Impact of technological creep on fishing effort and fishing mortality, for a selection of European fleets

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Face-to-face interviews were conducted to identify the main changes in gear and vessel technology that may have improved the fishing efficiency of a number of French, Danish, and Basque fleets over the past few decades. Important changes include the gradual appearance of twin trawls (Danish and French trawlers) and trammel-nets (French gillnetters), and the increased polyvalence of Basque bottom trawlers. The results suggest that fishing effort descriptors that are not traditionally measured (gear type, groundrope type, length of net used per day, headline length, crew size, number of winch or net drums) may have a substantial impact on catch rates. Adjusting fishing effort using such descriptors may generally improve the relationship between fishing effort and fishing mortality.

Keywords: catch rate, fishing effort, fishing mortality, generalized linear models, groundrope, technological creep, twin trawls.

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Introduction

Commercial fishers continuously adapt their activities to prevailing conditions by changing the physical inputs of production (technological development) and the way these inputs are used to harvest target species (tactical adaptation). There is evidence that the efficiency of fishing vessels has increased through technological creep. Quantifying the importance of fishers' reactions relies on an ability to define appropriate standardized effort measures, which itself depends on the detail of data available on fishing effort. Fishing effort is traditionally estimated by combining available physical measurements of fishing capacity (fixed production inputs) and fishing activity (variable production inputs). Fishing capacity is frequently approached by some physical attribute of the operating vessel (engine power, gross tonnage), but is also dependent on other factors, including gear technology and on-board equipment, which are often ignored. The introduction of new gear and technology includes both larger marked technological investments (e.g. acoustic fish-finding equipment, electronic navigation tools) and smaller stepwise improvements to the gear (e.g. stronger netting, changes in the design of trawl panels), which in themselves do not result in marked changes in a vessel's capacity but in combination cause a noticeable increase in capacity over time. Fishing activity is typically estimated by the duration of fishing trips. Such a definition ignores factors that potentially may impact fishing pressure, including the number and the sizes of gear deployed, or the effective time used for fishing.

A number of studies have been carried out to evaluate time variations in fishing efficiency (Cook and Armstrong, 1985; Millischer *et al.*, 1999; Marchal *et al.*, 2001, 2002). However, those studies did not investigate the extent to which such variations could be attributed to the technological development of fishing fleets. A number of other studies aimed to gain more insight into the key processes of technological creep. Such investigations were often based on the analysis of variations in either catch per unit effort (cpue) or catch value per unit effort (vpue), or profit, using a variety of modelling approaches ranging from simple general linearized models (GLMs) (Robson, 1966; Gavaris, 1980; Kimura, 1981; Hilborn, 1985) to more complex stochastic production frontier (Pascoe *et al.*, 2001) or multi-output distance functions (Squires, 1987; Squires and Kirkley, 1996). However, the scope of such approaches was generally restricted by vessel information available from logbooks, which typically includes engine power, vessel length, and/or gross tonnage.

This study investigates the technological development of fishing vessels, with the general objective of refining measures of fishing capacity and fishing activity. New information on historical vessel and technological developments has been collected through harbour enquiries. The information on technological developments has been analysed to assess their importance in terms of the catching efficiency of fleets, using GLMs. The most important elements of technological development are then used to adjust fishing effort. Finally, the benefits of adjusting fishing

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effort will be evaluated by examining the relationship between fishing mortality and fishing effort, for the fleets and fish stocks under investigation. The case studies examined in this study are based on a selection of Danish, French, and Spanish fleets and on their main target species.

Material and methods

Data

Collection of data on the evolution of fishing effort was carried out between April and October 2004 for the French fleets, between March 2004 and April 2005 for the Danish fleets, and

Table 1. Variables describing vessel attributes collected during the harbour enquiries for the French and Danish fleets.

Type	Variable	Unit
General characteristics (hull, equipment)	Date of construction	DD/MM/YYYY
	Date of acquisition	DD/MM/YYYY
	Date of sale	DD/MM/YYYY or NA
	Overall length	m
	Tonnage	grt
	Main engine power	Hp
	Number of revolutions per minute	rpm
	Date of acquisition of engine	DD/MM/YYYY
	Maximum speed	Knots
	Bollard pull	Tonnes
	Crew size	Number
	Hull type (displacement, surfing, catamaran)	D/S/C
	Hull material (steel/aluminium/GRP/wood)	S/A/G/W
	Bulb	Yes/no
	Kort nozzle	Yes/no
	Storage room capacity	m^3
	Freezer room capacity	m^3
	Ice-making machine	Y/N
	Deck surface	m^2
	Variable pitch propeller	Yes/no
	Winch (or net hauler) capacity (power)	kW
	Winch (loading) capacity	m (of cable)
	Winch speed (or net hauler)	$m\ s^{-1}$ or rpm
	Number of winch drums	Number
	Number of net drums	Number
	Net-disentangling machine	Yes/no
	Net-washing machine	Yes/no
Electronics	GPS	Yes/no
	Facsimile	Yes/no
	Radar	Yes/no
	Shore/ship confidential communication	Yes/no
	Computer	Yes/no
	Charting software (dedicated plotter or computer)	Yes/no
	Number of sounders	Number
	Sounder 1 frequency	kHz
	Computer interface of sounder 1	Yes/no
	Sounder 2 frequency	kHz
	Computer interface of sounder 2	Yes/no
	Number of sonars	Number
	Sonar frequency	kHz
	Computer interface of sonar	Yes/no
Catch handling	Conveyor	Yes/no
	RSW system	Yes/no
	Container/Boxes on board	Yes/no
	Deck crane	Yes/no

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Table 2. Variables describing gear attributes collected during the harbour enquiries for the French and Danish fleets.

Type	Variable	Unit
All gears	Gear unit	
	Number of fishing trips per year	number
	Number of days per fishing trip	days
	Number of fishing days per fishing trip	days
Trawls	Number of warps	2, 3, or NA if not trawl
	Number of panels	2, 4, 6, or NA if not trawl
	Yarn material	
	Yarn diameter in codend	mm
	Vertical opening	m or NA if not trawl
	Horizontal opening	m or NA if not trawl
	Mesh size of codend	mm or NA if not trawl
	Mesh size of wings	mm or NA if not trawl
	Length of headline	m or NA if not trawl
	Length of groundrope	m or NA if not trawl
	Type of groundrope	
	Rigging	
	Scanmar sensors	Y/N or NA if not trawl
	Trawleye (or netsonde)	Y/N or NA if not trawl
	Number of otter boards	0, 2, 4, or NA if not trawl
	Weight of otter boards	kg or NA if not trawl
	Average trawling speed	knots or NA if not trawl
	Selectivity device	
	Volume of water filtered per time unit	$m^3 s^{-1}$
	Number of hauls per fishing day	number or NA if not trawl
	Mean duration of a haul	h or NA if not trawl
Nets	Number of panels	number
	Smallest stretched mesh size	mm or NA if not net
	Stretched mesh size of the external panel	mm or NA if not net
	Net material	
	Total length of net set per fishing trip	m or NA if not net
	Total length of net set per fishing day	m or NA if not net
	Total height of net	m or NA if not net
	Soak time of nets	h or NA if not net
Seines	Diameter of seine rope	mm or NA if not seine
	Length of seine rope	m or NA if not seine
	Number of panels	2, 4, 6, or NA if not seine
	Yarn material	
	Yarn diameter in codend	mm
	Vertical opening	m or NA if not seine
	Horizontal opening	m or NA if not seine
	Mesh size of codend	mm or NA if not seine
	Mesh size of wings	mm or NA if not seine
	Length of headline	m or NA if not seine
	Length of groundrope	m or NA if not seine
	Type of groundrope	
	Rigging	
	Tickler chain	Y/N or NA if not seine
	Selectivity device	
	Number of hauls per fishing day	number or NA if not seine
	Mean duration of one haul	h or NA if not seine

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Table 3. Details of the sampling procedure for the harbour enquiries for the French, Danish, and Basque fleets.

Country	Fleet	Population (2003)	Sample	Sampling rate (%)
France	Gillnetters	99	21	21
	Otter trawlers (12–16 m)	125	35	28
	Otter trawlers (16–20 m)	87	19	22
	Otter trawlers (20–24 m)	106	26	25
Denmark	Otter trawlers	531	76	14
	Gillnetters	459	36	8
	Danish seiners	81	8	10
Spain, Basque Country	Bottom trawlers, Ondarroa (20–30 m)	5	4	80
	Bottom trawlers, Ondarroa (30–40 m)	27	25	93
	Bottom trawlers, Pasaia (30–40 m)	9	9	100

between June 2003 and February 2005 for the Spanish fleets. In France, the survey was conducted by seven technicians who interviewed a pre-selected sample of fishers located on the English Channel and Atlantic coasts, from Dunkerque to Bayonne. In Denmark, the survey was conducted by student employees and aimed at complete geographical coverage within the three vessel groups: demersal trawlers, gillnetters, and Danish seiners. In Spain, the survey was conducted in two harbours of the Basque Country, Ondarroa and Pasaia.

