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Partial fishing mortality per fishing trip: a useful indicator of effective fishing effort in mixed demersal fisheries

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Effort management has been proposed as an alternative for quota management in mixed demersal fisheries. It requires a metric to estimate the fishing mortality imposed by a given quantity of nominal fishing effort. Here, we estimate the partial fishing mortality rate imposed by one unit of fishing effort (F_{pue}) during individual fishing trips and explore the usefulness of this indicator for managing North Sea beam trawlers >300 hp targeting sole (*Solea solea*) and plaice (*Pleuronectes platessa*). F_{pue} is positively related to vessel engine power, and increased annually by 2.8% (sole) and 1.6% (plaice). The positive trend was due to an increase in skipper skills and investment in auxiliary equipment, the replacement of old vessels by new ones and, to a lesser extent, to upgrade engines. The average F_{pue} imposed per day at sea by a 2000 hp beam trawler was estimated to be 1.0×10^{-5} (sole) and 0.6×10^{-5} (plaice), and it showed substantial seasonal and spatial variations. The F_{pue} of sole and plaice were negatively related in summer and showed no relationship in winter. The existence of predictive seasonal and spatial patterns in F_{pue} opens up the possibility of fine-tuning management by directed effort restrictions and uncoupling management of plaice and sole.

Keywords: beam trawl, catchability, effort management, fishing effort, fishing mortality, mixed fishery, plaice, sole, technology creep.

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Introduction

In European Union waters, fish stocks are managed by setting annual catch limits (total allowable catch, TAC), accompanied by technical measures such as gear restrictions, mesh size regulations, and closed areas and seasons (Holden, 1994). Management has been unsuccessful for mixed fisheries (Holden, 1994; European Commission, 2001), and several demersal stocks have declined to historically low levels while exploitation levels remain too high (ICES, 2004).

The main problem in managing mixed fisheries by single-species TACs is that the latter do not restrict the catch but only the (official) landings, the over-quota catch of a species perhaps being discarded or landed illegally (Holden, 1994; Daan, 1997). This occurs because the TAC for different target species may not be depleted in synchrony, so fishing continues when the TAC for one species has been depleted. This has two main effects: (i) fishing mortality is not constrained by the TAC; (ii) deteriorating catch statistics lead to inaccurate assessments and uncertainty in the advice. Effort management has been proposed as a possible means of resolving these problems and improving the effectiveness of management (Daan, 1997; Ulrich *et al.*, 2002; Shepherd, 2003).

A prerequisite for effort management is that the relation between fishing effort and fishing mortality of a species is known. Assessing this relationship is not without problems (Martell and Walters, 2002). Efficiency varies among individual vessels owing to differences in the skill of the fishers and vessel characteristics (Hilborn, 1985; Squires and Kirkley, 1999), and it may increase over time through continuous developments in the fishing industry (Marchal *et al.*, 2001, 2002a; Pascoe *et al.*, 2001; Ulrich *et al.*, 2002; O'Neill *et al.*, 2003). However, the efficiency may be affected also by management regulations, for instance by the introduction of a closed area (Marchal *et al.*, 2002a, b), closed seasons, changes in mesh size, or cuts in quota (Pascoe *et al.*, 2001; Poos *et al.*, 2001). Therefore, efficiency of vessels incorporates three interrelated aspects: one technical, one biological, and one economic. Gear efficiency may be defined as the fraction of the fish present in

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the path of a trawl that is retained by the gear. It may vary with physical conditions, the skill of the skipper, and fish behaviour, but it is largely independent of the amount of fish present (although it may be influenced by catch rates). Catchability of a species refers to the chance that an individual fish in a population is caught by a gear, and therefore depends on both gear efficiency and the distribution of fish in relation to the distribution of the fleet. As such it is an aggregated measure that is affected by the skills of skippers to locate the greatest densities. Finally, economic efficiency combines gear efficiency and catchability, but it constrains individual vessels to fish only under profitable conditions by taking into account costs and returns.

Traditional stock assessment provides estimates of the catchability (q) by age group in tuning series, based on the assumed linear relationship between fishing mortality (F) and effort (E):

$$F = q \times E.$$

Using the ratio of the catch of fleets or individual vessels relative to the international catch, the annual fishing mortality may be decomposed into the partial F imposed by these fleets or vessels (Beverton and Holt, 1957) during a specific period, expressed as the fishing mortality induced per unit of effort (partial F_{pue}). This partial F_{pue} can be interpreted directly as catchability ($E = 1$) and integrates all aspects of gear efficiency, crew skill, and the proportion of a species available on the fishing ground. Therefore, the partial F approach should allow evaluation of the sources of variability in the relationship between fishing mortality and effort. Here, we explore the various components of the process (seasonal differences, spatial differences, effects of engine power, vintage of hull and engine, time that a vessel has been in operation) that leads from the operation of a single vessel on a fishing ground to the annual total fishing mortality imposed on a species by a mixed fishery, based on available data for the Dutch bottom trawl fleets targeting North Sea sole (*Solea solea*) and plaice (*Pleuronectes platessa*). Having quantified these components, we comment on the usefulness of partial F_{pue} as an indicator of effective fishing effort in an effort management context.

