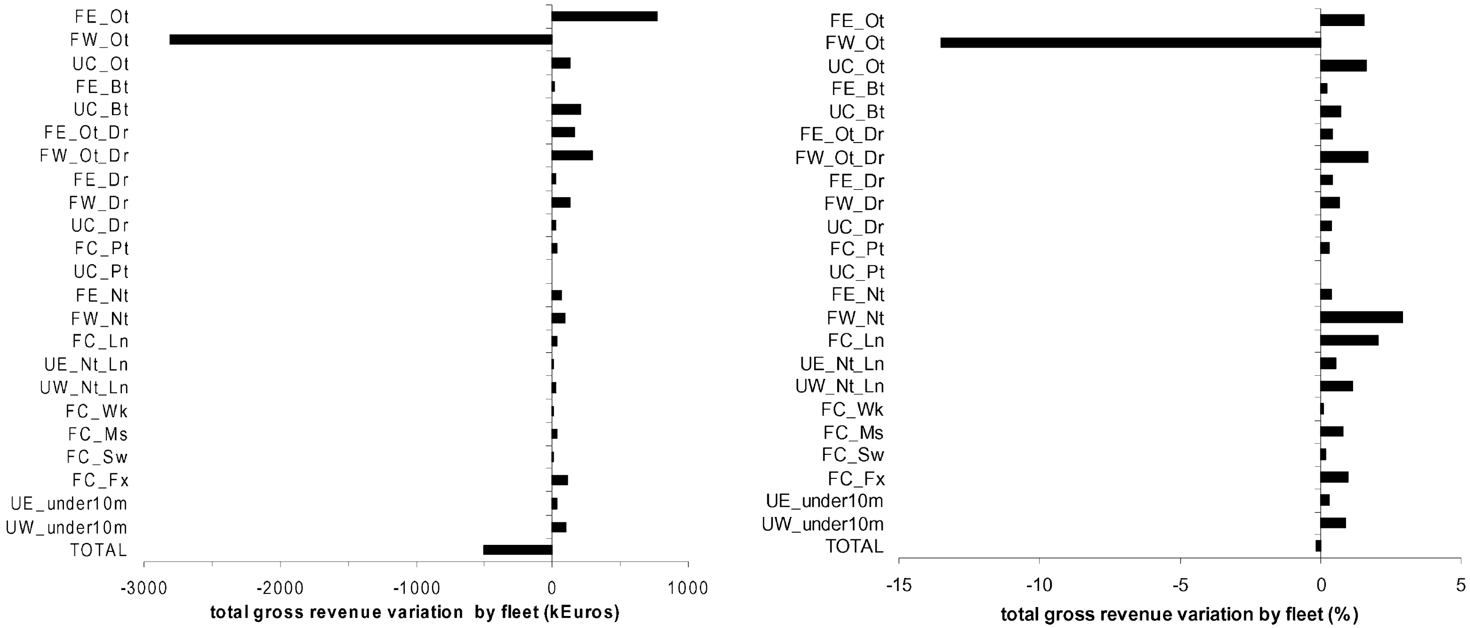

Fig. 7. Change in total annual long-term gross revenue by fleet following a 20% decrease of the French Western otter trawlers longer than 20 m nominal effort (days at sea reduction or number of boats reduction), in kEuros (left) and in percentage of the initial value (right). F: France; U: UK; W: West; E: East; C: Channel; Ot: Otter trawler; Bt: Beam trawler; Dr: Dredger; Pt: Potter; Nt: Netter; Ln: Liner; Wk: Whelker; Ms: Miscellaneous; Sw: Seaweeder; Fx: other fixed gears.

6. Long-term diagnostic

Multi-species biological and multi-fleet economic long-term diagnostics are set by collating each stock's production function, or each fleet's revenue function, respectively (Fig. 5). The whole fishery is considered as fully exploited and close to the MSY. The total production function is similar to a Fox surplus production function and total catches are stable when total effort varies around its current value $(mf = 1)$. Increase of groundfish production function is due to both underexploited bycatch stocks (dab, pout, dogfishes, red mullet), and partially external stocks (stocks for which a local and independent sub-population is presumed to exist within the Channel such as cod). On the other hand, most targeted groundfish stocks are overexploited.

Because of some price–quantity relationships set on some major stocks (e.g. sole and scallops), which lead to non-proportional variations of landings and revenues, and because of changes in relative catches of species with different prices, total revenue does not follow the same trend as total yield. It does not decrease when total effort increases. Half of total revenue is allocated to the French towing fleets (trawlers and dredgers) and all French fleets always account for more than 70% of total revenue. However, the main overexploited stocks are exploited by French fleets, and thus the relative part of the English fleet increases when total effort increases. External boats account for around 5% of total revenue.

7. Effort reduction simulation results

A 20% decrease of the FW_Ot largest boats's nominal effort (runs 1 and 2) does not have a significant effect on total catches (Fig. 6). The expected variation of production by stock depends on the current global level of exploitation and on the rate of total fishing mortality due to the French Western otter trawlers fleet. Most of the medium- to strongly-overexploited stocks ("Schaefer" stocks and some age-structured stocks such as monkfish and pollack) are commonly fished by this fleet (as target species or bycatch), and particularly skates and queens. An effort reduction of this fleet leads to an increase of the biomass and thus of the catches per unit of effort (CPUE). As the effort of other fleets remains constant, consequently their catches increase. Conversely, total catches decrease for under- and fully-exploited stocks ("Fox" stocks), and for external stocks.