Generally, the first contact with fishers was by telephone, by which an appointment was arranged after obtaining his consent to answer the questionnaire. Interviews lasted between 30 min and

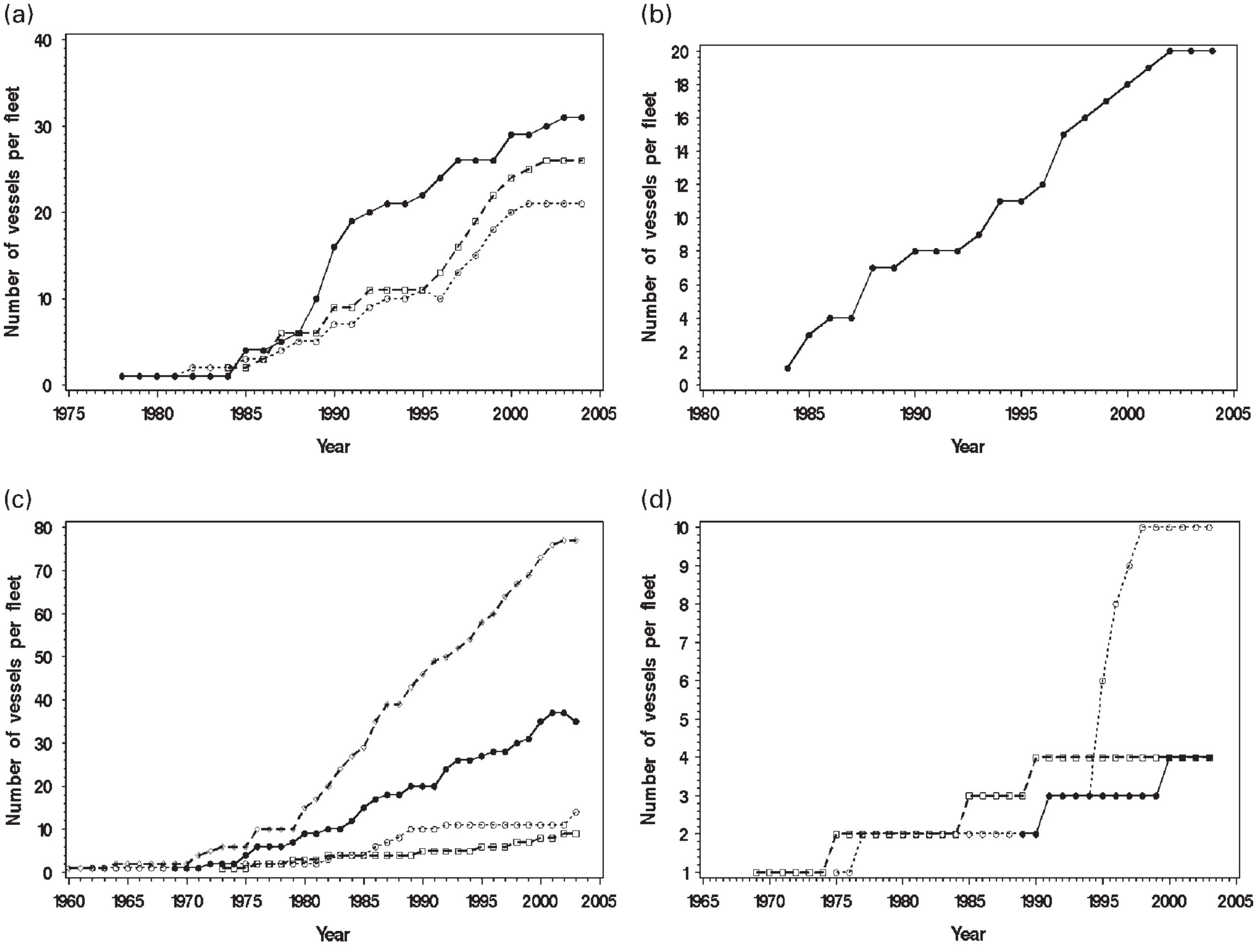

Figure 1. Number of vessels, by year, for which fishing effort data were recorded. (a) French otter trawlers (black dot, 12–16 m; circle, 16–20 m; square, 20–24 m), (b) French gillnetters, (c) Danish fleets (black dot, gillnetters; square, Danish seiners; diamond, trawlers; circle, others), and (d) Basque bottom trawlers (black dot, 20–30 m long registered in Ondarroa; circle, 30–40 m long registered in Ondarroa; square, 30–40 m long registered in Pasaia).

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1 h. On rare occasions, contacts and interviews were done on return of the vessel to harbour after a fishing trip. The questionnaires were divided into three main sections. The first part concerned the vessel owner surveyed, evolution of his career, of previously owned vessels, and the different métiers practiced since 1985. The second part concerned the current vessel owned, and the evolution of key variables such as hull, engine, deck equipment, electronics, handling, and conservation of catches on-board, crew size and, for trawlers only, electronic devices used for monitoring the gear. Finally, the questionnaire collected information on the fishing gears, their evolution, and the fishing effort deployed. The study builds on the technological data collected through the second and the third parts of the questionnaires. The key variables fishers were asked to document are listed in Tables 1 (vessel attributes) and 2 (gear attributes).

In France, the best questionnaire returns were achieved for vessels registered in Bay of Biscay harbours and belonging to four fleet segments. These fleets are otter trawlers (12–16 m, 16–20 m, and 20–24 m) targeting Norway lobster (*Nephrops norvegicus*) and hake (*Merluccius merluccius*), and gillnetters (>12 m) targeting sole (*Solea solea*), hake, and anglerfish (*Lophius* spp.). In Denmark and Spain, the questionnaires were designed in a manner similar to the French ones, but minor adjustments were made to accommodate differences in vessel characteristic and target species among the fleets and countries. In Denmark, the return quality of the questionnaires was best for Danish otter trawlers, and all subsequent analyses have been based on that vessel group. The main targets of Danish otter trawlers were cod (*Gadus morhua*), plaice (*Pleuronectes platessa*), and Norway lobster. In Spain, three Basque fleets were targeted: bottom trawlers of length 20–30 m registered in Ondarroa, bottom trawlers of length 30–40 m registered in Ondarroa, and bottom trawlers of length 30–40 m registered in Pasaia. The main target species of these three fleets were hake and anglerfish. However, as a consequence of relatively limited sampling during the surveys, the 20–30 m bottom trawlers registered in Ondarroa and the Pasaia bottom trawlers were excluded from further analyses. Table 3 and Figure 1 provide some details on sampling levels for the French, Danish, and Spanish fleets under investigation. Effort data for the French fleets could be traced back to the early 1980s, for the Spanish fleets to the early 1970s, and for the Danish fleets to the late 1950s.

In the fishing effort data set, each observation was a combination of one vessel and 1 year. A number of vessels used several gears during 1 year. For the French fleets, it was possible to identify which was the main gear used by each vessel throughout the year. For this fleet, therefore, the fishing-effort data set included the technological characteristics of both the fishing vessel and the

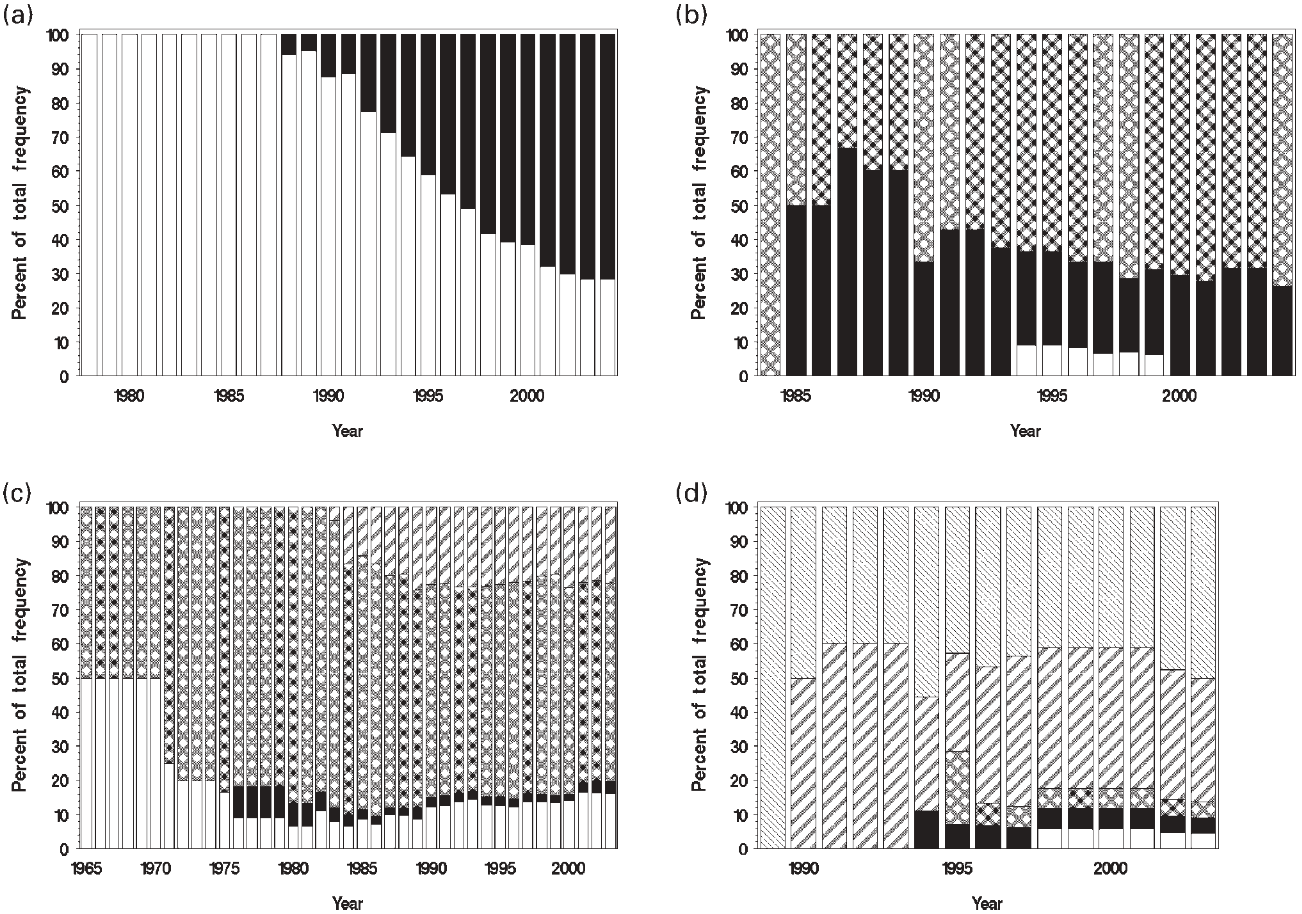

Figure 2. Annual changes in gear types for (a) French otter trawlers, all length classes (white, single otter trawls; black, twin trawls), (b) French gillnetters (white, drift nets; black, fixed nets; double-hatched, trammel-nets), (c) Danish otter trawlers (white, multi-rig trawls; black, pelagic trawls; double-hatched, single trawls; single-hatched, twin trawls), and (d) Basque bottom trawlers 30–40 m long registered in Ondarroa in 2003 (white, fixed nets; black, longlines; double-hatched, "Bou" otter trawls; thick single-hatched, single otter trawls; thin single-hatched, very high vertical opening bottom trawls).

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main gear used. For the Danish and the Basque fleets, it was not possible to determine the gear most used, so only the vessel characteristics were included in the fishing effort data set.

Landings in weight and value were extracted from Danish, French, and Spanish logbooks and sales slips databases for the period 1990–2003, for all vessels sampled during the harbour enquiries. Data were aggregated by vessel and year, then merged with the fishing-effort data set described above.