Material and methods

Data

Data on landings and effort by trip are available for the Dutch bottom trawl fisheries from 1990. This database (VIRIS) is held by the national fisheries inspectorate and comprises daily records of ship identity code, landings by species, area fished (ICES rectangle), gear, and hours out of port. As the daily records are not always accurate, catches were summed by trip and assigned to the rectangle having the largest share of the trip catch. Technical characteristics of the vessels are registered in a national vessel database (NRVI) comprising ship identity code, engine power, vintage of hull, vintage of engine, and ownership. For the analysis, individual vessels were uniquely coded for each period that no change occurred in the hull, engine, or ownership. The time that such a unit has been in operation was calculated relative to the date of entry of the unit and expressed in decimal year. For vessels that entered the fleet before the study period, 1 January 1990 was taken as date of entry.

Rectangles were grouped into fishing areas that reflect the spatial distribution of the two flatfish species in relation to management (Figure 1). Hence, areas were distinguished that comprised the 12-nautical mile zone (1, 2), the plaice box (6, 7, 8), the offshore fishing grounds in the southern (3), southwestern (4), and southeastern North Sea (5, 10), the Dogger Bank (13, 14), and the remaining central North Sea (16). In this classification, we took account of management regulations regarding mesh size (80 mm south of 55°N; 100 mm north of 55°N until 2000, when the line was shifted to 56°N for waters east of 5°E). The seasonal and spatial distributions of the fishing trips analysed are given in Table 1.

Dutch beam trawl fleet

Among the international fleets, the Dutch fleet is responsible for >80% of the F of sole, while for plaice a peak of about 60% was reached in the 1980s, followed by a decline to about 50% in the 1990s. The Dutch bottom trawl fleet is dominated by large beam trawlers (>300 hp), which contribute 51% of the total number of fishing days, and 89% and 92% of the landings of sole and plaice, respectively. The fleet operates in the offshore waters of the North Sea beyond the 12-mile coastal zone and outside the plaice box (Pastoors *et al.*, 2000). The number of large beam trawlers has declined progressively but stepwise since 1990 (Figure 2a), interspaced with periods of relative stability (1993–1995, 1998–2000), partly in response to the

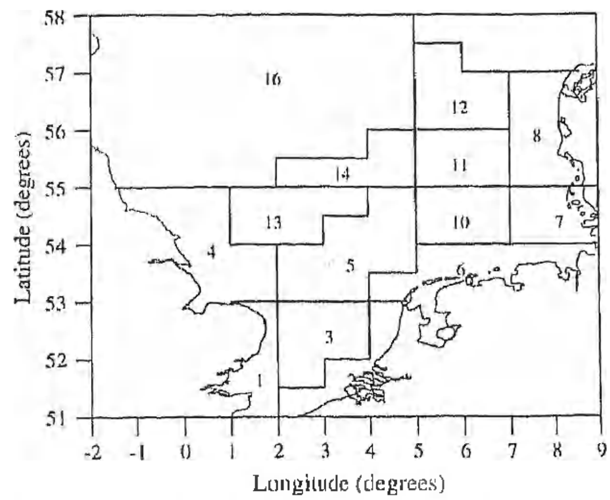

Figure 1. Map of the fishing areas distinguished in this study.

Table 1. Number of fishing trips with a trip duration between 2 and <5 days out of port by area and quarter during the study period 1990–2003. Area codes are shown in Figure 1.

	Quarter				
Area code	1	2	3	4	Sum
01	215	243	175	169	802
02	2 168	2 998	1 451	1 344	7 961
03	7 336	5 435	4 157	4 905	21 833
04	670	443	436	407	1 956
05	6 134	4 486	5 518	5 710	21 848
06	1 071	1 138	1 144	1 071	4 424
07	479	1 453	1 499	831	4 262
08	27	336	184	430	977
10	3 497	2 343	4 486	3 416	13 742
11	730	731	668	849	2 978
12	39	124	118	116	397
13	966	974	1 601	1 287	4 828
14	230	811	471	319	1 831
16	86	240	80	54	460
Sum	23 648	21 755	21 988	20 908	88 299

fleet-reduction policy of the European Union. The decline has generally been through the exit of older vessels with relatively low engine powers that have not been compensated for by replacements. New vessels mainly entered the fleet between 1990 and 1995. However, many more have renewed their engine (Figure 2b). This resulted in a small but gradual increase in mean engine power, from 1996 hp in 1990 to 2277 hp in 2003. The ageing of the beam trawl fleet is reflected in the increase in the proportion of vessels with a hull (or engine) ≤10 years old from 62% (79%) in 1990 to 28% (53%) in 2000. The mean vintage of the fleet increased between 1990 and 2003 at an annual rate of 0.64 (hull) and 0.76 (engine). The number of years that a modal vessel has been in operation was estimated at 21 years (hull) and 16 years (engine) using the "proc lifetest" of SAS (SAS, 1999; Figure 3).

