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Effects of fishing power and competitive interactions among vessels on the effort allocation on the trip level of the Dutch beam trawl fleet

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Variations in catch rates in relation to the spatial distribution of beam trawlers were analyzed using mandatory logbook data from the Dutch fleet for 1990–1996. Catch rates by trip, corrected for differences in market value, showed a consistent seasonal pattern with the highest values found during autumn and winter. Catch rates showed a log-linear relationship with engine power, indicating differences in competitive abilities among vessels. In 65% of the fishing trips, catch per unit of effort is equalized among fishing grounds. In the remaining trips, catch rates were below average, suggesting that vessels showed exploratory fishing. These results corroborate predictions of the ideal free distribution theory. More powerful vessels were over-represented on better fishing grounds as compared with less powerful vessels. As a special case the effect of vessel density on catch rate was investigated utilizing the convenient fact that a segment of the Dutch fleet stayed in port during one week each year ("week of prayer"). The catch rate of vessels that continued fishing was 10% higher than in the week before or following the week of prayer. No such differences were observed in a reference area where no change in vessel density was observed. Implications of this evidence of competitive interactions among vessels in relation to fisheries management are discussed.

Key words: fleet dynamics, effort allocation, ideal free distribution, fishing power, interference competition.

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Introduction

Fisheries biology has often focussed on the biological processes at work within exploited fish stocks. This narrow focus has led to management strategies that ignore the dynamic response of fishermen to developments in the stock and to management regulations itself (Hilborn and Walters, 1992). The objective of this paper is to contribute to the knowledge on the basic processes determining the behaviour of fishing fleets. The focus will be on the allocation of fishing effort in space and on the competitive interactions between fishing vessels.

Effort allocation will be studied within the theoretical framework of the ideal free distribution (IFD). This theory explains the distribution of foraging animals in relation to the distribution of their resources (Fretwell and Lucas, 1970; Sutherland, 1983). The assumptions of the IFD are that: (i) vessels have equal fishing power; (ii) skippers have perfect knowledge about the distribution of their target species; (iii) travel cost between fishing grounds is negligible; (iv) skippers select fishing grounds on the basis of maximizing fishing efficiency. Although the assumptions will certainly be violated in the real world, Milinski and Parker (1991) showed that the IFD presented a reasonably robust starting point for such analyses. The IFD has been applied successfully to a wide variety of biological systems (Kennedy and Gray, 1993; Van der Meer and Ens, 1997), as well as to the problem of effort allocation (Abrahams and Healey, 1990, 1993; Healey and Morris, 1992; Gillis *et al.*, 1993; Gillis and Peterman, 1998).

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The IFD theory predicts that vessels will distribute themselves over their resources such that density of vessels will be proportional to resource abundance and that vessels will have equal catch rates, irrespective of the vessel density. If vessels differ in competitive ability, better competitors will generally be over-represented in the better patches while poorer competitors will be over-represented in the poorer patches (Sutherland and Parker, 1985), although there may be exceptions (van der Meer, 1997).

One pre-requisite of the IFD is that the number of vessels exploiting the same fishing ground will be affected by competitive interactions among the vessels. If this is not the case, all vessels will aggregate on the best fishing ground. Indirect evidence for competition has been obtained in several studies analyzing commercial logbook data. Catch rates were generally equalized among fishing grounds, as predicted by the IFD (Hilborn and Ledbetter, 1979; Healy and Morris, 1992; Gilles *et al*., 1993). Gillis *et al.* (1993) inferred competitive interactions from changes in catch rate following a change in vessel density. However, direct evidence for competition among vessels is scarce, and only one experimental study of Abrahams and Healey (1993) showed that vessel density had a significant influence on the catch of chinook salmon and spiny dogfish, although not on coho salmon.