Changes in economic results are also different for each fleet (Fig. 7). The total gross revenue (price $\times$ quantity) is not affected by this reduction (the expected loss of 500 kEuros represents 0.2% of the initial revenue and is not significant at this scale). French western otter trawlers total gross revenue (i.e. the sum of each boat's individual gross revenue) suffers an important loss, but smaller than the decrease of their effort (13.5%). On the other hand, almost all other fleets, which are not subject to this management measure, benefit from it and increase their gross revenue. Their revenue increase depends on their level

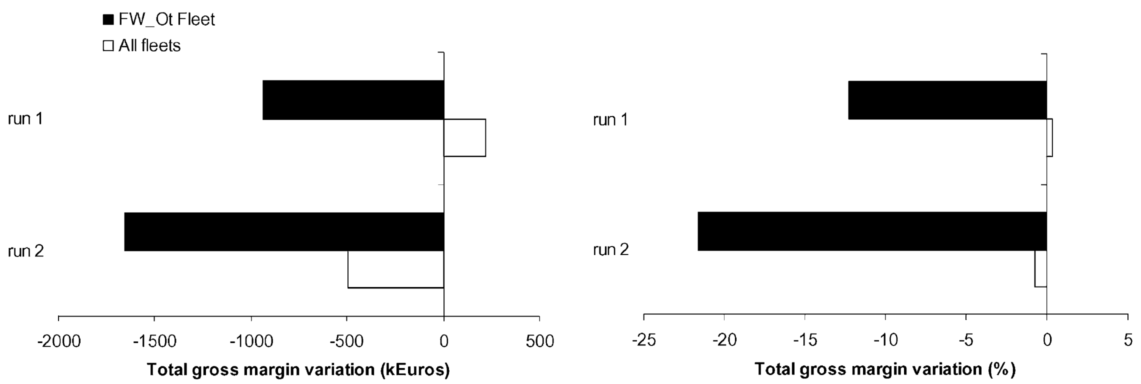

Fig. 8. Change in total annual long-term gross margin following a 20% decrease of the French Western otter trawlers longer than 20 m nominal effort, in kEuros (left) and in percentage of the initial value (right), for this fleet (black bars) and at the whole fishery scale (white bars). Run 1: number of boats reduction; run 2: number of days at sea reduction.

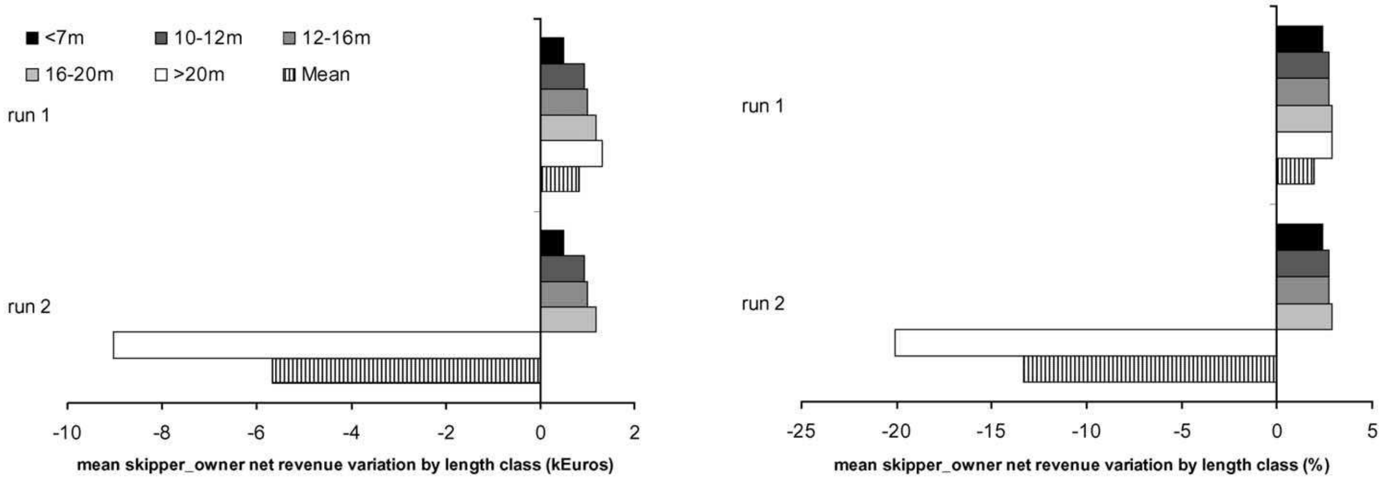

Fig. 9. Change in skipper–owner net revenue by boat length class for the French Western otter trawlers fleet, following a 20% decrease of this fleet's boats longer than 20 m nominal effort, in kEuros (left) and in percentage of the initial value (right). Run 1: number of boats reduction; run 2: number of days at sea reduction.