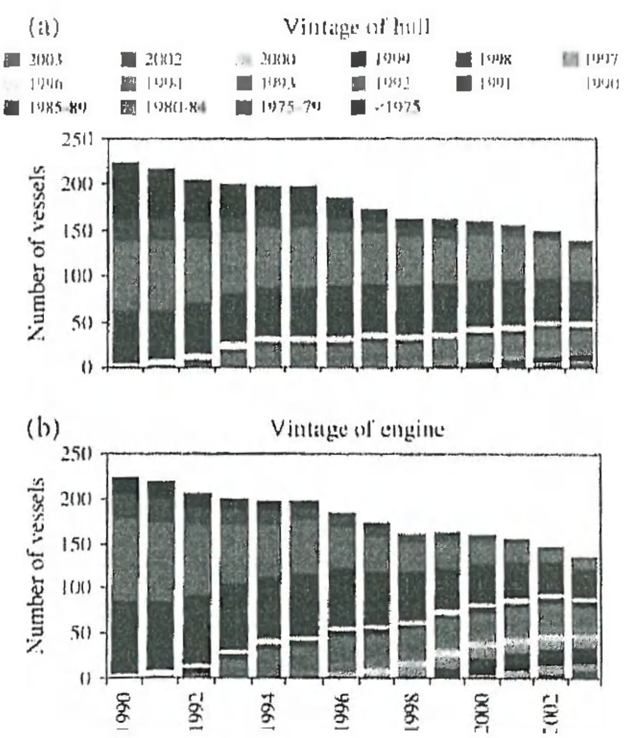

Figure 2. Changes in the composition of the active beam trawl fleet in respect of (a) hull vintage, and (b) engine vintage. Before 1990, vintage is grouped by 5-year periods.

Partial fishing mortality

Total F by quarter for both species was taken from multispecies virtual population analysis (MSVPA) of quarterly catch-at-age data from the total international fleet (ICES, 2002), updated to 2003. The approach is similar to quarterly single-species VPA, because in this model, plaice and sole are not preyed upon. Because of the higher temporal resolution, the quarterly model was preferred to the annual VPA routinely performed for management advice. Quarterly F, averaged over age classes 2–8, was decomposed into partial F according to proportional catch, first by country, then by fleet, individual vessel, and finally by week (=trip). Therefore, the partial F imposed by an individual vessel i per day in week j ($F_{\mathrm{puc}_{ij}}$) was

$$F_{\mathrm{puc}_{ij}} = \frac{c_{ij}}{C} \cdot \frac{F}{d_{ij}},$$

where c_{ij} are the landings of vessel i in week j, C the total quarterly landings, F the quarterly F of the total international fleet, and d_{ij} is the number of days fished by vessel i in week j. $F_{\mathrm{puc}_{ij}}$ is determined by the gear efficiency of the individual vessel and the number of fish available in the area, and is a measure of the local catchability of a particular vessel.

This approach is a rather crude approximation of the actual contribution of each trip to total fishing mortality, because we had to assume similarity in exploitation patterns among vessels and across weeks.

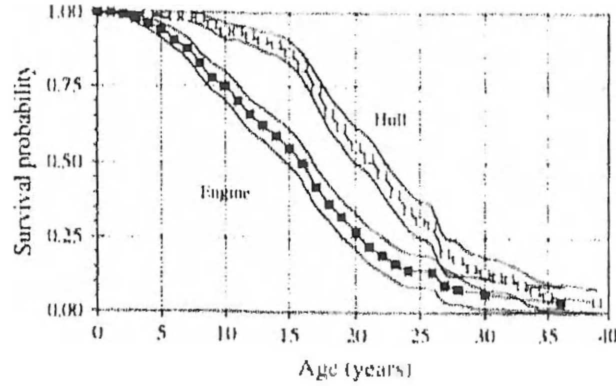

Figure 3. Survivorship curve (mean and 95% confidence limits) of a hull and engine operating in the Dutch beam trawl fleet.

Statistics

Generalized linear models were used to analyse the contribution of temporal and spatial covariables as well as ship characteristics to the variability in F_{pue} (SAS, 1999 – Proc genmod). As the F estimates from VPA have not yet converged in the most recent years, they were down-weighted by applying an arbitrary weight vector $1 - \exp -0.68 \times (2004 - \text{year})$ that increased the weight from 50% in the final year (2003) to >93% in years up to 2000.

Two types of models were fitted, both using a log link function and a Poisson error. Although residuals were slightly correlated to model predictions, we preferred to retain the Poisson distribution rather than a lognormal or Gamma distribution, because of the complications in handling zero observations in the latter. Our focus is on the development of new methodology, rather than on data-fitting procedures.

The first, more parsimonious, one modelled the seasonal patterns in F_{pue} for each fishing area by a periodic regression model, allowing for a linear time trend (model 1):

$$F_{pue} = \exp\left[\ln(P) + \text{area} \times \sum_{n}^{3}(\sin^{n}\varphi + \cos^{n}\varphi) + t\right], \quad (1)$$

where P is the engine power of the vessel, area the code for the fishing area, φ the $2\pi \times$ week number/52, representing a periodic function with a period of 1 year, and t is the time in decimal year. Higher-order terms were included to fit seasonal peaks and lows of different levels at different times during the year.

Second, to check the fit of the periodic model, a more complex model was applied including each week × year and area × week combination separately, accounting for detailed temporal variation (model 2):

$$F_{pue} = \exp[\ln(P) + \text{year} \times \text{week} + \text{area} \times \text{week}]. \quad (2)$$

In the third step, the contribution to the time trend in F_{pue} of the recruitment of a new vessel (vintage of hull, vh), the upgrade of the engine (vintage of engine, ve), and the autonomous trend (time that a vessel has been in operation, tu) were estimated by replacing t in Equation (1) with vh + ve + tu (model 3):

$$F_{pue} = \exp\left[\ln(P) + \text{area} \times \sum_{n}^{3}(\sin^{n}\varphi + \cos^{n}\varphi) + \text{vh} + \text{ve} + \text{tu}\right]. \quad (3)$$

The statistical fit of the models was compared by the percentage explained deviance, as well as Akaike's information criterion (AIC) (Akaike, 1973).