Effort allocation will be studied in the Dutch beam trawl fleet in the North Sea. This fleet targets at sole *Solea solea* (L.) and plaice *Pleuronectes platessa* L., with a valuable bycatch of other flatfish species turbot, *Scophthalmus maximus*, brill *S. rhombus* and dab *Limanda limanda*, and roundfish species cod *Gadus morhua* and whiting *Merlangus merlangius* (Daan, 1997). Sole, plaice, cod and whiting are managed by annual total allowable catch (TAC). In the Netherlands, the share of the TAC is converted in individual transferable quota (ITQ) (Salz, 1996). In addition, technical measures are in operation with regard to mesh size and closed areas. In the area south of 55°N a legal minimum mesh size of 80 mm may be used if the fishery targets sole. Otherwise, the minimum mesh size is 100 mm. The beam trawl fishery is mainly carried out by vessels with engine power of >300 hp from the Netherlands, Belgium and England. The total number of beam trawl vessels fishing in the North Sea is 325, of which 233 are Dutch (Lindeboom and de Groot, 1998). A fleet of smaller vessels (Euro cutters, engine power <=300 hp) employs beam trawls for part of the time and is allowed to fish in the protected coastal waters (12 miles zone, plaice box). The flatfish stocks have been overexploited for several years and the biological advice is to reduce the level of fishing mortality. Despite restrictive quota set to achieve the reduction in fishing mortality, no such reduction has been observed until now (Daan, 1997; ICES, 1999).

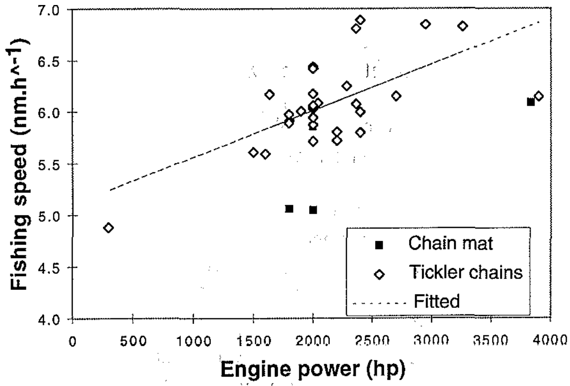

Figure 1. Relationship between fishing speed and engine power in beam trawlers fishing with tickler chains and beam trawlers fishing with chain mats.

Firstly, some characteristics of the beam trawl fishery (trip duration and distance to the fishing grounds) are analyzed. Then the relationship between catch rate and engine power is analyzed to estimate the difference in competitive ability among vessels, because the beam trawl fleet comprises vessels which differ substantially in size and engine power. Next, the predictions of the IFD that the vessels will be distributed so as to have equal catch rates is tested, as well as the prediction that poorer competitors will be over-represented in the poorer fishing grounds. Finally, the effect of a change in vessel densities on catch rates will be studied utilizing the opportunity offered by the week of prayer during which the fleet of Urk, one of the major fishing villages, stays in port. This tradition serves as an "experiment" in vessel density manipulation, which allows a comparison of catch rates of vessels from other harbours, but exploiting the same fishing grounds prior, during and following the week of prayer.

Materials and methods

Data

The basic data analyzed have a spatial resolution of ICES rectangles (0.5° latitude and 1° longitude; ± 30 × 30 nm; Fig. 2) and a temporal resolution of one week. The data originate from the logbooks that each fishing vessel must fill in and hand over to the authorities at the end of each fishing trip. Although, these logbooks are primarily imposed for management purposes, data are made available for research. The data comprise: vessel code; engine power of the engine; type of fishing gear; date and time of departure; harbour of departure; date; time and harbour of entering; landings by quota species only; and ICES rectangle. Because the logbook data does not comprise landings of non-quota species such as turbot, brill and dab, the overall catch rate was expressed as the "revenue" per unit of effort (RPUE) comprising only quota species and taking account of differences in market value between species:

$$\text{RPUE}=(4\times \text{kg (sole)}+\text{kg (plaice)}+\text{kg (roundfish)})/\text{fishing hours.} \quad (1)$$

An annual mean conversion factor of 4 was used to correct for the mean price difference between sole and plaice/roundfish. This factor was based on the overall price difference between the species. The RPUE is a crude proxy of the true economic revenue, because differences in market value between size categories by species were not available on the trip level. The mean percentage of plaice, sole and roundfish (cod and whiting) in the revenue per trip was 56% (CV=44%), 40% (CV=58%) and 4% (CV=108%), respectively.