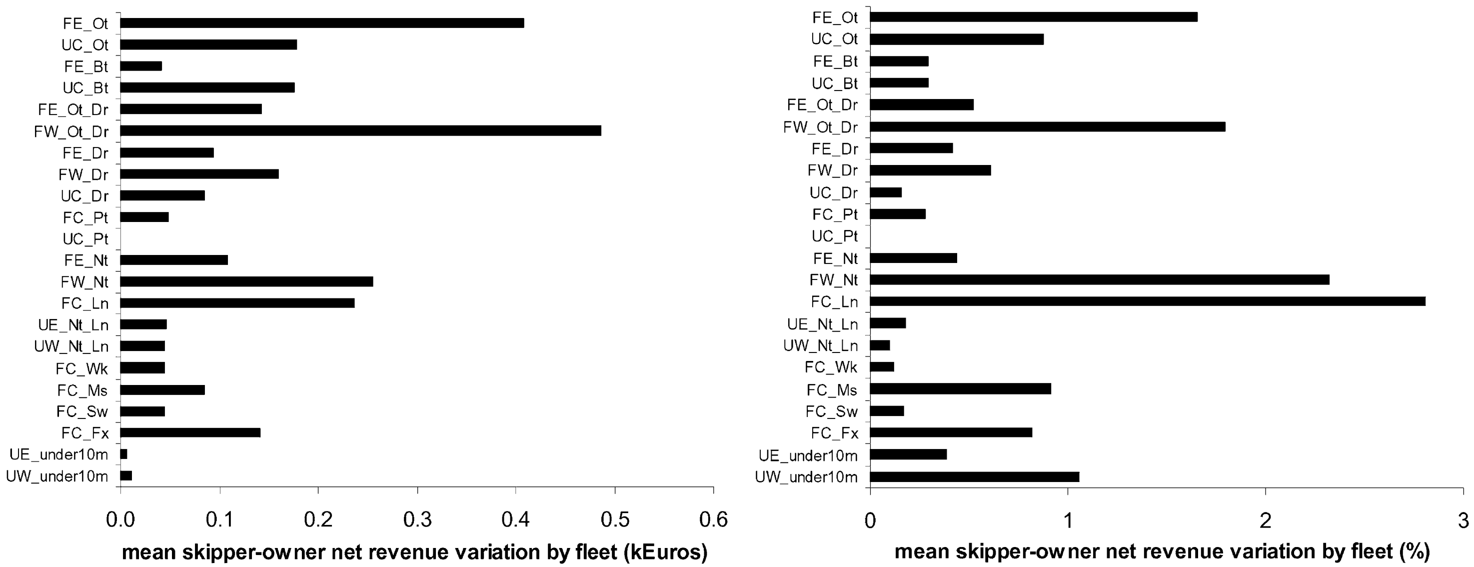

Fig. 10. Change in mean skipper–owner net revenue by fleet following a 20% decrease of the French Western otter trawlers longer than 20 m nominal effort (days at sea reduction or number of boats reduction), in kEuros (left) and in percentage of the initial value (right).

of technical interaction with the otter trawler fleet. The highest rates of increase occur for the most interacting fleets, i.e. the fleets which either engage in the same métiers (French western trawlers–dredgers) or target the same stocks (other otter trawling fleets, netters and liners). Independent fleets such as pots, whelk pots and seaweeds fleets do not obtain great revenue gains.

Both reduction measures do not have similar consequences on economic results (Figs. 8–10). When decreasing the number of boats, mean individual fixed and variables costs remain constant, whereas total fleet costs decrease. On the other hand, decreasing the individual number of annual days at sea only decreases the mean and total variable costs. Simulated effort reductions induce important loss for this fleet (Fig. 8). Total gross margin loss exceeds 900 kEuros in both runs. Decreasing the number of annual days at sea has the strongest impact on the fleet's economic results. The above-observed 13.5% decrease in revenue is slightly compensated by the decrease of total costs in run 1 (the gross margin only decreases by 12.3%). In the second simulation, total costs, although decreasing (due to a decrease of variable costs), remain high and the gross margin loss represents more than 20% of the initial value. However this fleet remains profitable, as its gross margin remains positive in both cases (6.7 and 6.01 MEuros in runs 1 and 2, respectively). At the whole Channel scale, both reduction measures do not have significant impact on the fishery results, as the variation, lower than 500 kEuros, represents less than 1% of variation.

This global economic loss of the fleet does not affect similarly all boat length classes (Fig. 9). All boats smaller than 20 m, that were not included in the reduction measure, get positive return from it. Similarly for other fleets, their effort remains constant during simulations, so that they take advantage from the long-term increase of biomass and CPUE following the decrease of total fishing effort for most stocks. The revenue and gross margin loss is then solely supported by the fleet segment to be managed, the boats longer than 20 m, either individually (run 1) or collectively (run 2).

Both measures have, as previously discussed, similar impacts on other fleets margin and profit (Fig. 10). The fleet's gross revenue increase induces a proportional increase of the mean crew wage, as more important as the fleet is more in interaction with the French Western otter trawlers fleet. In particular, the French Western netters fleet and the French liners–longliners, very sensitive to the trawlers fleets level of effort and whose economic performances are relatively low compared to other fleets, take great advantage to these effort reduction measures.