Total international landings and estimated fishing mortality (F) by stock were derived from ICES advisory documents (ICES, 2003). The stocks investigated are Celtic Sea and Bay of Biscay anglerfish, North Sea cod, northern hake, Bay of Biscay Norway lobster, Celtic Sea Norway lobster, North Sea plaice, Bay of Biscay sole, Celtic Sea sole, and North Sea sole. Separate estimates of F were available for the two anglerfish species (*L. budegassa* and *L. piscatorius*), so a combined anglerfish fishing mortality was calculated by averaging the landings-weighted F of each species.

Data exploration and modelling

The data collated during the enquiries were first examined to check for missing values. Poorly documented fishing effort descriptors were excluded from subsequent analyses. The annual trends in the remaining variables were then inspected visually. Special consideration was given to variables exhibiting substantial trends over the study period.

Catch rates (cpue), calculated for each vessel and each year, are modelled using GLMs (McCullagh and Nelder, 1989). Two models were considered. In model 1, the explained variable is cpue, which is assumed to follow a gamma distribution, and in model 2, the explained variable is ln(cpue), which is assumed to follow a normal distribution. To choose between these two models, the distribution of cpue was tested visually against a gamma distribution, using QQ plots, and the distribution of ln(cpue) was similarly tested against a normal distribution. The most appropriate combination of explained variable and probability distribution (cpue/gamma distribution, model type 1, or log-transformed cpue/normal distribution, model type 2) was selected. The link function was either Logarithm (model type 1) or Identity (model type 2).

The explanatory variables were year and the different descriptors of fishing effort. Some descriptors are discrete factors (e.g. gear unit), others are continuous variables (e.g. soak time). Assuming that technological creep is described by fishing effort variables, the "Year" effect may indicate annual abundance changes for the species (or combination of species) under

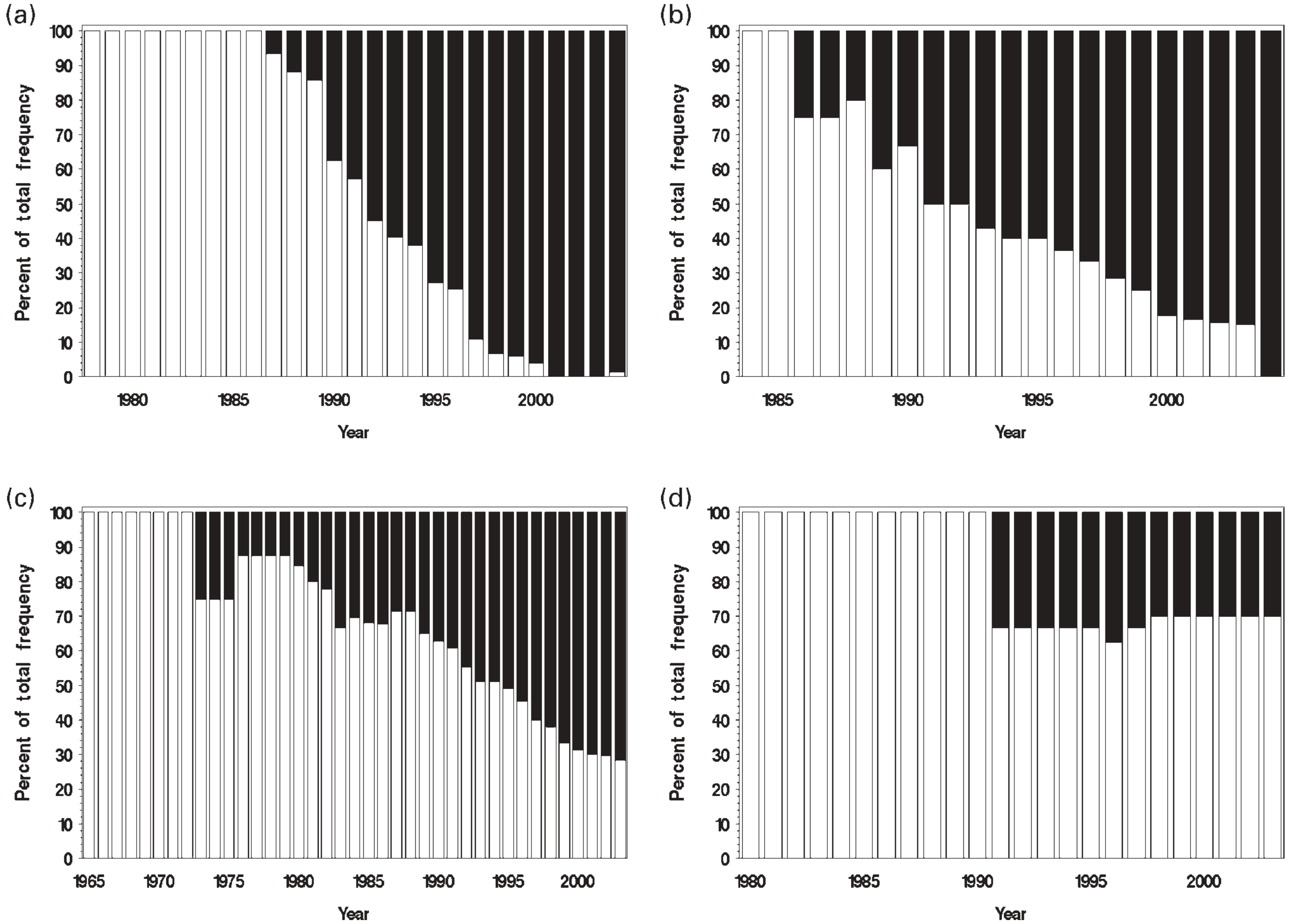

Figure 3. Annual changes in (a–c) GPS availability, and (d) computer availability for (a) French otter trawlers, all length classes combined, (b) French gillnetters (white, driftnets; black, fixed nets; double-hatched, trammel-nets), (c) Danish otter trawlers, and (d) Basque bottom trawlers 30–40 m long registered in Ondarroa. White bars represent the absence of electronic devices (GPS or computers) and black bars their presence.

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consideration. Each observation cell is a combination of vessel and year. A general formulation of the models is:

$$\text{Model 1:}\qquad \ln(\overline{\text{cpue}}) = \hat{\alpha} + \hat{\beta}_y + \hat{\varepsilon}_h + \sum_{k=1}^{NI} \hat{\theta}_k e_k \qquad \text{(1a)}$$

$$\text{Model 2:}\qquad \overline{\ln(\text{cpue})} = \hat{\alpha} + \hat{\beta}_y + \hat{\varepsilon}_h + \sum_{k=1}^{NI} \hat{\theta}_k e_k, \qquad \text{(1b)}$$

where α is the intercept, β the year effect, ε the effect of the discrete-effort descriptors, θ_k the regression coefficient associated with e_k, *NI* the number of fishing effort descriptors, and *e* the vector of the continuous fishing effort descriptors.

The model is preliminarily parameterized using the outcome of data exploration, which allows *a priori* selection of the most appropriate model (1 or 2). The model chosen was validated by reference to the residual plots resulting from the analysis. Residuals were plotted against predicted values and tested for normal distribution (QQ plot, Kolmogorov–Smirnov test). Once an appropriate model type (1 or 2) had been selected, the goodness-of-fit of the model was evaluated using the model's scaled deviance and Pearson chi-square, and two criteria, the Akaike Information Criterion (AIC) and the Schwarz Bayesian Information Criterion (BIC). If the selected model fitted the data reasonably well, the AIC and the BIC should be low. In addition, both scaled deviance and Pearson chi-square should have a chi-square distribution, with degrees of freedom (d.f.) equal to the number of observations minus the number of parameters estimated. It follows that the ratio between scaled deviance and degrees of freedom and that between Pearson chi-square and d.f. should be close to 1. Finally, only the most contributive explanatory variables were retained in the final model (Type III analysis).

Adjusting fishing effort and evaluating its benefits

The method used for this analysis was adapted from the traditional approach of Kimura (1981). The adjustment factors were the effects of the different variables characterizing fishing effort, estimated by either Equation (1a) or Equation (1b). If ε_* is the effect of the reference effort factor, the relationship between the adjusted (or effective) log of the fishing effort (ln E*e*) and the nominal (or untransformed) log fishing effort ln E*n* may be expressed as

$$\ln \mathrm{E}e_{v,y} = \ln \mathrm{E}n_{v,y} + (\hat{\varepsilon}_h - \hat{\varepsilon}*) + \sum_{k=1}^{NI} \hat{\theta}_k e_{k,v,i}. \qquad (2)$$