The number of fishing hours was calculated according to:

$$\text{Fishing hours}=(\text{trip duration}-\text{travel time})\times(1-\text{proportion gear handling}). \quad (2)$$

Trip duration was calculated directly from the time elapsed between the start and end of the trip recorded in the logbook. The travel time between the harbour and fishing ground was estimated from the distance between the port and the fishing ground, measured as a straight line. Speed (12 nm h^{-1}) and proportion of gear handling (0.167; 4 h per 24 h) were set in accordance to Rijnsdorp *et al.* (1998).

The analysis was restricted to the records of vessels with an engine power of >300 hp, which all operate under the same set of regulations with regard to mesh size, access to fishing grounds and number (2) and size of beam trawl (12 m). Trips for which the rectangle was not recorded were excluded from the analysis. Because the TAC regulations may affect the behaviour of fishing vessels, particularly at the end of the year when quota are almost always taken, the data for November and December were not included in the final analysis, unless stated otherwise.

The fishing speed of beam trawlers is a function of engine power (Fig. 1). The relationship was analyzed based on automated position recordings collected at 6 min intervals of a sample of beam trawlers (Rijnsdorp *et al.*, 1998). The fishing speed varies considerably among vessels. The speed of vessels deploying the chain mat type of gear is substantially lower than that of the traditional beam trawl with tickler chains. The relationship between fishing speed (v) and engine power (hp) can be described by the following linear regressions:

Tickler chain: $v=5.1+0.000451$ hp ($r^2=0.42$, $n=30$)

Chain mat: $v=4.5+0.000414$ hp ($r^2=0.55$, $n=4$).

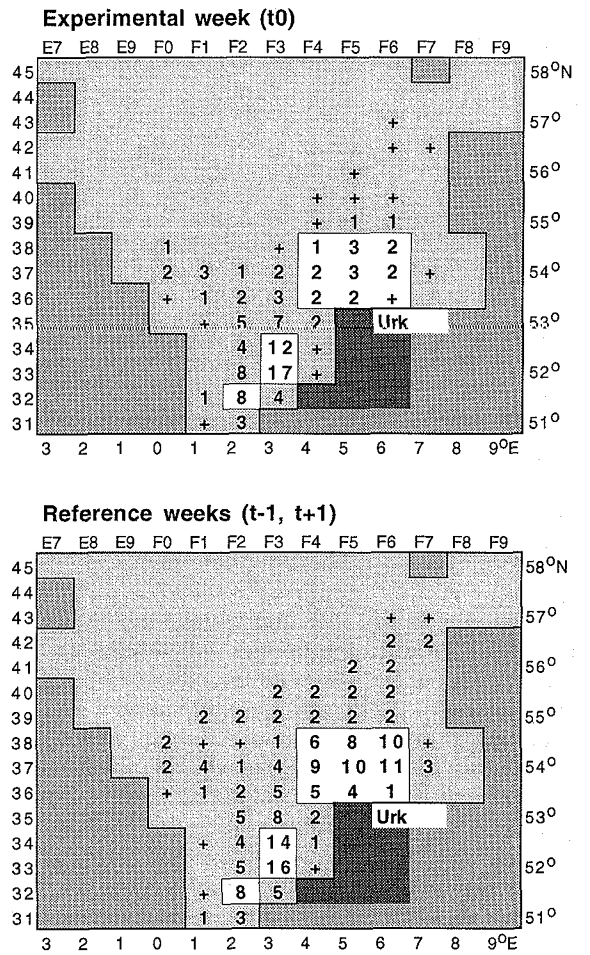

Figure 2. Schematic map of the fishing grounds of the Dutch beam trawl fleet and their main ports. Numbers show the number of fishing trips per ICES rectangle in the experimental week (week of prayer) and the reference week. + denotes a vessel density <1. The white areas indicate the reference and experimental area used to study the effect of a change in vessel density on catch rate. The dark area represents the Netherlands.