8. Discussion and conclusion

The long-term diagnostics results seem rather optimistic. This may partly be due to the assessment models used and to some basic hypotheses to parameterise them. However, this also makes intuitive sense. Channel fisheries mostly involve small-scale inshore boats, diversifying their activity on a large range of stocks (including a large number of sold bycatches), and allocating their effort depending on stocks sale price and abundance. Fishing pressure is different from an industrial offshore fishery targeting a small number of stocks and with little flexibility. Further, these results are consistent with results obtained on some other northern Atlantic areas, where most bycatch species are considered to be underexploited (e.g. Greenstreet and Rogers, 2000).

Other results underline the impact a management measure, dealing with one particular segment of the fishery, may have on other segments. Many similar simulations can be run with any other fleet, and may output similar results, more or less significant, depending on the level of interaction between the fleet and other fleets. In all cases, a decrease of a fleet fishing effort induces positive benefits to other fleets catching same stocks. Technical interactions are thus measured through the variation of biological or economic outputs of fleets of interest. Such simulations at the whole fishery scale lead to define classifications of fleets and métiers, based on their level of interactions (Ulrich, 2000). However, such simulations run for one fleet, with effort assumed constant for other fleets, are mostly useful to compare the relative level of interactions of different fleets, as it is likely that in reality the fishing effort in other fisheries will expand if a major fleet decreases.

A framework for examining technical interactions between fleets has thus been provided. Each single component of fisher's profitability is integrated in the general model. The complexity of the fishery and the diversity of stocks, fleets and fishing activities has lead to the development of a homogeneous framework, allowing the integration of any of these entities, whatever is the level of knowledge and data. This model is not the first large-scale bioeconomic model of composite and complex fisheries. A number of them have previously been implemented. Most deal with a particular case of study, e.g. the Barents Sea (Eide and Flateen, 1992), the Celtic Sea (Laurec et al., 1991), the Italian (Placenti et al., 1992) or Senegalese fisheries (Laloë and Samba, 1991). Some others are aimed to be more generic and versatile, and might theoretically be used for a large range of fisheries (e.g. GBFSM, Grant et al., 1981; BEAM IV, Sparre and Willmann, 1993a,b). The BECHAMEL model is based on the same principles as most of these, which all include simplifying assumptions. But its improvements are twofold: first, it represents the first attempt to model a fishery including so many different fleets, gears, species and life history characteristics, and with such a low level of previously available and reliable data. Second, it highlights the potential benefits of multi-disciplinary and international collaborative work. Most subcited models were implemented either by biologists or by economists only, leading to an unequal level of development and improvement of their various components. The Channel model was constructed with a link between the biology and economics being its core feature. By co-ordinating the data collection and analysis, it was possible here to develop a model that could accommodate both biological and economic considerations, on both sides of the Channel. It represents an improvement in the emerging knowledge on this fishing area without precedent. Considering the lack of global studies previously implemented in this area, the BECHAMEL model represents currently the best quantitative information available on this fishery. Furthermore, some particular questions have been investigated for the modelling purposes, like the problems of overlapping stocks (Ulrich et al., 1998), or seeking relevant economic indicators (Boncoeur et al., 2000a). An original and easy-to-use Internet interface has also been implemented, widely improving the possibilities of demonstration and utilisation of the model.

However, at this stage of implementation, it might not be directly used as an operational management tool. Parameter estimation remains uncertain for various inputs, and some basic hypotheses would deserve further validation. The model's complexity and interesting features arise rather from its whole-scale scope and its exhaustivity, than from its mathematical formalism, based on simple and usual algorithms. Because of their inshore and small-scale characteristics, English Channel fisheries are only partly subjected to EU quotas and effort regulations, and are therefore little studied and controlled. The resulting heterogeneous level of existing data prevents the use of improved assessment methods (as no relevant long catch effort time series exists for non-quotas species, for instance), and modelling abilities are limited by the less known elements of the fishery. The general model cannot be more precise as biological assessments are. The first step of the modelling process was then to construct a relevant database, whose data are summarised here. An increase of this fishery's quantitative knowledge can be derived only from a constant comparison between available data, which allow inputs parameterisation, and the modelling process, which in return points out main gaps and deficiencies which deserve particular scientific and administrative effort.

In particular, the model at this stage is only a static equilibrium and deterministic model. It is based on equilibrium equations leading to long-term (in the biological sense) production and profit estimations. It would deserve further simulations on short-term transition situations. Secondly, there is no attempt to model fleet behaviour and endogenous allocation of effort. In particular, there are no feedback relationships between the stock levels and the level of effort. Endogenous allocation of effort has been investigated, with the same model, from an optimal fleet structure point of view by Pascoe and Mardle (2001) in single- and multi-objective optimisation frameworks. In this paper, the main range of simulations deal rather with how a change in fishing effort may affect long-term production and profit rates, than the reverse. BECHAMEL is mostly adapted to simulate effort management measures, rather than quota, tax or price policies, as with some other multi-species multi-fleet bioeconomic models (e.g. Sparre and Willmann, 1993a,b; Overholtz et al., 1995), although some of these management measures may be approached (Ulrich, 2000). However, studies on fishing tactics and effort allocation are still under achievement. They may lead to relevant dynamic modelling of fleets, more appropriate to simulate outputs control measures. Neither is there any attempt to integrate biological relationships among species and discards behaviour. This latter point represents a major deficiency in studying technical interactions, as important economic externalities may arise from it (Boncoeur et al., 2000b). All of this leads us to consider this model rather as a comprehensive comparing tool, able to compare relative benefits of various management scenarios and to output qualitative knowledge on the fishery, than as a relevant predictive tool.