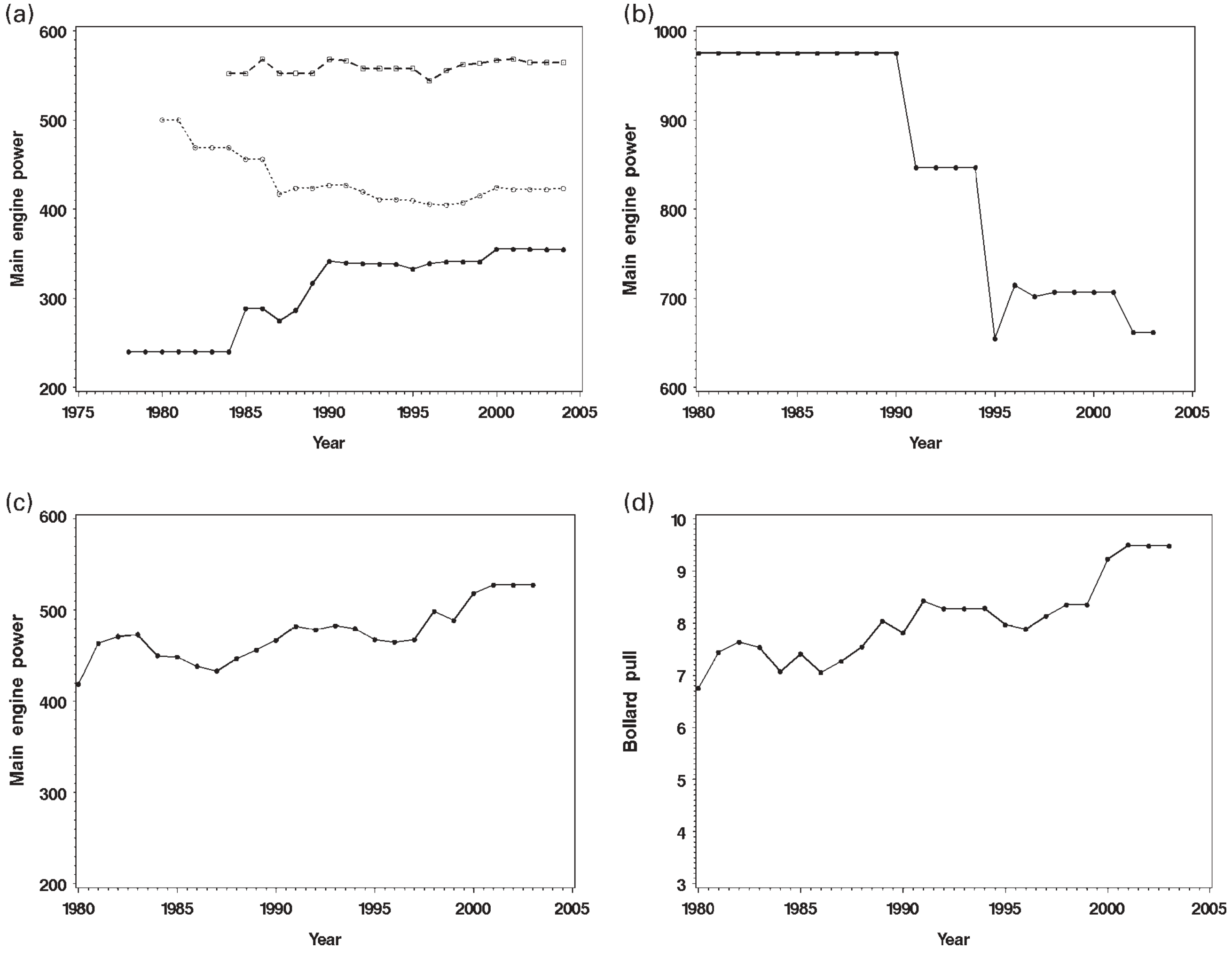

Figure 4. Annual changes in average (a–c) horse power, and (d) bollard pull (t) for (a) French otter trawlers (black dot, 12–16 m; circle, 16–20 m; square, 20–24 m), (b) Basque bottom trawlers 30–40 m long registered in Ondarroa, and (c and d) Danish otter trawlers.

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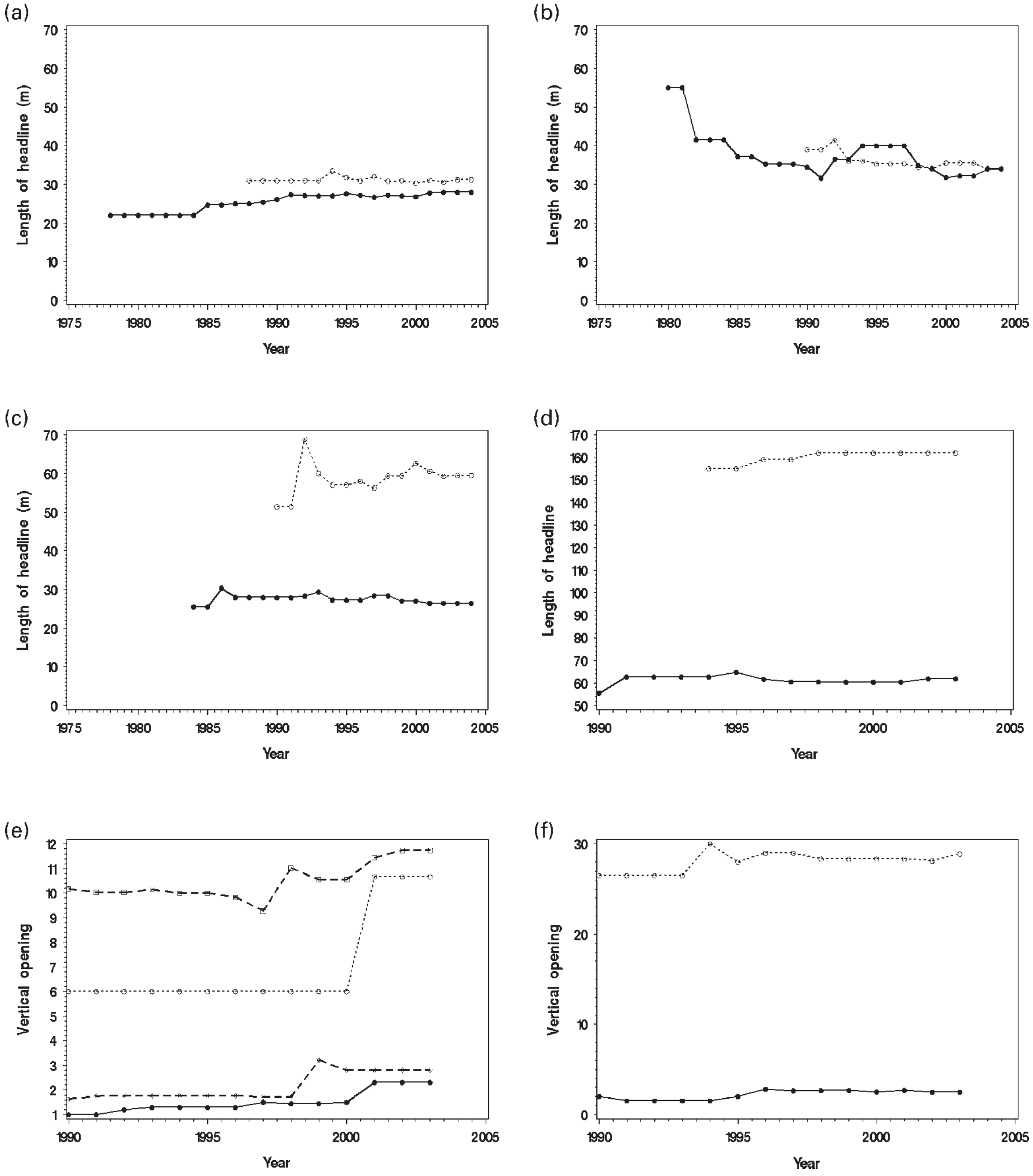

Figure 5. Annual changes in (a–d) headline length, and (e and f) vertical opening (m) for (a) French otter trawlers 12–16 m long (black dot, single trawls; circle, twin trawls), (b) French otter trawlers 16–20 m long (black dot, single trawls; circle, twin trawls), (c) French otter trawlers 20–24 m long (black dot, single trawls; circle, twin trawls), (d and f) Basque bottom trawlers 30–40 m long registered in Ondarroa (black dot, single trawls; circle, very high vertical opening trawls), and (e) Danish otter trawlers (black dot, multi-rig trawls; circle, pelagic trawls; square, single trawls; diamond, twin trawls).

Table 4. Summary of the results of the analysis of cpue by GLMs for French gillnetters targeting hake, sole, and anglerfish

Species	d.f.	SCC/d.f.	Gear type		Net length	Soak time	Vessel length
			GNS	GTR			
Hake	136	1.04	2.15	0.00	0.04	−0.05	0.001
Sole	113	1.04	−3.06	0.00	0.04	0.04	–
Anglerfish*	137	1.02	−0.78	0.00	–	–	–

The statistics include the degrees of freedom (d.f.), the ratio of the scaled Pearson chi-square to d.f. (SCC/d.f.), and the values of the coefficients associated with the significant fishing effort descriptors ($p < 0.05$). Gear types are fixed nets (GNS) or trammel-nets (GTR).

* indicates that the hypothesis that residuals are normally distributed is not rejected on the basis of a Kolmogorov–Smirnov test ($p < 0.05$).

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Table 5. Summary of the results of the analysis of cpue by GLMs for French otter trawlers targeting hake and Norway lobster.

Length (m)	Species	d.f.	SCC/d.f.	Gear type										Headline length	Towing speed	Haul duration	Computer		Vessel horse power
				OTB1	OTB3	OTB4	OTB5	OTB6	TTB1	TTB3	TTB4	TTB5	TTB6				Yes	No	
12–16	Norway lobster	176	1.14	1.23	0.48	0.33	1.22	1.30	1.55	0.32	1.85	0.92	0.00	0.03	–	–	–	–	–
	Hake*	176	1.15	0.11	0.16	1.03	0.51	0.58	−0.01	−0.42	0.19	−0.40	0.00	0.04	0.62	–	0.00	0.49	–
16–20	Norway lobster	107	1.18	0.38	−2.96	–	−0.23	–	−0.38	–	0.33	0.00	–	–	–	–	–	–	–
	Hake	96	1.24	0.53	1.67	–	0.37	–	0.46	–	1.24	0.00	–	0.04	1.29	–	0.00	0.44	−0.01
20–24	Norway lobster	88	1.22	−0.77	0.14	–	–	–	−0.65	0.38	–	0.00	–	–	–	−1.87	–	–	–
	Hake*	160	1.13	0.97	0.74	–	–	–	−0.53	−0.21	–	0.00	–	0.02	−0.56	0.23	–	–	–

The statistics include d.f., the ratio of the scaled Pearson chi-square to d.f. (SCC/d.f.), and the values of the coefficients associated with the significant fishing effort descriptors ($p < 0.05$). Gear types are single trawls (OTB) or twin trawls (TTB), combined with different groundropes: diabolo (1), chains (3), spheres (4), rubber (5), plain wire (6).

* indicates that the hypothesis that residuals are normally distributed is not rejected on the basis of a Kolmogorov–Smirnov test ($p < 0.05$).

The benefits of adjusting fishing effort were evaluated by scrutinizing the relationship between fishing mortality and fishing effort, effort being defined as either nominal or adjusted effort. Partial fishing mortality was calculated for each fishing vessel by weighting the total annual F using the ratio of the vessel's landings to the total international landings for the stock under consideration. The relationship between F and effort was examined for the main stocks harvested by the fleets under investigation, and for which a stock assessment was available. The linear regression between log-transformed F and effort was tested with effort defined as nominal or adjusted. The goodness-of-fit of the regression was appraised by (i) eyeballing the plots between $\ln(F)$ and ln(effort), (ii) comparing the values of r^2, and (iii) testing using the t-statistic the value of the regression slope, which should be close to 1 if regression model (2) is appropriate.

Implementation

As a consequence of data availability, analyses were restricted to four French fleets fishing in the Bay of Biscay (otter trawlers of lengths 12–16 m, 16–20 m, and 20–24 m, and gillnetters >12 m), one Danish fleet of otter trawlers, and one Basque fleet of bottom trawlers (30–40 m) registered in Ondarroa. The methods developed in this study were mainly implemented using the SAS/STAT (1999) procedure GENMOD.