Vessel density manipulation experiment

Each year, the fleet of Urk, comprising about 30% of the Dutch fleet of vessels >=300 hp, stays in harbour for one week for religious reasons. This week of prayer is set well in advance. Figure 2 shows the area affected and the magnitude of the reduction in fishing effort in the Dutch fleet. The time periods considered are indicated as the week relative to the experimental week (week of prayer) with the experimental week=t_0. The experimental and reference areas were chosen based on the main fishing grounds exploited during this period of the year. The reference area comprised three ICES rectangles between 51°30′ and 53°N and 2° and 4°E (32F2, 33F3 and 34F3). The experimental area comprised nine rectangles

Table 1. Frequency distribution, distance to fishing ground (nautical miles, nm) and mean engine power in relation with duration of fishing trips of Dutch beam trawlers (>300 hp) between 1990–1996.

Trip duration (days)	Number of trips	Percentage	Mean distance to fishing ground (nm)	Mean engine power (hp)
0	295	0.5%	28	1841
1	1245	2.2%	34	1869
2	2909	5.2%	45	1980
3	15 070	27.0%	48	2190
4	31 727	56.8%	64	2061
5	2257	4.0%	100	2279
6	504	0.9%	159	2258
7	364	0.6%	147	2063
8	517	0.9%	165	2117
9	614	1.1%	167	2268
10	280	0.5%	200	2570
11	32	0.1%	227	3001
12	6	0.0%	226	2184
13	2	0.0%	100	2830
Total	55 822	100%		1973

between 53°30′N and 55°N and 4° and 7°E. The number of trips in the experimental area was reduced by 73% during the experiment from an average of 67 trips in the week before (t_{-1}) and after the experimental week (t_{+1}) to an average of 18 trips in the experimental week (t_0). In the reference area, the average number of trips showed a minor change from 34 weeks in week t_{-1} and t_{+1}, to 33 trips in the week t_0. A second analysis was conducted by selecting only those vessels which had been fishing during the three week period from t_{-1} to t_{+1}. The reference area was similar as before. The experimental area was restricted to those rectangles in the southeastern North Sea where a substantial reduction in effort was observed in the week t_0. This additional selection criterion reduced the data set to 130 sets of 60 individual vessels.

In order to test whether the reduction in vessel density had an effect on the catch rate, the catch rates were compared between week t_{-1} and t_{+1} (reference weeks) and week t_0 (experimental week).

Statistical analysis

All statistical analysis were carried out with SAS employing the GENMOD routine (SAS, 1993). Only those interaction terms were included which *a priori* allowed a biological interpretation. All models tested were of type 3. The assumption of a normally distributed error term ε was tested by visual inspection of a probability plot of the residuals.

Results

Beam trawl vessels typically make trips of 3 to 5 days duration, leaving the harbour on Monday and landing their fish between Thursday and Friday (Table 1). Trips of more than 2 weeks did not occur. Trip duration is related to distance to the fishing ground and engine power. Larger vessels do generally make longer trips and go slightly farther offshore. The frequency distribution of the distance between port and fishing grounds is skewed and peaks at a distance between 30 and 90 nm (Fig. 3). A substantial difference exists between the distance to the fishing grounds between vessels sailing from southern harbours (<53°N) and those sailing from northern harbours (>53°N) (Table 2).