Acknowledgements

The development of the bioeconomic model of the Channel is part of the EU-funded project FAIR CT96/1993. It has involved collaboration between biologists from CEMARE (Centre for the Economics and Management of Aquatic Resources, Portsmouth, UK) and ENSAR (Ecole Nationale Supérieure Agronomique de Rennes, France) with the collaboration of IFREMER (Institut Français de Recherche pour l'Exploitation de la Mer, Brest, Port-en-Bessin and Boulogne, France), FRS (Fisheries Research Station, Oostende, Belgium) and CEFAS (Centre for Environment, Fisheries and Aquatic Science, Lowestoft, UK), and economists from CEMARE and CEDEM (Centre de Droit et d'Economie de la Mer, Brest, France). The authors would like to thank all their colleagues in this project who brought their data, knowledge and advice, and made the successful completion of the model possible. They also thank the two anonymous referees for their helpful and constructive comments.

Appendix A. Mathematical description of the model[7]

A.1. Effort and fishing mortality

Effort in each métier is estimated by

$$E_{m,c} = \sum_f \sum_g b_{f,g,c} d_{f,g,c} a_{f,m} \mathrm{fp}_{m,g} \tag{A.1}$$

where $E_{m,c}$ is the level of effective (standardised) effort expended in métier m by boats from country c, $b_{f,g,c}$ the number of boats in each sub-fleet f in size class g in country c, $d_{f,g,c}$ the average number of days fished by a boat in each sub-fleet by size class g, $a_{f,m}$ the proportion of time each sub-fleet spends in each métier m and $\mathrm{fp}_{m,g}$ the relative fishing power of a boat of a particular size g operating in a given métier m.

Fishing mortality of each species produced by the Channel fleet is estimated by

$$\mathrm{F1}^{(*)}_{s,a,c} = \sum_m \mathrm{q1}^{(*)}_{s,a,m} E_{m,c} \quad \text{for } s \in S^a \tag{A.2a}$$

$$\mathrm{F2}_{s,c} = \sum_m \mathrm{q2}_{s,m} E_{m,c} \quad \text{for } s \notin S^a \tag{A.2b}$$

where Eq. (A.2a) relates to species for which age-structured models are available (i.e. the set S^a, a subset of the full set of species S) and Eq. (A.2b) relates to species for which surplus production models are employed. The superscript '$*$' denotes the three fishing mortality classifications of age-structured species for the In/Out stock model (i.e. 1, 1a and 2—global fishing mortality, fishing mortality in the global stock from Channel catches and local fishing mortality—Ulrich et al., 1998, 2000). $\mathrm{F1}^{(*)}_{s,a,c}$ is the fishing mortality of age-structured species s at age a by country c and $\mathrm{F2}_{s,c}$ the fishing mortality of the surplus production species by country c; $\mathrm{q1}_{s,a,m}$ and $\mathrm{q2}_{s,m}$ are the catchability coefficients[8] for the different species in each métier m.

A number of external boats (i.e. boats that are from ports outside the Channel) also operate in the Channel for part of the year. These boats contribute to fishing mortality, and so they need to be taken into account in the estimation of total catch. The estimated fishing mortality produced by these boats was estimated by

$$\mathrm{F1}^{(*)\mathrm{ext}}_{s,a,c} = \sum_m \sum_g \mathrm{q1}^{(*)}_{s,a,m} b^{\mathrm{ext}}_{c,g} d^{\mathrm{ext}}_g a^{\mathrm{ext}}_{m,g} \mathrm{fp}^{\mathrm{ext}}_{m,g} \quad \text{for } s \in S^a \tag{A.3a}$$

$$\mathrm{F2}^{\mathrm{ext}}_{s,c} = \sum_m \sum_g \mathrm{q2}_{s,m} b^{\mathrm{ext}}_{c,g} d^{\mathrm{ext}}_g a^{\mathrm{ext}}_{m,g} \mathrm{fp}^{\mathrm{ext}}_{m,g} \quad \text{for } s \notin S^a \tag{A.3b}$$

The number of external boats ($b^{\mathrm{ext}}_{c,g}$) was assumed fixed in the model, resulting in a fixed level of fishing

[7] Variables are represented in upper case and parameters in lower case.

[8] These were derived for each métier on the basis of the estimated fishing mortality attributable to each métier for each species and the level of standardised effort applied to each métier (i.e. $q_{s,a,m} = F_{s,a,m}/E_m$).

mortality produced by these boats. The other parameters are similar to those described in Eq. (A.1).