Results

Data exploration

Gear types have varied considerably over time for most of the fleets under investigation (Figure 2). For the French (Figure 2a) and Danish trawlers (Figure 2c), the main feature was the emergence of twin trawls in the 1980s, which was associated with fishing for *Nephrops*. For French gillnetters (Figure 2b), the main feature was the increasing importance of trammel-nets for fishing sole. Trammel-nets have been the main gear since 1996. For Basque trawlers registered in Ondarroa of length 30–40 m (Figure 2d), the proportion of the two main gear types (single otter trawls and pair trawls with a very high vertical opening, VHVO) remained stable over the period 1990–2003, but since 1995, the fleet appeared to be increasingly polyvalent, as reflected by the emergence of another trawl type (the so-called "Bou" otter trawls) and the increasing use of static gears (fixed nets and longlines).

On-board electronics (GPS or computers) emerged for all fleets over time. In particular, GPS appeared in the 1960s and 1970s in the Danish fleet (Figure 3c), and in the 1980s in the French fleets (Figure 3a and b). All Basque trawlers were equipped with GPS and on-board computers around 1990. In 2004, all French and Basque vessels were equipped with GPS, but 10–30% of Danish vessels were not equipped with the device.

The horse power of the small French otter trawlers (Figure 4a) and the Danish trawlers (Figure 4c) increased over time, whereas that of the Basque (Figure 4b) and the larger French trawlers (Figure 4a) either remained constant or decreased. The decrease in horse power of the Spanish fleet resulted from the emergence of new vessels working as pair-trawlers. Such vessels do not need as much horse power as traditional single-trawl vessels. Bollard pull for the Danish fleets appeared to increase over time, along with horse power.

For both small and large French otter trawlers (Figure 5a and c), the headline length increased slightly over the study period. Otter

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Table 6. Summary of the results of the analysis of cpue by generalized linear models for Danish otter trawlers targeting cod, Norway lobster, and plaice.

Species	d.f.	SCC/d.f.	Date of construction	Crew size	Vessel length	Number of winch drums	Number of net drums	Number of sounders
Cod	208	1.09	–	0.70	-0.27	1.00	–	–
Norway lobster	180	1.11	-5.0×10^{-4}	–	-0.25	2.55	1.87	–
Plaice*	178	1.12	-3.0×10^{-4}	0.77	-0.31	1.38	1.38	0.74

The statistics include degrees of freedom (d.f.), the ratio of the scaled Pearson chi-square to d.f. (SCC/d.f.), and the values of the coefficients associated with the significant fishing effort descriptors ($p < 0.05$).

* indicates that the hypothesis that residuals are normally distributed is not rejected on the basis of a Kolmogorov–Smirnov test ($p < 0.05$).

Table 7. Summary of the results of the analysis of cpue by generalized linear models for Basque bottom trawlers, registered in Ondarroa, of length 30–40 m, targeting hake and anglerfish.

Species	d.f.	SCC/d.f.	Variable pitch propeller		Number of net drums
			Yes	No	
Hake	114	1.10	0.86	0.00	-0.37
Anglerfish	114	1.10	0.83	0.00	0.79

The statistics include d.f., the ratio of the scaled Pearson chi-square to d.f. (SCC/d.f.), and the values of the coefficients associated with the significant fishing effort descriptors ($p < 0.05$).

trawlers equipped with twin trawls had a longer headline than those equipped with single trawls. For the medium-sized French otter trawlers (Figure 5b), the headline length decreased over time. Headline length of otter trawlers equipped with twin trawls was similar to that of those equipped with single trawls. For the Basque fleet, both headline length (Figure 5d) and vertical opening (Figure 5f) increased over time. Trawlers equipped with VHVO trawls had longer headlines and higher vertical openings than those equipped with single trawls. The vertical opening of Danish trawlers (Figure 5e) increased over time. Danish trawlers equipped with single trawls had the highest vertical opening, and those equipped with multi-rig trawls had the smallest.

Modelling catch rates and adjusting fishing effort

Model 2 was more appropriate than model 1 in all cases. The GLM residuals diagnostics are shown in Tables 4–7 and Figure 6. The Kolmogorov–Smirnov tests indicate that the assumption of normal distribution could not be rejected for just a few cases. However, inspection of the QQ plots indicates that, except in a few cases where outliers made the observed plot deviate slightly from the reference line (Figures 6b, e, g, i, and m), the distribution of residuals was close to normal.

Results of the GLM are summarized in Tables 4–7 and Figures 7 and 8. For French gillnetters, the greatest catch rates of hake were achieved with fixed nets and the greatest catch rates of sole and anglerfish with trammel-nets (Table 4, Figure 7). Net length had a positive effect on catch rates of hake and sole, but the effect of soaking time was unclear. Vessel length had an effect on catch rates for hake only.

A gear type variable was created by combining the gear unit with the type of groundrope used by the French trawlers. The effect of gear type was dominant for all combinations of fleets and species, but it was also fleet- and species-dependent (Table 5, Figure 8). For small trawlers (12–16 m), the greatest catch rates of *Nephrops* were with twin trawls using metallic spheres, whereas chains seemed to function better for larger trawlers (20–24 m). The greatest catch rates of hake by both small and large French trawlers were achieved with single trawls equipped with diabolos. Large trawlers operating single trawls equipped with chains also yielded good catch rates of *Nephrops* and hake. The effect of gear type was not so clear for the medium-sized trawlers (16–20 m). Headline length generally had a positive effect on catch rates for all fleets. Short hauls (reflecting either a relatively fast towing speed or a short haul duration) often had a positive impact on catch rates, except for the large trawlers harvesting hake, where the effect was negative. Finally, the effect of on-board electronics and engine power was unclear and/or limited.

The smallest Danish trawlers equipped with the largest number of winch drums had the best catch rates for all species (Table 6). Other technological factors had a positive impact on the cpue for some species under investigation: crew size on cod and plaice, number of net drums on Norway lobster and plaice, and number of sounders on plaice. Finally, the newest vessels appeared to be the least efficient at catching both Norway lobster and plaice.

The availability of variable pitch propellers increased the catch rates of both hake and anglerfish by Basque trawlers (Table 7). The number of net drums had a positive effect on catch rates of anglerfish, but a negative effect on catch rates of hake.

Evaluating the benefits of adjusting fishing effort

The relationships between ln(effort) and ln(F) were investigated in situations where reliable stock assessments were available (Table 8, Figures 9 and 10). Adjusting fishing effort generally led to an improvement in the relationship between log-transformed fishing effort and fishing mortality, except for the French medium-sized trawlers (16–20 m) harvesting hake and the French gillnetters harvesting Bay of Biscay sole. In two cases (French gillnetters harvesting Bay of Biscay sole and Bay of Biscay/Celtic Sea anglerfish), the slope of the relationship was not significantly different from zero, and the model was clearly not appropriate, whatever the measure of fishing effort. The average slope of the regression with adjusted effort was not significantly different from 1 for French gillnetters harvesting hake and North Sea/Western Scotland anglerfish, Danish otter trawlers harvesting North Sea cod and plaice, and Basque bottom trawlers harvesting hake and both anglerfish stocks. For these combinations of fleets and species, the assumption that fishing mortality is directly proportional to fishing effort is not unreasonable.

Discussion

An important feature revealed by the data exploration was the gradual appearance of twin trawls since the early 1980s, in both Danish and French trawler fleets, a development clearly associated with the gradual emergence of Norway lobster as target species.

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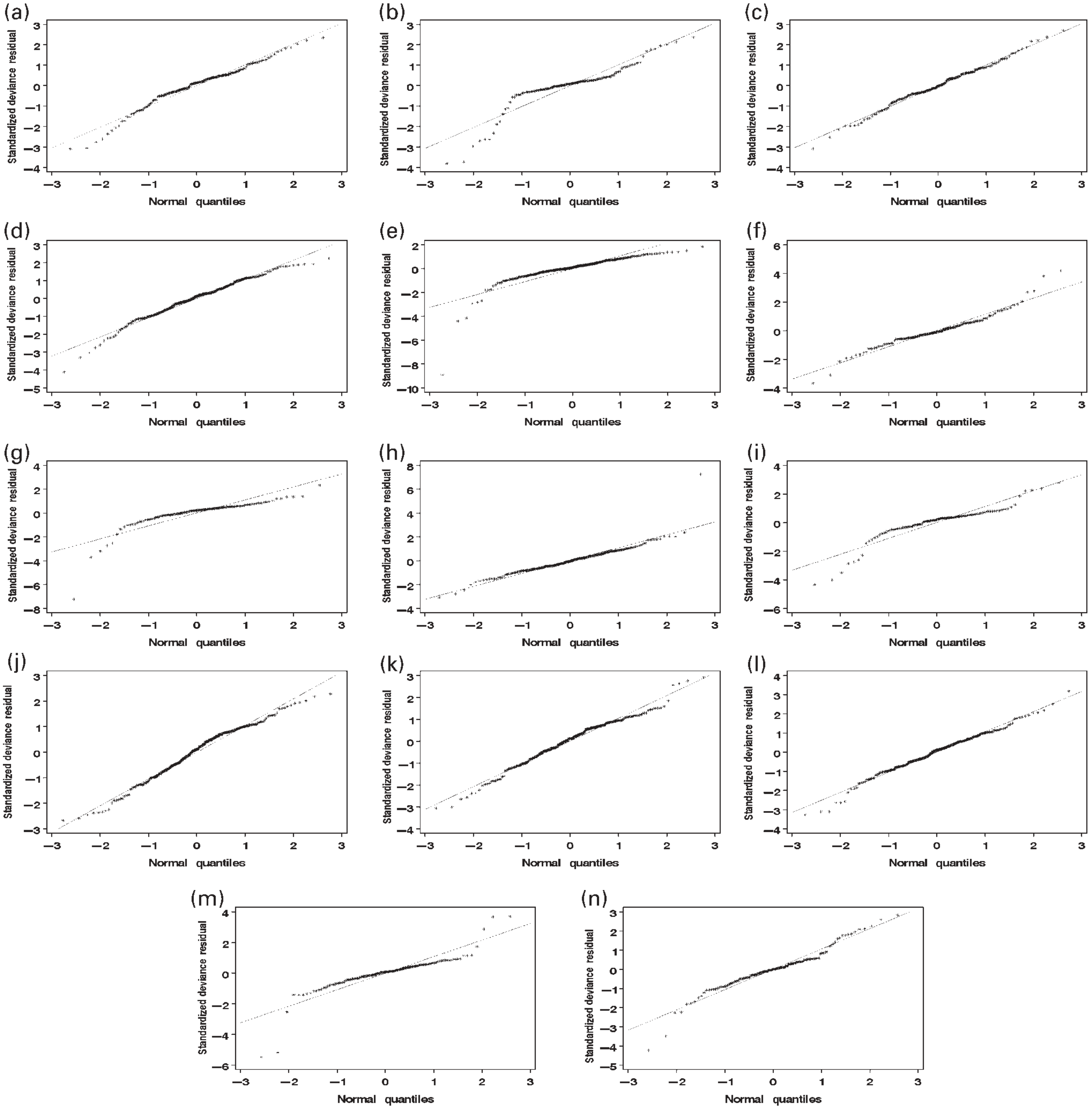

Figure 6. GLM residuals inspection through QQ plots. French gillnetters harvesting (a) hake, (b) sole, (c) anglerfish; French otter trawlers (12–16 m) harvesting (d) hake, (e) Norway lobster; French otter trawlers (16–20 m) harvesting (f) hake, (g) Norway lobster; French otter trawlers (20–24 m) harvesting (h) hake, (i) Norway lobster; Danish otter trawlers harvesting, (j) cod, (k) Norway lobster, (l) plaice; Basque bottom trawlers (30–40 m) registered in Ondarroa harvesting (m) hake, (n) anglerfish.