Revenue by trip (RPUE) were correlated to engine power (HP) and week number (WK=1 to 53) for each year separately:

$$\log_e RPUE = \alpha + \beta \log_e HP + WK + \varepsilon. \quad (3)$$

Only trips between 2 and 5 days were analyzed. The models explained between 44% and 62% of the variance. The regressions showed considerable differences among years, both in intercept and slope (Table 3). Revenues were highest in 1991 and lowest in 1996. The increase in revenue with engine power is partly due to the higher fishing speed in more powerful vessels. After correcting the revenues for the differences in fishing speed, the positive relationship between revenues and engine power remained (Fig. 4). Fitted revenues for a 2000 hp vessel varied seasonally with a peak in winter and autumn and a low during spring and summer (Fig. 5). In 1996, no autumn increase was observed. In other years, revenues tended to decrease towards the end of the year. This was particularly the case in 1990 and 1991 when revenues dropped at the end of the year and increased again in the last week of the year or in the first week of the new year.

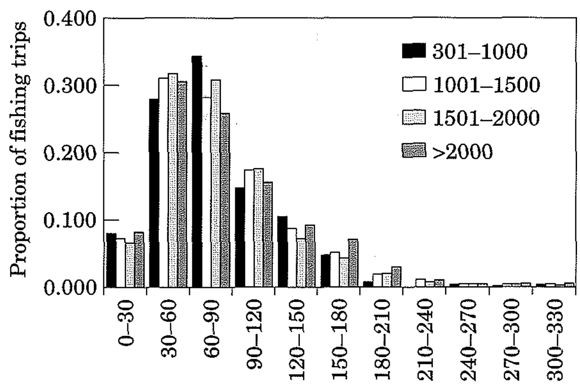

Figure 3. Frequency distribution of fishing trips by distance between port and fishing ground for four engine power classes (HP) of vessels.

In the next step, model (3) was extended to include year (YR), week number (WK), distance between port and fishing ground (D) and two interaction term between engine power and year and between distance and engine power class (HP):

$$\mathrm{Log_eRPUE} = \alpha + \beta \log_e \mathrm{HP} + \mathrm{YR} + \mathrm{WK} + \beta \log_e \mathrm{HP} \times \mathrm{YR} + \log_e \mathrm{HP} \times \log_e \mathrm{D} + \varepsilon \quad (4)$$

The full model explained 54% of the variance in log catch rate (Table 4). Although both interaction terms were statistically significant, each one explained only ± 0.2% of the variance. Engine power and week number explained most of the variance in RPUE, 23% and 24%, respectively, while distance between port and fishing ground explained 0.4% of the variance. The fitted revenues calculated from the full model showed a slight increase with distance from port, but the rate of increase was slightly smaller with increasing engine power (Fig. 6).

The positive relationship between RPUE and engine power raises the queston as to whether vessels of different engine power classes differ in their distribution in relation to the profitability of the fishing grounds. In the absence of independent data, profitability of a fishing ground (ICES rectangle) was estimated by the differenced between the observed RPUE and fitted RPUE from model 4. This residual RPUE estimates the relative profitability of an ICES rectangle in a particular week. A plot of the cumulative distribution of trips against profitability reveals that less powerful vessels (300–1000 hp and 1000–1500 hp) tended to allocate a larger proportion of their trips in less profitable rectangles, whereas the larger vessels allocated a larger proportion of their trips in the most profitable rectangles (Fig. 7). A comparison of the two largest engine power classes did not show such a difference in distribution. Tested against the cumulative distribution of the total fleet showed significant differences (Kolmogorov Smirnov, $p<0.01$) for all engine power classes except the >2000 hp.

The residual RPUE increases with vessel density up to 6 vessels per rectangle (Fig. 8a). Beyond this density residual RPUE appears to be independent of vessel density, although at high vessel densities (>20 vessels) some very high values of more than twice the weekly mean were observed as well as some values well below the weekly mean. On average 10 vessels fish in a rectangle with above average profitability.

The standard deviation of the residual RPUE showed a significant decline with increasing vessel density (Fig. 8b), indicating that the variability in individual

Table 3. Results of the GLM analysis of the log revenue per unit of fishing effort ($\log_e$ RPUE) as a function of log engine power (HP) and week number (WK), according to the model: $\log_e \mathrm{RPUE} = \alpha + \beta \log \mathrm{HP} + \mathrm{WK}$.