Results

Partial fishing mortality

Engine power, seasonal pattern, and fishing area all explained a significant part of the variance in F_{pue} (Table 2). F_{pue} increased with engine power. The slope of the log–log regression (sole, $\beta = 0.809$, s.e. = 0.006; plaice, $\beta = 0.516$, s.e. = 0.006) was <1, indicating that an increase in engine power did not enhance the F_{pue} to the same extent. Also, the slopes of the regressions differed between species. Hence, the increase in mean engine power in the fleet observed between 1990 and 2003, from 1996 to 2277 hp (+14%), resulted in an increase in F_{pue} of 11% in sole and 7% in plaice.

The periodic regression model (model 1) included the statistically significant first, second, and third order terms. This model explained 39% (sole) and 43% (plaice) of the variance in F_{pue}, but performed poorer than model 2, including the week × area and year × week interaction terms (57% and 56%, respectively; Table 2); the change in AIC amounted to 53 176 for sole and 24 874 for plaice. Obviously, model 2 is preferred in terms of variance explained.

Figure 4 shows a rather close correspondence between the fitted seasonal patterns of the two models for plaice. In sole, however, the periodic model showed discrepancies during some periods. For instance, in 1996 and autumn 1998, the weekly estimates were consistently higher than the fitted values of the periodic model, whereas the weekly estimates in winter 1995 and 2001 were consistently lower. In some years, the autumn peak in sole also occurred earlier (1999) or later (1995, 2002) than predicted by the periodic

Table 2. Percentage of the deviance in F_{pue} explained by the covariables: ln-transformed engine power (ln(P), hp), fishing area (area; cf. Figure 1), season and time trend (t: model 1 only). The seasonal pattern was included as a periodic function (model 1: $\sum^{n}(\sin^{n}\varphi + \cos^{n}\varphi)$) or as class variables week and year (model 2). All explanatory variables explained a significant part of the variance ($p < 0.001$).

	Sole		Plaice	
Covariable	% Explained	d.f.	% Explained	d.f.
Model 1				
ln(P)	20.4	1	6.0	1
Area × period	14.8	53	35.8	77
Time trend	3.8	1	1.0	1
Total	39.0	55	42.8	79
Model 2				
ln(P)	20.4	1	6.0	1
Area × week	17.2	468	38.2	670
Year × week	19.5	676	11.6	676
Total	57.1	1 145	55.8	1 347

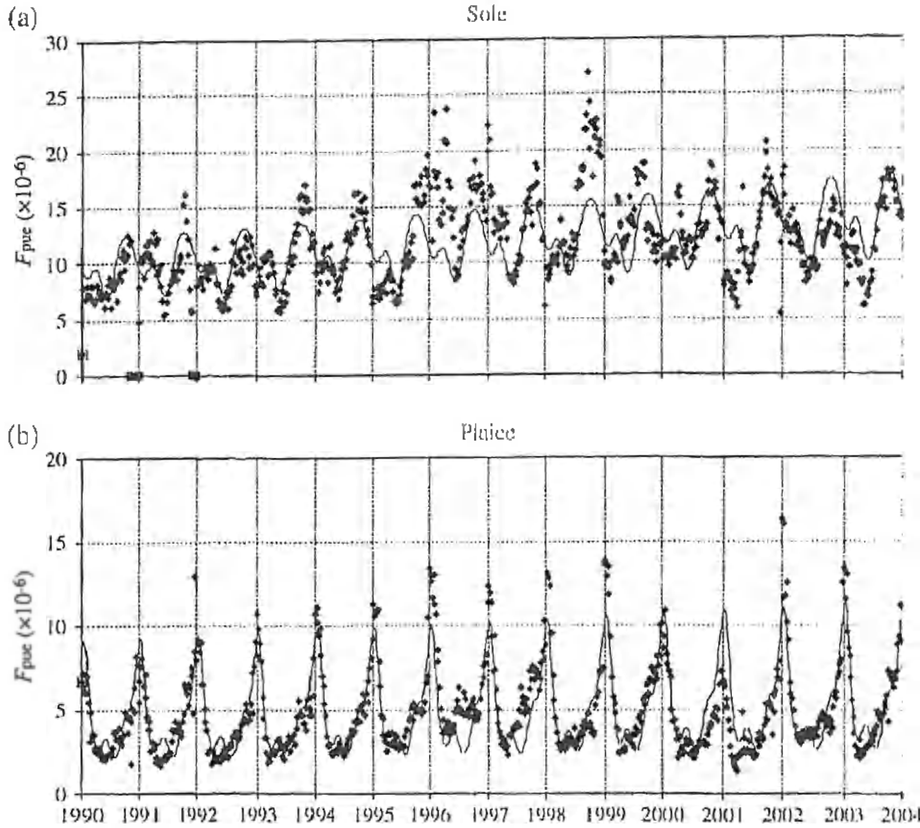

Figure 4. Seasonal pattern in predicted F_{pue} for (a) sole and (b) plaice for a 2000 hp beam trawler fishing in area 3 (Southern Bight) from (periodic) model 1 (lines) and model 2 (diamonds).

model. Despite these differences, the periodic model performed sufficiently well to be used as the basis for the further analysis. The results also revealed a significant positive trend in the F_{pue} over time.

The seasonal pattern estimated by the periodic model differs among fishing areas. Sole F_{pue} peaks in autumn and bottoms out in summer in all areas, except in the eastern central North Sea (Figure 5a). There, F_{pue} peaks in late autumn and bottoms out in early spring. Throughout the year, substantial differences in F_{pue} exist among areas. Between November and April, the difference may exceed a factor of 2, reducing to about 1.5 in June and July. Plaice F_{pue} shows a seasonal pattern in the southern and eastern areas, with high values between November and January and low values between April and August (Figure 5b). North of 55°N, values are relatively high throughout the year. As in sole, plaice F_{pue} differs substantially among areas. Between November and February, the values may differ by a factor of 1.5, increasing to about 3 during summer. Hence, the contribution of a vessel to total F depends to a large extent on fishing area and season.