Total mortality of each species is estimated by

$$\mathrm{TM1}_{s,a}^{(1)} = \sum_c \left[\mathrm{F1}_{s,a,c}^{(1)} + \mathrm{F1}_{s,a,c}^{(1)\mathrm{ext}}\right] + M_{s,a} + \sum_{\mathrm{om}} \mathrm{ofm1}_{s,a,\mathrm{om}}^{(1)} \quad \text{for } s \in S^a \tag{A.4a}$$

$$\mathrm{TM1}_{s,a}^{(1a)} = \sum_c \left[\mathrm{F1}_{s,a,c}^{(1a)} + \mathrm{F1}_{s,a,c}^{(1a)\mathrm{ext}}\right] + M_{s,a} + \mathrm{fm1}_{s,a}^{(1b)} + \sum_{\mathrm{om}} \mathrm{ofm1}_{s,a,\mathrm{om}}^{(1a)} \quad \text{for } s \in S^a \tag{A.4b}$$

$$\mathrm{TM1}_{s,a}^{(2)} = \sum_c \left[\mathrm{F1}_{s,a,c}^{(2)} + \mathrm{F1}_{s,a,c}^{(2)\mathrm{ext}}\right] + M_{s,a} + \sum_{\mathrm{om}} \mathrm{ofm1}_{s,a,\mathrm{om}}^{(2)} \quad \text{for } s \in S^a \tag{A.4c}$$

$$\mathrm{TM2}_s = \sum_c \left[\mathrm{F2}_{s,c} + \mathrm{F2}_{s,c}^{\mathrm{ext}}\right] + \sum_{\mathrm{om}} \mathrm{ofm2}_{s,\mathrm{om}} \quad \text{for } s \notin S^a \tag{A.4d}$$

where $\mathrm{TM1}_{s,a}^{(*)}$ and $\mathrm{TM2}_s$ are the total mortality of each species, $M_{s,a}$ the natural mortality for the age-structured species, and $\mathrm{ofm1}_{s,a,\mathrm{om}}^{(*)}$ and $\mathrm{ofm2}_{s,\mathrm{om}}$ are fishing mortality associated with other métiers not directly specified in the model.[9] This additional fishing mortality is assumed constant. Similarly, $\mathrm{fm1}_{s,a}^{(1b)}$ is a constant additional fishing mortality for the age-structured species whose stocks extend beyond the Channel.

A.2. Catch and landings

Catch of each species ($Y_{s,c}$) by the Channel fleet is estimated by

$$Y_{s,c}^{(*)} = n_s \left\{ \sum_{a=1}^{T-1} \left[\left(\prod_{i=0}^{a-1} \mathrm{e}^{-\mathrm{TM1}_{s,i}^{(*)}} \right) \frac{\mathrm{F1}_{s,a,c}^{(*)} w_{s,a}}{\mathrm{TM1}_{s,a}^{(*)}} \left(1 - \mathrm{e}^{-\mathrm{TM1}_{s,a}^{(*)}}\right) \right] + \left(\prod_{i=0}^{T-1} \mathrm{e}^{-\mathrm{TM1}_{s,i}^{(*)}} \right) \frac{\mathrm{F1}_{s,T,c}^{(*)} w_{s,T}}{\mathrm{TM1}_{s,T}^{(*)}} \right\} \quad \text{for } s \in S^a \tag{A.5a}$$

$$Y_{s,c} = \mathrm{F2}_{s,c} a_s \, \mathrm{e}^{b_s \mathrm{TM2}_s} \quad \text{for } s \notin S^a \tag{A.5b}$$

$$Y_{s,c} = \mathrm{F2}_{s,c}(a_s + b_s \, \mathrm{TM2}_s) \quad \text{for } s \notin S^a \tag{A.5c}$$

where n_s is the number of new recruits of each species to the fishery, and $w_{s,a}$ the average weight at age of each species. Eq. (A.5a) describes the generic catch–effort equation for age-structured species. For species that whole exist (or are assumed to exist) in the Channel, then $Y_{s,c} = Y_{s,c}^1$. The total catch for the age-structured species that are also caught outside the Channel is given by $Y_{s,c} = Y_{s,c}^1 + Y_{s,c}^{1a} + Y_{s,c}^2$ (see the description of the In/Out model in Ulrich et al., 1998).

Eq. (A.5b) is used for those species where a Fox surplus production model was determined most appropriate, and the third equation for those species best approximated by a Schaefer curve. Parameters are estimated from historic data. A similar set of catch equations are used to calculate catch of the external fleet by replacing the estimated fishing mortalities of the Channel fleet with those of the external fleet. The catches of both Channel and external fleets are combined to produce the total catch ($\mathrm{TC}_{s,c}$) of each species in the Channel by France and the UK.

A.3. Economic equations

Revenue of the Channel fleet is estimated by

$$R_c = \sum_s p_{s,c} Y_{s,c} \tag{A.6}$$

where $p_{s,c}$ is the price of species s in country c. The revenue of the external fleet operating in the Channel is estimated in a similar fashion, substituting the catch of the external fleet in the above equation.

Many of the Channel boats also fished outside of the Channel for a portion of the year. The revenue arising from this is estimated by

$$R_{c,\mathrm{ext}} = \sum_f \sum_g r_{f,g,c} b_{f,g,c} d_{f,g,c} a_{f,\mathrm{ext}} \tag{A.7}$$

where $r_{f,g,c}$ is the estimated average revenue per day from fishing outside of the Channel by boats in each sub-fleet by size class, and $a_{f,\mathrm{ext}}$ the proportion of time each sub-fleet spends operating in métiers outside the Channel.

Net revenue (NR_c) of the Channel fleet is estimated by

$$\mathrm{NR}_c = (R_c + R_{c,\mathrm{ext}})(1 - l_c) - \sum_f \sum_g b_{f,g,c} \left(\sum_m d_{f,g,c} a_{f,m} v_{f,g,m} \right) \tag{A.8}$$

[9] These were estimated as a residual after fishing mortality from all the activities incorporated into the model was deducted from total fishing mortality estimated using the stock assessment techniques. This was generally small in relation to total fishing morality.

where l_c is the average market levy paid in each country and $v_{f,g,m}$ the variable cost per day (trip cost) of the different boats associated with fishing in métier m.