Year	α	SE	β	SE	r^2
1990	0.750	0.198	0.616	0.012	0.44
1991	0.525	0.186	0.707	0.012	0.54
1992	0.326	0.088	0.691	0.010	0.61
1993	0.000	0.088	0.735	0.011	0.62
1994	− 0.231	0.091	0.735	0.010	0.58
1995	− 0.942	0.093	0.850	0.011	0.57
1996	− 0.508	0.119	0.737	0.013	0.60

Table 2. Distance between port and fishing ground (nautical miles, nm) for different classes of engine power of vessels working from southern (<53°N) and northern harbours (>=53°N).

	Southern harbours			Northern harbours		
Engine power (hp)	Mean distance (nm)	sdev	n	Mean distance (nm)	sdev	n
301–1000	31.9	48.3	224	68.6	35.4	1255
1001–1500	44.6	41.9	3835	77.9	44.1	4363
1501–2000	44.5	46.7	6688	65.2	41.0	15 635
>2000	59.0	61.5	8096	65.0	41.4	12 174

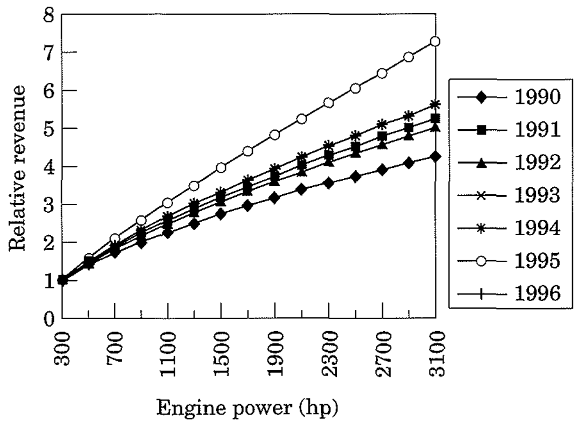

Figure 4. Relationship between the relative revenue per swept area and engine power by year.

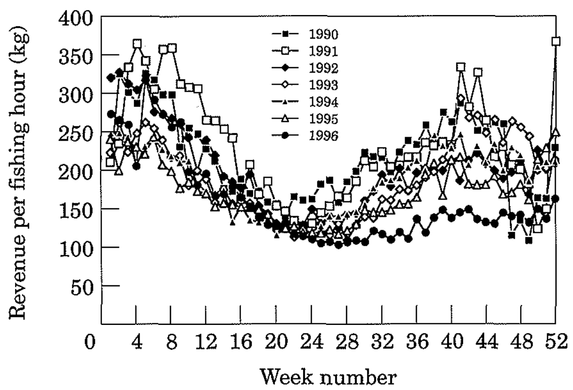

Figure 5. Weekly changes in revenue per fishing hour of vessels of 2000 hp between 1990–1996.

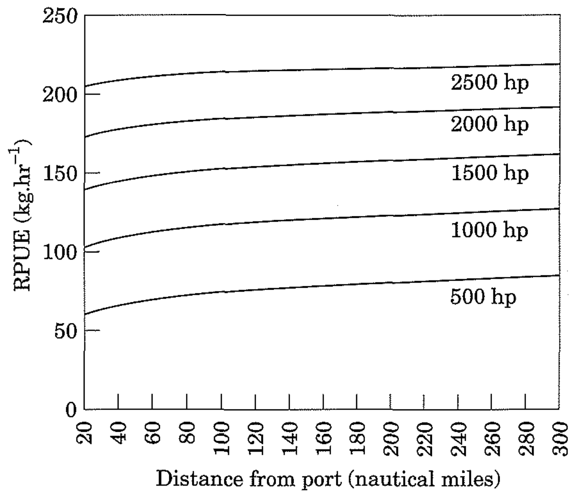

Figure 6. Relationship between the fitted revenue per unit of fishing effort and distance between port and fishing ground for different engine power classes.