For French trawlers, the emergence of twin trawls was accompanied by the appearance of new groundropes (diabolos, metallic spheres), which allow fishing on harder grounds, areas that could scarcely be exploited before. A similar change in fishing technologies was observed for the French gillnetters, for which the increased importance of trammel-nets was associated with sole becoming the dominant target species. These shifts are likely to be due to both Norway lobster and sole having a high market value, and by the diminished abundance of hake, the traditional target of both fleets. For the Basque bottom trawlers, the main feature was the increased polyvalence of fishing vessels, which may reflect the greater opportunism of skippers in recent years.

Analysis of the effects of vessel and gear properties on fishing efficiency for the six fleets clearly shows that collecting non-trivial information on fine-scale technological change allows more insight into the factors affecting fishing power. For the four

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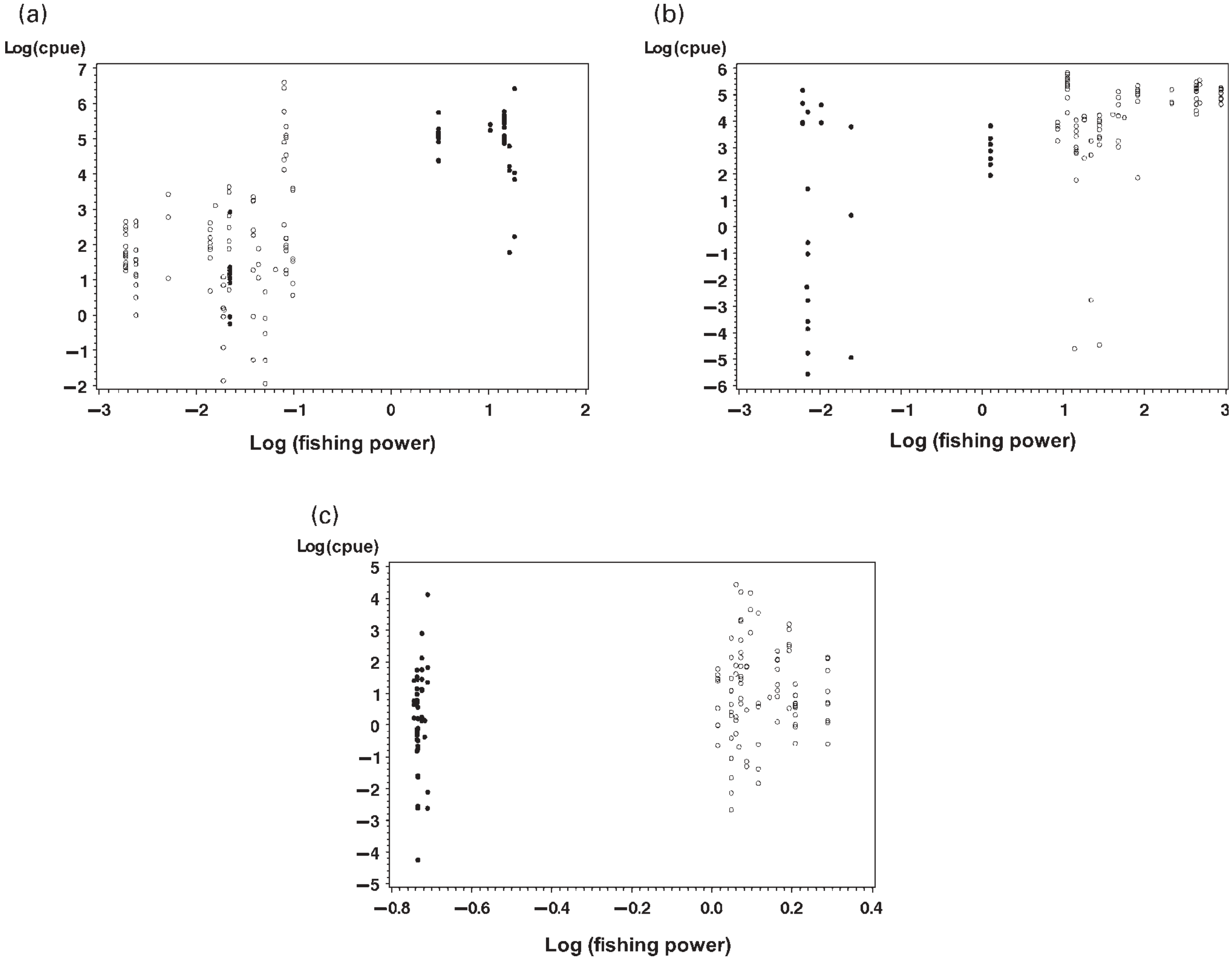

Figure 7. Relationships between log-transformed cpue and fishing power by net type (black dot, fixed nets; circle, trammel-nets), as derived from generalized linear models. French gillnetters harvesting (a) hake, (b) sole, and (c) anglerfish.

French fleets, where both vessel and gear information were compiled in the fishing effort data set, the gear effect appeared to be dominant over the vessel effect, bearing out the great plasticity of these fleets' fishing strategies. For French gillnetters, trammel-nets were clearly utilized to target sole by night, when the fish rise in the water column, and fixed nets were traditionally used to target hake. Therefore, it would be anticipated that vessels equipped with trammel- and fixed nets would be more efficient with regard to sole and hake fishing, respectively. Other characteristics of gillnets, such as twine thickness, are thought to have a substantial effect on fishing power (Holst *et al.*, 2002), but information on such attributes was not consistently available from the questionnaires. Also, the length of net towed had a positive effect on fishing efficiency for the main target species (sole and hake), and could from now on be considered as a useful measure of fishing capacity. Soak time, sometimes evoked as a measure of the fishing activity of gillnetters (Marchal *et al.*, 2001, 2002), did not have a clear effect on catch rates. It could be anticipated that an increasing soak time would allow more fish to be caught, but discussion with skippers who participated in the survey indicated that leaving fish more than 24 h in the net would adversely impact the quality of the fish flesh, making it unmarketable. Therefore, it is likely that soak time has a non-linear effect on catching efficiency, but this requires further investigation.

We had anticipated that, within each groundrope category, French otter trawlers using twin trawls would have a greater efficiency than single trawls when fishing Norway lobster, but a lesser efficiency when fishing hake (Sangster and Breen, 1998). This expectation was fulfilled for small (12–16 m) and large (20–24 m) otter trawlers, but not for medium-sized vessels (16–20 m). The reason why medium-sized trawlers did not have the expected efficiency when fishing for Norway lobster and hake could be the result of those vessels targeting other benthic (e.g. flatfish, anglerfish) or demersal species (e.g. cod, whiting), which were not included in this analysis. French trawlers chose different groundropes depending on the type of ground visited. For 8 of 12 combinations of fleet, species, and gear type categories, vessels equipped with hard bottom groundropes (diabolos, metallic spheres) had a greater efficiency than those equipped with soft bottom groundropes (plain wires, chains, rubber), irrespective of the target species. Before the advent of diabolos and metallic spheres for fishing, operating on hard bottom was very risky

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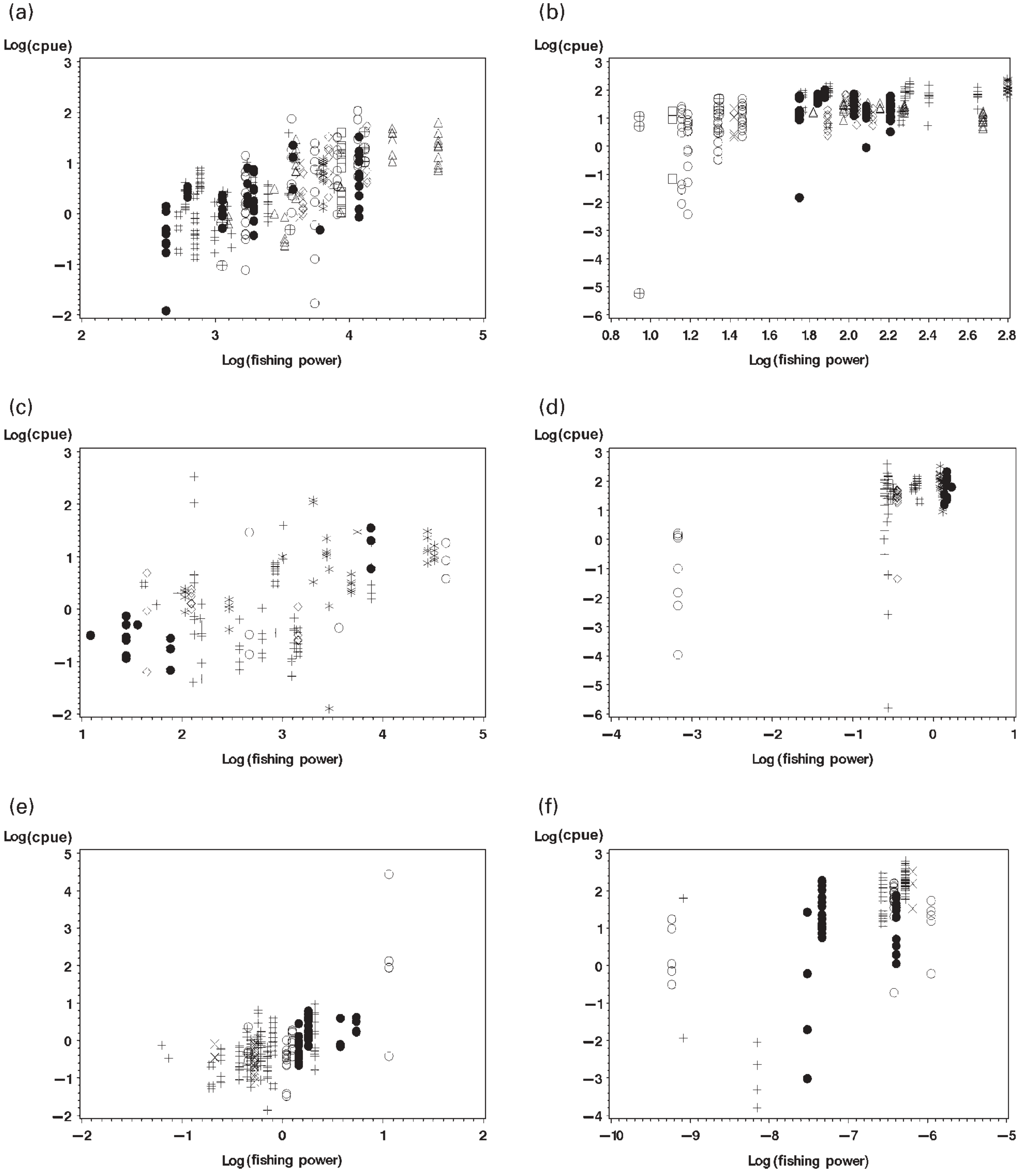