A plot of weekly estimates of sole F_{pue} against plaice F_{pue} by area (model 1) shows that the fisheries on the two species are to a large extent uncoupled (Figure 6). During summer, indicated by red, there is an overall negative relationship between the two species, whereas during winter (blue) a high F_{pue} on plaice may coincide with either a high or a low F_{pue} on sole.

Time trend in catchability

According to model 1, F_{pue} increased annually by 2.8% (s.e. = 0.04) in sole and 1.6% (s.e. = 0.04) in plaice. To explore the contribution of technological creep to this increase, F_{pue} was analysed in relation to the vintage of the hull, the vintage of the engine, and the time that a vessel had been in operation (model 3). All covariables showed a significant positive contribution to F_{pue} and explained 3.9% and 1.2% of the variance in sole and plaice, respectively (Table 3). A substantial part of the explained variance (1.8% and 0.4%, respectively) could not be ascribed to a single covariable. Comparing model 3 with model 1, AIC changed by 445 for sole and 496 for plaice.

The mean vintage of the fleet increased between 1990 and 2003 at an annual rate of 0.64 (hull) and 0.76 (engine), while the mean operation time of the vessels in the fleet increased by 0.58. Combining these rates with the slopes of the catchability relationships gives an estimate of the overall increase in F_{pue} of 2.5% in sole and 1.4% in plaice, close to the time trend estimated in model 1 (Table 4). The overall trend is mainly due to an increase in efficiency when the vessel unit is in operation (42% and 48% for sole and

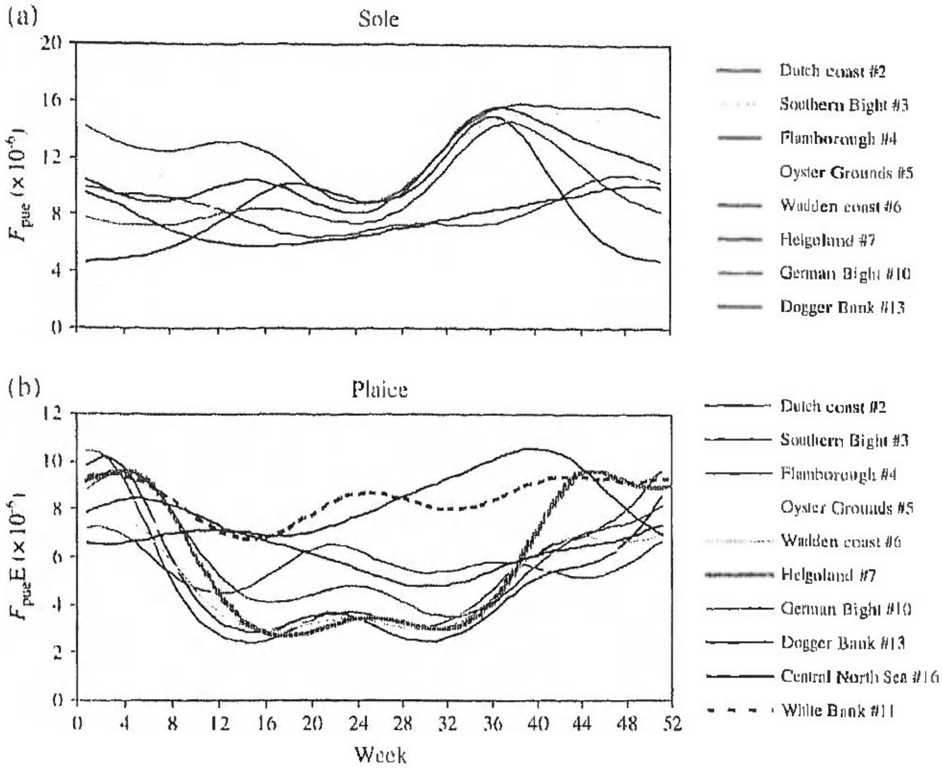

Figure 5. Seasonal patterns in F_{pue} for (a) sole and (b) plaice by fishing ground (cf. Figure 1) predicted by model 1 for a 2000 hp beam trawler.

plaice, respectively). Replacement of vessels ranks second in importance, whereas upgrading the engine is of equal importance in sole but less important in plaice. The parameter estimate for the effect of operation time (tu) on F_{pue} (model 3) is

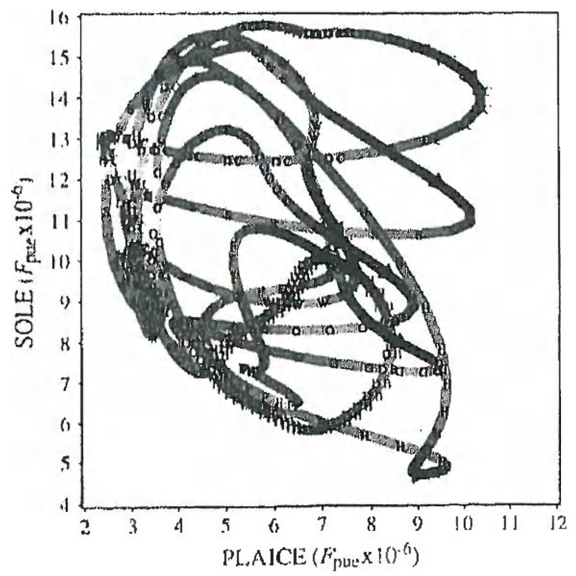

Figure 6. Seasonal patterns in the relationship between F_{pue} for sole and plaice in different areas: Dutch Coast (DC, fishing area 2); Southern Bight (S, #3); Flamborough (F, #4); Oyster grounds (O, #5); Wadden coast (W, #6); Helgoland (H, #7); German Bight (G, #10); Dogger Bank (DB, #13). Colours indicate the season (deep blue = December–January; deep red = June–July).