The profit of the Channel fleet in each country is estimated by

$$P_c = \mathrm{NR}_c(1 - \mathrm{cs}_c) - \sum_f \sum_g b_{f,g,c} f_{f,g,c} \qquad (A.9)$$

where NR_c is the total net revenue in country c, cs_c the average crew share of net revenue, $b_{f,g,c}$ the number of boats in each sub-fleet f by size class g in each country c and $f_{f,g,c}$ are the fixed costs associated with each boat (including the non-cash costs such as depreciation and the opportunity cost of capital).

For most species, prices were assumed exogenous. However, for a small number of species on the French side of the Channel, a significant price–quantity relationship was found. For these species, prices are estimated in the model by

$$\ln(p_{s,c}) = \alpha_s \ln(Y_{s,c}) + \beta_s \qquad (A.10)$$

where $p_{s,c}$ is the annual average first sale price of fish of species s. Possible substitution effects between various species have not yet been considered.

The total employment in each country (excluding the external fleet) is estimated by

$$\mathrm{EM}_c = \sum_f \sum_g b_{f,g,c} \mathrm{cr}_{f,g,c} \qquad (A.11)$$

where EM_c is the total employment in the fishery in each country c and $\mathrm{cr}_{f,g,c}$ the average number of full-time equivalent crew (including skipper) employed on each boat.

References

Biseau, A., 1998. Definition of a directed fishing effort in a mixed species trawl fishery and its impact on stock assessments. Aquat. Living Resour. 11, 119–136.

Boncoeur, J., Coglan, L., Le Gallic, B., Pascoe, S., 2000a. On the (ir)relevance of rates of return measures of economic performance to small boats. Fish. Res. 49, 105–115.

Boncoeur, J., Fifas, S., Le Gallic, B., 2000b. Un modèle d'évaluation économique du coût social des rejets au sein d'une pêcherie complexe. Economie et Prévision 143–144, 185–199.

Charles, A.T., Reed, W.J., 1985. A bioeconomic analysis of sequential fisheries: competition, coexistence and optimal harvest allocation between inshore and offshore fleets. Can. J. Fish. Aquat. Sci. 42, 952–962.

COM, 2000. Annual Report from the Commission to the Council and the European Parliament on the Results of the Multi-annual Guidance Programmes for the Fishing Fleets at the End of 1999, Vol. 738. Commission of the European Communities, 43 pp.

Dunn, M.R., 1999. Exploitation of selected non-quota species in the English Channel. Ph.D. Thesis. University of Portsmouth, Southsea, UK.

Eide, A., Flateen, O., 1992. Bioeconomic multispecies modelling of the Barents Sea Fisheries. In: Antona, M., Catanzano, J., Sutinen, J.G. (Eds.), Proceedings of the Sixth Biennial Conference of the International Institute of Fisheries, Economics and Trade, Paris. IFREMER, pp. 183–196.

Fox, W.W.J., 1970. An exponential surplus-yield model for optimizing exploited fish populations. Trans. Am. Fish. Soc. 99, 80–88.

Gascuel, D., Ménard, F., 1997. Assessment of a multispecies fishery in Senegal, using production models and diversity indices. Aquat. Living Resour. 10, 281–288.

Gordon, D.V., Hannesson, R., 1996. On prices of fresh and frozen cod. Mar. Res. Econ. 11, 223–238.

Grant, W.E., Isakson, K.G., Griffin, W.L., 1981. A general bioeconomic simulation model for annual-crop fisheries. Ecol. Model. 13, 195–219.

Greenstreet, S.P.R., Rogers, S.I., 2000. Effects of fishing on non-target fish species. In: Kaiser, M.J., De Groot, S. (Eds.), Effects of Fishing on Non-target Species and Habitats. Biological, Conservation and Socio-economic Issues. Blackwell Scientific Publications, Oxford, pp. 217–250.

ICES, 1997a. Report of the working group on the assessment of southern shelf demersal stocks. ICES CM 1997/Assess: 5.

ICES, 1997b. Report of the working group on the assessment of demersal stocks in the North Sea and Skagerrak. ICES CM 1997/Assess: 6.

Ioannides, C., Whitmarsh, D., 1987. Price formation in fisheries. Mar. Pol. 11, 143–145.

Jabeur, C., Gobert, C., Missaoui, H., 2000. Typology of the small-scale fishing fleet in the gulf of Gabes (Tunisia). Aquat. Living Resour. 13, 421–428.

Jaffry, S., Pascoe, S., Robinson, C., 1997. Long run price flexibilities for high-valued species in the UK: a co-integration systems approach. In: Boncoeur, J., Boude, J.P. (Eds.), Proceedings of the Ninth Annual Conference of the European Association of Fisheries Economists. CEDEM, Université de Bretagne Occidentale, Brest/Département Halieutique, ENSAR, Rennes, pp. 334–348.

Laloë, F., Samba, A., 1991. A simulation model of artisanal fisheries of Senegal. ICES Mar. Sci. Symp. 193, 281–286.