Figure 8. Relationships between log-transformed cpue and fishing power by trawl type and groundrope type: single trawl equipped with diabolos (dot), chains (circle), metallic spheres (square), rubber (diamond), plain wire (triangle); twin trawl equipped with diabolos (plus sign), chains (cross), metallic spheres (star), rubber (hash), plain wire (encircled plus), as derived from generalized linear models. French otter trawlers of length range (a, b) 12–16 m, (c and d) 16–20 m, (e and f) 20–24 m harvesting (a, c, and e) hake and (b, d, and f) Norway lobster.

(gear breakage, etc.). The emergence of such devices made it possible for vessels to have greater access to alternative fishing grounds, perhaps less exploited than the traditional ones. This greater local stock density could be the reason why efficiency was higher when trawls were equipped with diabolos and metallic spheres.

The effect of gear size on trawl selectivity and catching efficiency has been investigated before (e.g. Rose and Nunnallee, 1998; Dahm *et al.*, 2002). One might expect that increasing the trawl opening would enhance its efficiency, but Rose and Nunnallee (1998) found that restricting the trawl opening did not

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Table 8. Outputs comparison of (model a) the regression between log fishing mortality (ln F) and log nominal fishing effort (ln En), and (model b) the regression between log fishing mortality (ln F) and log-adjusted fishing effort (ln Ee).

Fleet	Stock	*n*	r^2 (a)	r^2 (b)	Standard error of slope (b)	Equation (b)
French otter trawlers (12–16 m)	Hake	246	0.29	0.39	0.05	$\ln F = -23.73 + 0.59 \ln Ee$
French otter trawlers (16–20 m)	Hake	246	0.63	0.31	0.07	$\ln F = -25.46 + 0.76 \ln Ee$
French otter trawlers (20–24 m)	Hake	246	0.00	0.07	0.05	$\ln F = -19.38 + 0.22 \ln Ee$
French gillnetters	Hake	194	0.00	0.43	0.07*	$\ln F = -21.51 + 0.90 \ln Ee$
	Bay of Biscay sole	49	0.21	0.03	0.21	Not significant
	Bay of Biscay and Celtic Sea anglerfish	130	0.01	0.01	0.29	Not significant
	North Sea and Western Scotland anglerfish	45	0.00	0.09	0.50*	$\ln F = -23.45 + 1.06 \ln Ee$
Danish otter trawlers	North Sea cod	64	0.03	0.51	0.14*	$\ln F = -13.92 + 1.14 \ln Ee$
	North Sea plaice	73	0.06	0.79	0.07*	$\ln F = -22.11 + 1.14 \ln Ee$
Basque bottom trawlers (30–40 m)	Hake	170	0.11	0.19	0.17*	$\ln F = -14.76 + 1.06 \ln Ee$
	Bay of Biscay and Celtic Sea anglerfish	95	0.03	0.35	0.14*	$\ln F = -18.35 + 0.98 \ln Ee$
	North Sea and Western Scotland anglerfish	47	0.01	0.35	0.24*	$\ln F = -19.03 + 1.16 \ln Ee$

The standard error of the slope of model regression (b) is provided, and marked with an asterisk (*) when the slope is not significantly different from 1 ($p < 0.05$).

necessarily lead to decreased catch rates. In our study, we found that trawl size, as reflected by the headline length, had a positive effect on catch rates of hake by all French trawlers and on catch rates of Norway lobster by the small trawlers. Such results seem to be in accord with expectations, but it is difficult to compare our results, which are based on interviews, with those of Rose and Nunnallee (1998), which were based on field experiments.

One would expect that towing speed would have an effect on the capture of mobile species (e.g. hake) but not on capture of sedentary species (e.g. Norway lobster). Our results seem to confirm this hypothesis, but whether increasing towing speed results in an increase or a decrease in catching efficiency is clearly fleet-dependent and requires further investigations.

For the Danish and Basque trawling fleets, gear information could not be used to adjust fishing effort, and only vessel characteristics were examined in relation to fishing efficiency. Small, old Danish trawlers generally appeared to be more efficient than large, new ones, an unexpected result. About the vessel size effect on catch rates, a plausible explanation could be that larger vessels periodically targeted other species (e.g. pelagic fish) than those included in the analysis here. The negative effect of the date of construction on fishing efficiency may indicate that vintage is a misleading descriptor of fishing effort. Because these days vessels are continuously rebuilt, older vessels may in fact have more up-to-date equipment and technology, and hence be more efficient, than the newer ones. Also, although it cannot be shown with the data available here, one cannot exclude the possibility that more experienced skippers fish with older vessels.

The major contributors to the fishing power of the Danish and Basque fleets appeared to be mainly crew size, the number of winch drums, and the number of net drums. Bollard pull, sometimes advanced as an appropriate metric of fishing power, had no apparent effect on catching efficiency. As for Danish trawlers, the number of net drums on Basque trawlers had an impact on fishing efficiency, but the effect was species-dependent. In fact, the main positive influence on fishing efficiency was the availability of a variable pitch propeller. In itself, this result is not surprising, because variable pitch propellers allow a more optimal transfer of energy from the engine to the propeller, especially during trawling, thus enhancing fishing efficiency. However, we had not anticipated that this would be the only vessel attribute positively to impact fishing efficiency. The results obtained for the Danish and Basque fleets should be treated with caution, because the gear effect could not be included in the analyses.

The effect of on-board electronics and technological efficiency was overall unclear and/or limited for the French, Danish, and Basque fleets under investigation. This unexpected result bears out the findings of Kirkley *et al.* (2004), who suggested that adoption of electronic aids (e.g. GPS) could be associated with other types of unmeasured output-dampening impacts, such as stock or regulation changes, that are being picked up as part of the electronics effect.

The cpue analysis has been carried out using a GLM. Although it is a standard procedure in that field of research (Robson, 1966; Kimura, 1981; Hilborn, 1985; Marchal *et al.*, 2002), it has a number of limitations. First, the data set used in this investigation is unbalanced (not all vessels are present over all time-series). Not explicitly accounting for the vessel effect by a fixed or a random effects model may lead to biased and inconsistent parameter estimates. A fixed or random effect specification could help to explain unobserved heterogeneity between vessels, including the skipper effect. In such a context, one may consider the use of generalized

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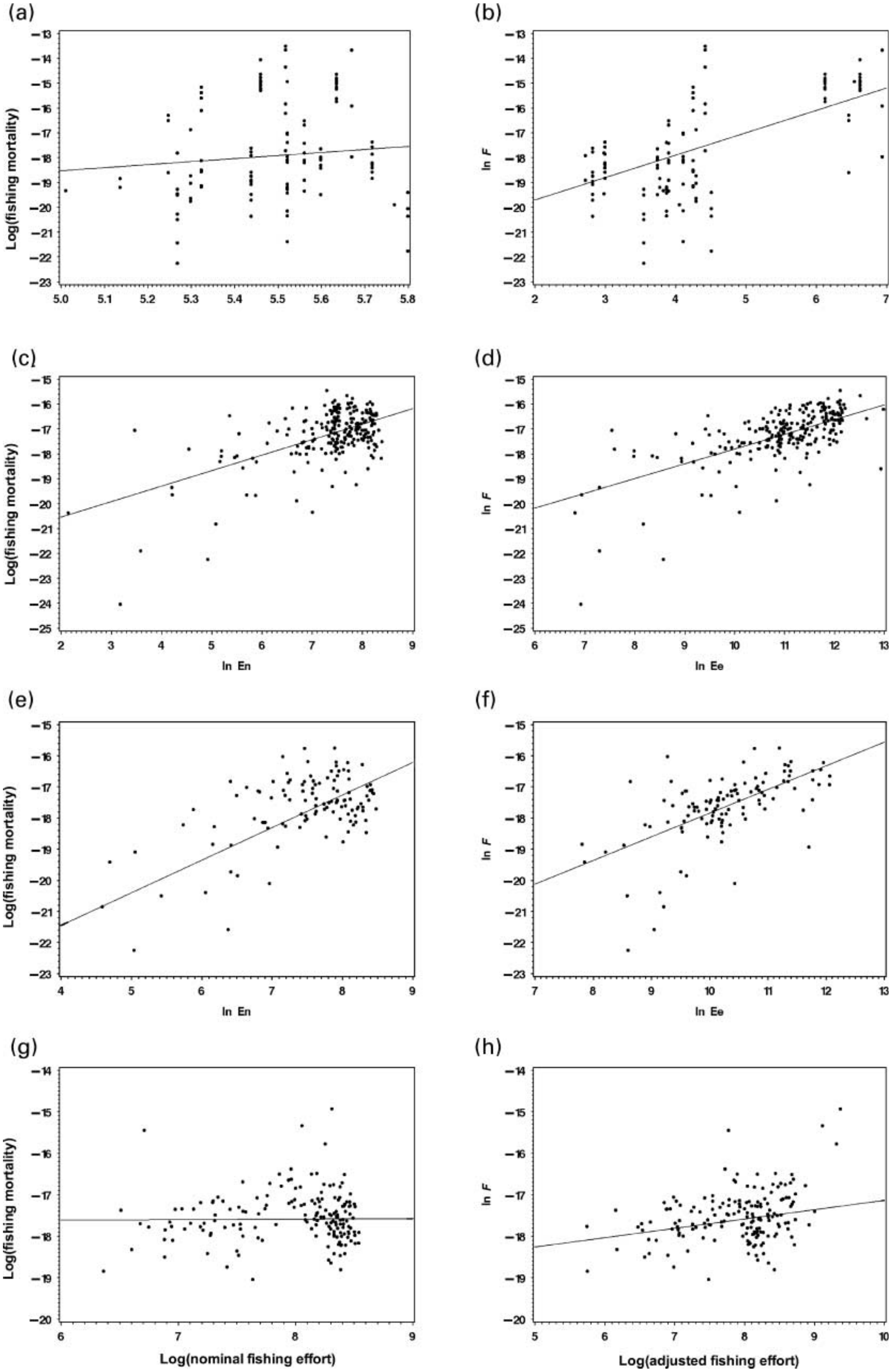

Figure 9. Relationships between log-transformed (a, c, e, g) partial fishing mortality, log(*F*), and nominal fishing effort, log(En); (b, d, f, and h) partial fishing mortality, log(*F*), and adjusted fishing effort, log(Ee). French (a and b) gillnetters, (c and d) otter trawlers (12–16 m), (e and f) otter trawlers (16–20 m), and (g and h) otter trawlers (20–24 m) harvesting hake.