smaller than the overall increase in efficiency t (Table 4). This implies that a vessel becomes less efficient relative to the fleet as new vessels enter the fleet.

The parameter estimates for the effect of hull vintage and engine vintage can be related to the number of years after which 50% of the vessels or engines have been replaced. With an estimated survival time of 21 (hull) and 16 (engine) years (Figure 3), the replacement of a vessel (hull) increases efficiency by 25% (21 × 1.17) in sole and by 19% (21 × 0.91) in plaice. Replacement of an engine increases efficiency by 15% (16 × 0.91) in sole and by 3% (16 × 0.19) in plaice.

Cumulative partial F by vessel

The partial F exerted by a vessel depends on the area and season chosen in which to operate. Restrictions on the number of fishing days, therefore, might not translate directly into a proportional reduction in F. The relationship between the number of fishing days and fishing mortality was explored for each vessel by plotting the cumulative predicted values of F_{pue} against cumulative effort, after sorting the weeks in descending order of F_{pue} or revenue (Figure 7). This assumes that fishers will restrict their effort predominantly in those weeks and areas for which they expect a low catch rate. The more convex this relation is, the better a fisher can select an inefficient week.

The relationship was slightly convex for the (target) species for which the F_{pue} was sorted (Figure 7a, d), whereas

Table 3. Percentage of the variance in F_{pue} explained by model 1 ($\ln(P)$ + area × ($\sum^3 \sin\varphi + \sum^3 \cos\varphi$)), hull vintage (vh in year), engine vintage (ve in year), and time that the unit has been in operation (tu in decimal year). The percentage explained by vh, ve, and tu was calculated against the full model (type 3 analysis).

	Sole			Plaice		
Parameter	% Explained	d.f.	p	% Explained	d.f.	p
$\ln(P)$ + area × ($\sum^3 \sin\varphi + \sum^3 \cos\varphi$)	35.7	54	<0.001	41.8	78	<0.001
vh	0.7	1	<0.001	0.4	1	<0.001
ve	0.5	1	<0.001	0.02	1	<0.001
tu	1.0	1	<0.001	0.3	1	<0.001
Multicollinearity	1.8			0.4		
Full model	39.6	57		43.0	81	

the relationship was slightly concave for the assumed by-catch species (Figure 7b, c), but there was considerable variation among vessels. This means that, for target species, a small proportion of fishing trips contributed more than proportionally to the annual partial F, while for by-catch species the average cumulative F was slightly below the proportional relationship. The relationships only marginally differed between species, showing a slightly more convex shape if plaice was the target species. Because we sorted the predicted values for the area and week fished excluding the random error, fishers should be able to select their best trips on the basis of personal experience if faced with effort reductions. On average, therefore, a 40% reduction in fishing effort might lead to a reduction in F on the target species of 30% for sole and 20% for plaice, whereas a reduction in F on bycatch species would be slightly larger than the effort reduction (45% and 50%, respectively). However, because fishers make individual choices, some targeting sole and others targeting plaice, the overall effect should be less than assuming that all fishers target one species or the other. If the trips were sorted by descending observed revenue[1] per day at sea (Figure 7e, f), the cumulative relationships became more linear, especially when operating on sole. The shapes of these relationships suggest that if the total allowable fishing effort is reduced and fishing vessels redistribute their fishing effort to obtain the highest revenue, there would be a slightly lower than proportional decrease in total F for sole, and a substantially less than proportional decrease in F for plaice.

Discussion

Seasonal patterns in F_{pue} and the differences between fishing areas (Figure 5) reflect changes in the availability of the two species attributable to seasonal migrations of adult fish and to recruitment. Adult plaice migrate seasonally between the spawning grounds in the southeastern North Sea in winter and the feeding areas in the central North Sea in summer (De Veen, 1978; Rijnsdorp and Pastoors, 1995; Hunter *et al.*, 2003, 2004). Adult sole migrate in spring from offshore feeding areas to inshore spawning grounds along the continental and English coast (ICES, 1965; De Veen, 1976; Rijnsdorp *et al.*, 1992). As a consequence, adult sole may become less vulnerable because the beam trawl fleet is not allowed to exploit the spawning grounds within the 12-mile zone or the plaice box. In autumn, a new year class leaves the cooling inshore waters and recruits to the offshore fishing grounds (Beverton and Holt, 1957; De Veen, 1978). Other factors influencing the observed patterns in F_{pue} may relate to variations in the efficiency of the gear caused by changes in fish behaviour. During the spawning season, male plaice are easier to catch, because they appear to be more active (Rijnsdorp, 1993; Solmundsson *et al.*, 2003), while females may be less vulnerable because they spend a larger proportion of their time in midwater (Arnold and Metcalfe, 1996; Metcalfe and Arnold, 1997). Sole can even be observed near the surface during their spawning migrations (De Veen, 1967). Catchability may be affected also by water temperature (Woodhead, 1964; Winger *et al.*, 1999).