Laurec, A., Biseau, A., Charuau, A., 1991. Modelling technical interactions. ICES Mar. Sci. Symp. 193, 225–236.

Le Gallic, B., 2001. Modélisation bioéconomique et gestion durable d'un système complexe de ressources communes renouvelables. Application au cas des pêcheries de la Manche. Thèse de Doctorat. Université de Bretagne Occidentale, Brest.

Le Pape, O., Vigneau, J., 1998. Influence of fishing vessels properties and polyvalence on their fishing capacity: interest for management measures. ICES CM 1999/T: 08.

Marchal, P., Horwood, J., 1996. Long-term targets for the Celtic Sea mixed-species multi-métiers fisheries. Aquat. Living Resour. 9, 81–84.

Mesnil, B., Shepherd, J.G., 1990. A hybrid age- and length-structured model for assessing regulatory measures in multiple-species, multiple-fleet fisheries. J. Cons. Int. Explor. Mer. 47 (2), 115–132.

Overholtz, W.J., Edwards, S.F., Brodziak, J.K.T., 1995. Effort control in the New England groundfish fishery: a bioeconomic perspective. Can. J. Fish. Aquat. Sci. 52, 1944–1957.

Pascoe, S., 1997. Bycatch management and the economics of discarding. FAO Fisheries Technical Paper 370. FAO, Rome, 137 pp.

Pascoe, S., Mardle, S., 2001. Optimal fleet size in the English Channel: a multi-objective programming approach. Eur. Rev. Agric. Econ. 28 (2), 161–183.

Pawson, M.G., 1995. Biogeographical identification of English Channel fish and shellfish stocks. MAFF Fisheries Research Technical Report 99. CEFAS, Lowestoft, 72 pp.

Placenti, V., Rizzo, G., Spagnolo, M., 1992. A bioeconomic model for the optimisation of a multi-species, multi-gear fishery: the Italian case. Mar. Res. Econ. 7 (4), 275–295.

Pope, J.G., 1991. The ICES multispecies assessment working group: evolution, insight, and future problems. ICES Mar. Sci. Symp. 193, 22–33.

Rijnsdorp, A.D., van Mourik Broekman, P.L., Visser, E.G., 2000. Competitive interactions among beam trawlers exploiting local patches of flatfish in the North Sea. ICES J. Mar. Sci. 57, 894–902.

Scheafer, M.B., 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. Bull. Inter-Am. Trop. Tuna Comm. 1, 25–56.

Sparre, P., Willmann, R., 1993a. Software for bio-economic analysis of fisheries. BEAM 4. Analytical Bio-economic Simulation of Space-structured Multispecies and Multi-fleet Fisheries. Vol. 1. Description of the Model. FAO Computerized Information Series (Fisheries) 3, 186 pp.

Sparre, P., Willmann, R., 1993b. Software for bio-economic analysis of fisheries. BEAM 4. Analytical Bio-economic Simulation of Space-structured Multispecies and Multi-fleet Fisheries. Vol. 2. User's Manual. FAO Computerized Information Series (Fisheries) 3, 46 pp.

Tétard, A., Boon, M., Bennett, D., Berthou, P., Bossy, S., Casey, J., De Clerck, R., Delpech, J.P., Dintheer, C., Giret, M., Large, P., Latrouite, D., Lemoine, M., Milner, R., Morizr, Y., Ozanne, S., Palmer, D., Pawson, M., Pickett, G., Vince, M., 1995. Catalogue international des activités des flottilles de la Manche: approche des interactions techniques. IFREMER, Brest, 337 pp.

Thompson, W.F., Bell, F.H., 1934. Biological statistics of the Pacific halibut fishery. 2. Effect of changes in intensity upon total yield and yield per unit of gear. Rep. Int. Fish. (Pacific Halibut) Comm. 8, 49.

Ulrich, C., 2000. Modélisation multi-flottilles et multi-métiers des pêcheries artisanales de la Manche. Evaluation plurispécifique des stocks, étude des interactions techniques et intégration dans la modélisation bioéconomique. Thèse de Doctorat. l'ENSAR, Rennes, 350 pp.

Ulrich, C., Gascuel, D., Maury, O., 1998. A proposal for stock assessment and management in mixed stock fisheries: the In/Out model. Application to the western English Channel cod. ICES CM 1998/AA: 11.

Ulrich, C., Le Gallic, B., Dunn, M.R., 1999. Bioeconomic modelling of English Channel fisheries and their technical interactions: presentation of the simulation model BECHAMEL (BioEconomic CHAnnel ModEL). ICES CM 1999/S: 04.

Ulrich, C., Gascuel, D., Bellail, R., 2000. Quantification de l'importance des stocks locaux dans la Manche: application du modèle In/Out à 7 stocks. In: Gascuel, D., Chavance, P., Bez, N., Biseau, A. (Eds.), Les Espaces de l'Halieutique. Proceedings of the Fourth Forum Halieumétrique, Rennes, June 29–July 1, 1999. Editions IRD, Collection Colloques et Séminaires, pp. 125–146.

Ye, Y., Beddington, J., 1996. Modelling interactions between inshore and offshore fisheries: the case of the East Chine Sea hairtail (*Trichirus haumela*) fishery. Fish. Res. 27, 153–177.