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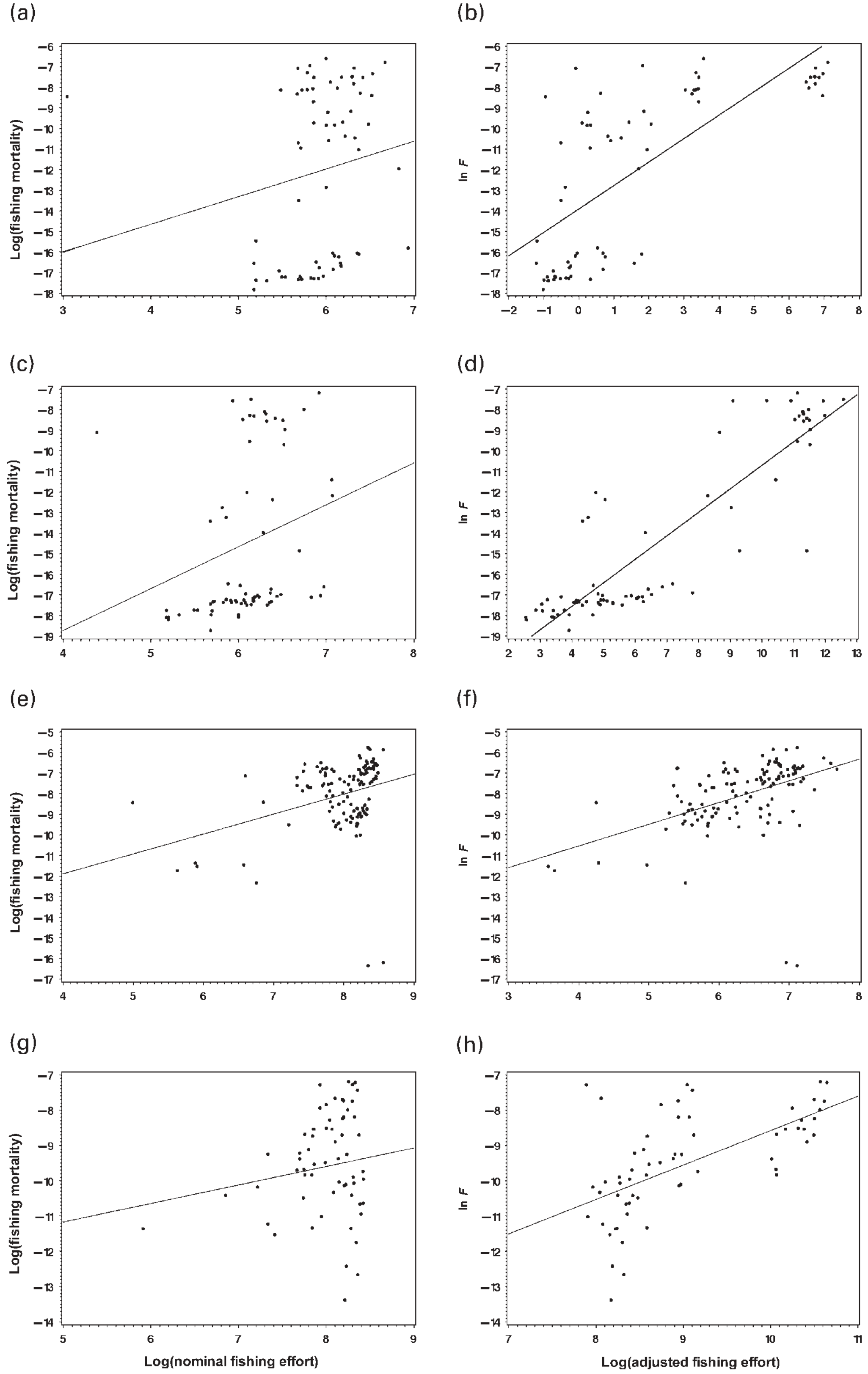

Figure 10. Relationships between log-transformed (a, c, e, and g) partial fishing mortality, log(F), and nominal fishing effort, log(En); (b, d, f, and h) partial fishing mortality, log(F), and adjusted fishing effort, log(Ee). (a and b) Danish otter trawlers harvesting North Sea cod, (c and d) Danish otter trawlers harvesting North Sea plaice, (e and f) Basque bottom trawlers harvesting hake, (g and h) Basque bottom trawlers harvesting Celtic Sea and Bay of Biscay anglerfish.

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linear mixed models (GLMMs) as an alternative to GLMs (Venables and Dichmont, 2004). GLMMs make it possible to include both fixed and random terms in the linear predictor. Although still a research topic, this method has been applied to the field of fisheries research (Squires and Kirkley, 1999). Second, the model used here is entirely linear. To allow for a broader use of the approach, more general models could be contemplated. For instance, the GLM model used in this study is consistent with the Cobb–Douglas function used by fisheries economists to model production in relation to economic inputs (capital, labour, fuel) and various dummy variables (e.g. accounting for spatial and annual effects). A Cobb–Douglas function has therefore been used by Kirkley *et al.* (2004) to evaluate the technological effects on the production of the Sète trawl fishery. The Cobb–Douglas function is in fact a simplification of the trans-log production function which includes, in addition to linear explanatory variables, a quadratic functional term. This quadratic term could in principle be used to account for elasticities of substitution between the fishing effort descriptors and also, to some extent, the non-linear effects of the explanatory variables. However, given the relatively large number of explanatory variables, a quadratic functional form might be intractable because of multi-collinearity. A more general approach could be to account for non-linear effects of explanatory variables (e.g. the effect of soak time on the catch rates of gillnetters) using generalized additive models (GAMs). GAMs may extend the scope of GLMs by substituting the linear predictor by a generalized additive (and possibly non-linear) predictor (Maunder and Punt, 2004). Overall, although the GLM may oversimplify the processes underlying the dynamics of fishing effort, the diagnostics and analyses of residuals suggest that, for our case studies, the main outcomes of the investigation are reasonably robust to the assumptions made.

The link between fishing mortality and effort was investigated for a number of combinations of fleets and stocks. In most case studies, adjusting fishing effort led to (i) a gain in the precision of the relationship between fishing mortality and fishing effort (10 of 12 case studies) and (ii) fishing mortality being directly proportional to fishing effort (7 of 12 case studies). However, the results also indicated that the linkage between fishing mortality and effort could still be enhanced. This could be done by both revisiting some of the assumptions and refining the scale of the investigation. First, it has been assumed in the GLMs that the “Year” effect is indicative of changes in annual abundance of the stocks, whereas technological creep is embodied in the different fishing-effort descriptors. This assumption could be violated for several reasons. Therefore, there may be factors contributing to improved technological efficiency that have not been captured by the survey. In particular, gear-related factors of the Danish and the Basque fleets could not be used for this study. In such cases, the annual effect may reflect a combination of both stock fluctuations and improved gear efficiency. Additionally, an implicit assumption made in this study was that the skipper effect is captured by the different fishing effort descriptors in the GLM. It has been demonstrated that skipper skill is an important determinant in explaining catch rates (e.g. Houghton, 1977; Hilborn, 1985; Hilborn and Ledbetter, 1985; Squires and Kirkley, 1999). Skipper skill may be reflected by, for instance, choice of fishing ground (Marchal *et al.*, 2006) and experience and education levels (Kirkley *et al.*, 1998). Shifts in target species observed for the fleets under investigation have required an adaptation of technologies, but also of skippers’ skills from year to year. Moreover, it is likely that vessel skippers have changed over time during the period examined. Not accounting for the skipper effect can likely lead to an omitted variable bias for the parameter estimates. Information on skippers’ skill and on comings and goings of skippers on different vessels over time was not available to us. It is therefore likely that part of the skipper effect has been embedded in the “Year” effect. Finally, the “Year” effect may pick up other excluded factors that are correlated with time, including changes in the environment, along with changes in institutions and markets (Pascoe *et al.*, 2001). Second, an improvement in our results could be expected with more appropriate estimates of *F*. Such estimates from stock assessments have great uncertainty, and estimates for the most recent years of VPAs (Virtual Population Analysis) assessments may not have converged. Third, the linkage between fishing effort and fishing mortality could be enhanced by refining both the time (month or fishing trip, instead of year) and spatial scales of this analysis.

Another unsettled issue pertaining to modelling cpue and, more generally, of any production function is that of endogeneity. Some researchers have claimed that endogeneity bias may arise if input (or output) quantities are not exogenous to the dependent, left-hand side variable, in turn leading to biased and inconsistent estimates of the parameters. Others, however, have suggested that the stochastic nature of catch levels and composition (attributable to weather conditions, the “luck” component of fishing, or imperfect gear selectivity) implies that errors in input choice based on expected profits will be non-correlated with the error terms associated with estimation (Bjorndal, 1989; Campbell, 1991; Kirkley *et al.*, 1998; Pascoe and Coglan, 2002). Zellner *et al.* (1966) show more formally the conditions under which such bias will not arise.

Overall, despite some limitations, this study has provided some insight into the key processes of technological creep. The results suggest that fishing effort descriptors that are not traditionally measured (gear type, length of net used per day, headline length, number of winch and net drums) may have a substantial impact on catch rates. Such variables are currently not routinely recorded in logbooks. The results of this analysis suggest that they should be.

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