These factors may also have contributed to the observed differences in the predicted F_{pue} of models 1 and 2 (Figure 4). Seasonal changes in distribution may relate to variations between years attributable to local variations in recruitment and/or spawning-stock biomass. Based on the proportion of the variance explained by the week × area interaction in model 2, interannual variations in distribution appear to be larger in sole than in plaice (Table 2). Indeed, sole show larger interannual variation in year-class strength as well as a lower spatial consistency across years than plaice (van Beek *et al.*, 1989; Rijnsdorp *et al.*, 1992; Fox *et al.*, 2000). Moreover, sole exhibit a distinct evasive response to low water temperature during cold winters (e.g. 1963 and 1996), when dense aggregations formed in the relatively warm water of the southwestern North Sea

[1] Revenue was calculated as the sum of the landings × relative price. The relative price of sole is five times higher than that of plaice and cod.

Table 4. Comparison of the overall trend (t) of model 3 with the trend estimated by model 1. The contribution of vintage of hull (vh), vintage of engine (ve), and the time in operation (tu) to the overall time trend (t) in F_{pue} as estimated by model 3 was calculated as the product of the annual increase in the covariable (column A) and the parameter estimates for the covariables in model 3 (column B).

		Sole			Plaice		
Covariable	Slope of time trend (A)	Slope from model 3 (B)	Contribution to t	Contribution (%)	Slope from model 3 (B)	Contribution to t	Contribution (%)
Model 3							
vh	0.640	0.0117	0.0075	30	0.0091	0.0059	42
ve	0.764	0.0091	0.0070	28	0.0019	0.0015	10
tu	0.584	0.0181	0.0105	42	0.0115	0.0067	48
Overall trend (t)			0.025			0.014	
Model 1							
Overall trend (t)			0.028			0.016	

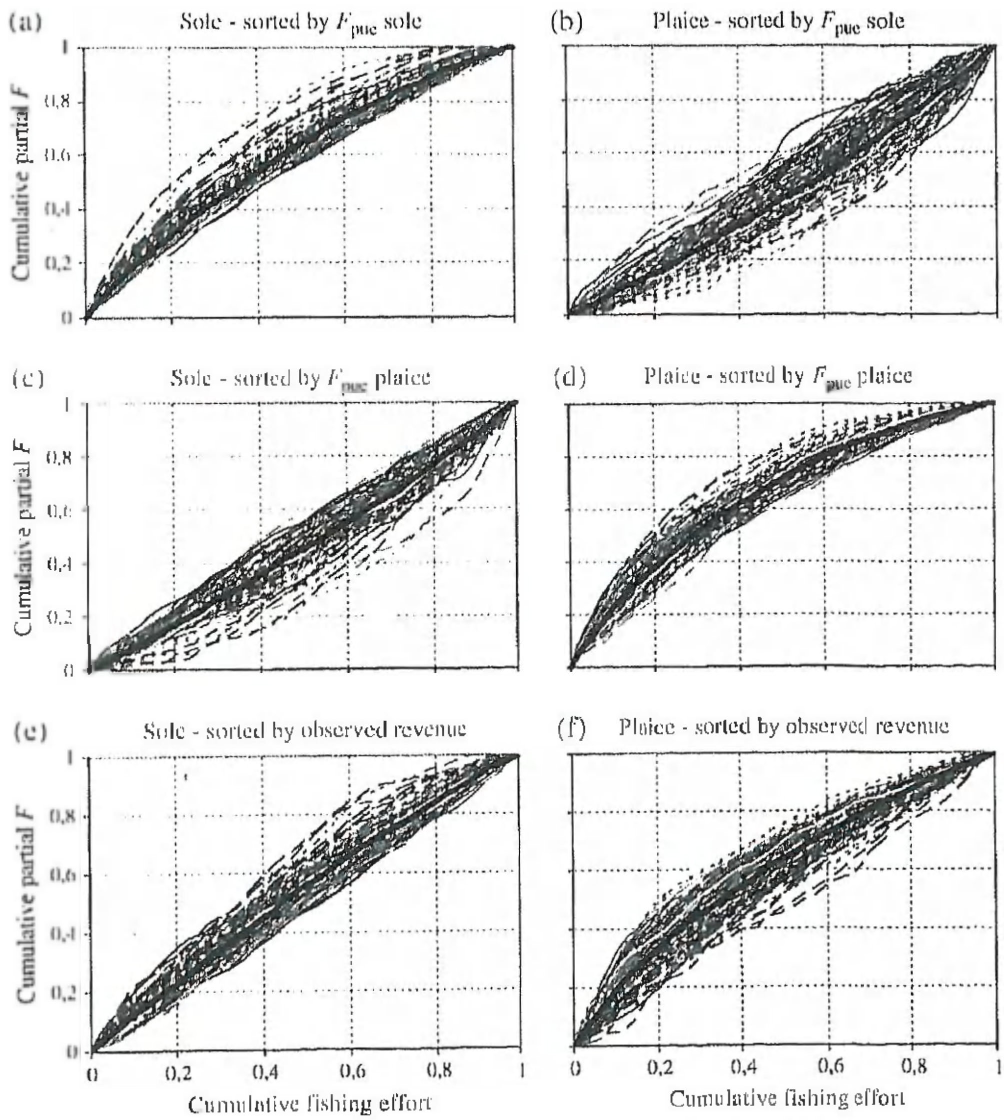

Figure 7. Relationship between the cumulative proportion of the predicted F_{pue} for (left) sole and (right) plaice and the cumulative effort for individual vessels in 2000 when trips were sorted in descending order of F_{pue} of sole (a, b), plaice (c, d) and observed revenue (e, f). The heavy black line shows the average relationship over all ships.

(Woodhead, 1964; Horwood and Millner, 1998). Such aggregations could positively influence the F_{pue}.

Trawling activities may also affect the catching efficiency. Disturbance on fishing grounds may make fish less susceptible to being caught (Ona and Godø, 1990; Engås *et al.*, 1995; Albert *et al.*, 2003), negatively affecting the efficiency of trawlers working closely together in large numbers. This process of interference competition (or crowding) is often assumed in fleet dynamic studies (Gillis and Peterman, 1998; Gillis and Frank, 2001; Gillis, 2003) and econometric studies (Pascoe *et al.*, 2001). So far, there is only indirect evidence for this effect (Rijnsdorp *et al.*, 2000a, b; Gillis, 2003). Finally, changes in the directedness of the fishery on either sole or plaice within the spatial units used in our analysis may explain variability in catchability.

The observed increase in catching efficiency with engine power corroborates the results of earlier studies (Rijnsdorp *et al.*, 2000a; Pascoe *et al.*, 2001). The increase is attributable to a combination of the increase in towing speed (Rijnsdorp *et al.*, 2000b) and the larger number of tickler chains that can be towed at greater engine power. Increasing the latter strongly enhances the catching efficiency for sole (Creutzberg *et al.*, 1987) because of their tendency to dig into the sediment in response to disturbance, whereas plaice will be more affected by towing speed, because they attempt to swim away (Main and Sangster, 1981; Winger *et al.*, 1999).

In estimating F_{pue} we had to make a number of simplified assumptions. The most important is that we had to ignore the age composition of individual landings, because these are not available. Also, F_{pue} was estimated for individual weeks, whereas total F estimates were only available with quarterly resolution. It is difficult to judge what effects this may have had on the results in terms of bias, but such simplifications will undoubtedly contribute to unexplained variance. However, we did not see consistent changes in F_{pue} around the end of each quarter. We further assumed that logbook data accurately record the catch of individual vessels. This may not be true, because the fishery is managed by individual transferable quota as shares in the Dutch portion of the TAC. Such a management system may result in discarding of over-quota fish or the cheaper fraction of the catch to increase the overall value of the landings (Anderson, 1994; Gillis *et al.*, 1995a, b). Although highgrading does occur from time to time, no quantitative information is available.

Despite these uncertainties and weaknesses, our study seems capable of estimating the effect of engine power on the catching efficiency of the gear, as well as the effects of the spatial and temporal components on the fishing mortality induced during a fishing day. Also, it is clearly shown by these analyses that the efficiency of the fleet has increased over time, irrespective of engine power.

The positive effect of operation time on F_{pue} may reflect a gradual improvement of the skills of the crew as well as technological advances in auxiliary equipment (DGPS, echosounders, etc.). Disentangling the contribution of technological improvements and fishing skill requires currently unavailable information on investments of individual vessels and acting crew members.

A second contribution to the increase in catch efficiency could be the replacement of old vessels by new ones. The rate of increase appeared to be somewhat higher for sole (the target species) than for plaice. The origin of this efficiency increase may be partly the same technological innovations discussed above, as well as improvements in propulsion.

A 6% increase in efficiency for sole, but none for plaice was reported for the period 1991–1998 (Marchal *et al.*, 2002a), whereas no overall change in the efficiency was observed using a stochastic frontier analysis of annual vessel records of economic output (Pascoe *et al.*, 2001). The last authors investigated the contribution of several technical attributes of the vessel as well as changes in the management regime on the annual economic output of individual vessels, but they did not consider changes in efficiency for individual fish species, nor did they take into account the important effect of seasonal changes in availability of the species. This comparison shows that technology creep can be estimated in different ways with different results. Our study has estimated the trend in catchability after taking account of changes in engine power within the fleet and changes in the seasonal distribution of fishing effort. Hence, our estimate comes close to the increase in catching efficiency of a vessel.

Our study showed that a standard 2000 hp beam trawler would generate an average fishing mortality rate of about 1.0×10^{-5} (sole) and 0.6×10^{-5} (plaice) per day at sea, but seasonal and spatial variations were large. The variations in F_{pue} induced on the two species appear to a large degree to be uncoupled and fully dependent on the choice of fishing ground and fishing season. It is therefore surprising that the relationship between cumulative F and cumulative fishing effort, after sorting the fishing trips of individual vessels in descending order of revenue, only weakly deviated from a linear proportional relationship for sole. This suggests that for the target species of the beam trawl fishery, effort management would result in a close to proportional reduction in fishing mortality. In contrast, the more convex relationship observed for plaice indicates that a reduction in fishing effort would likely result in a less than proportional decrease in F in by-catch species.

We conclude that F_{pue} might be used as a tool in an effort management regime, allowing a careful design that could take account of the predictable effects of seasonal changes in distribution on catchability, as well as of the gradual increase in the catching efficiency (technology creep). Introduction of effort management may lead to substantial changes in fishing patterns resulting in changes in catchability. Our method may be useful in monitoring changes in catchability, permitting fine-tuning of management regulations. The approach seems particularly useful for mixed demersal fisheries and can be applied easily to other gear if data on a trip level are available to correct for seasonal changes in availability of the resource.

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