RPUE is highest on fishing grounds fished by only one or a few vessels.

The cumulative distribution of effort in relation to vessel density showed that 65% of all fishing trips were allocated to rectangles with an above average RPUE and densities of >=6 vessels (Fig. 8c). Only in 35% of the fishing trips, rectangles were fished with a below average RPUE and at densities of less than five vessels. Mean density was estimated at eight vessels per rectangle per week. The mean engine power shows a slight decrease in relation with vessel density (Fig. 8c).

The effect of a change in vessel density in the week of prayer was analyzed by comparing the changes by week of the mean $\log_e$ RPUE in the experimental and reference area (Table 5). After back-transformation, the RPUE in the week of prayer is 15% higher than in the neighbouring weeks in the experimental area, whereas in the reference area the RPUE is only 2% higher. The relative increase in RPUE in the experimental area coincides with an almost fourfold reduction in fishing effort as measured by the number of observations in the experimental area. In the reference area, only a minor

Table 4. Analysis of covariance table from the GLM analysis of $\log_e$ RPUE and engine power (log HP), distance from port (D), year (YR) and week number (WK) according the model: $\log_e \text{RPUE}=\alpha+\beta\log \text{HP}+\gamma\log \text{D}+\text{YR}+\text{WK}+\beta i\log\text{HP}\times\text{YR}+\log\text{HP}\times\log\text{D}+\varepsilon$. Data: VIRIS 1990–1996, excluding November and December records.

	SS	df	MS	F	P-value
logHP	2396.7	1	2396.7	21 717	<0.01
logD	45.6	1	45.6	414	<0.01
YR	712.0	6	118.7	1076	<0.01
WK	2533.5	51	58.9	413	<0.01
Error	4954.1	44 951	0.1102		
logHP × YR	21.8	6	3.63	33.2	<0.01
logHP × logD	16.3	1	16.31	149.0	<0.01
Error	4913.7	44 900			
Total	10603.2	44 958			

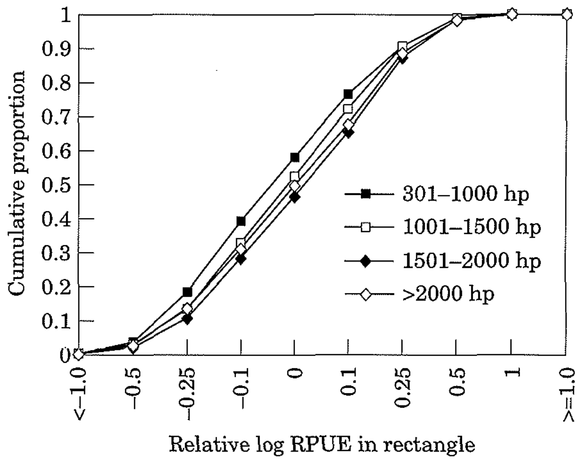

Figure 7. Relationship between the cumulative proportion of trips and rectangle profitability for four engine power classes. Profitability was expressed as the mean residual revenue per unit of fishing effort by rectangle by week.

change in fishing effort during the week of prayer was observed.

Because a specific component of the fleet left the fishery during the week of prayer, the above results may be biased if that component has a different engine power. Therefore, a more refined analysis was conducted that was limited to vessels that fished during the experimental week, as well as in the two reference weeks in the experimental area or in the reference area. In the experimental area the mean RPUE was 9% higher in the experimental week than in the neighbouring weeks, in contrast to the RPUE in the reference area that declined steadily over the three weeks (Table 6). Analysis of covariance of $\log_e$ RPUE as a function of ship (individual vessel code), Year, Area (two levels: 1 = experimental area; 2 = reference area), Week-class (1 = week of prayer; 2 = week prior to and week following the week of prayer) and the interaction terms between Area and Week-class and between Ship and Year corroborated this result. The parameter estimate of the experimental effect indicated that the RPUE of the selected vessels was 10% higher in the experimental area when the vessel density was reduced. The difference was significant at the 5% level (Table 7).

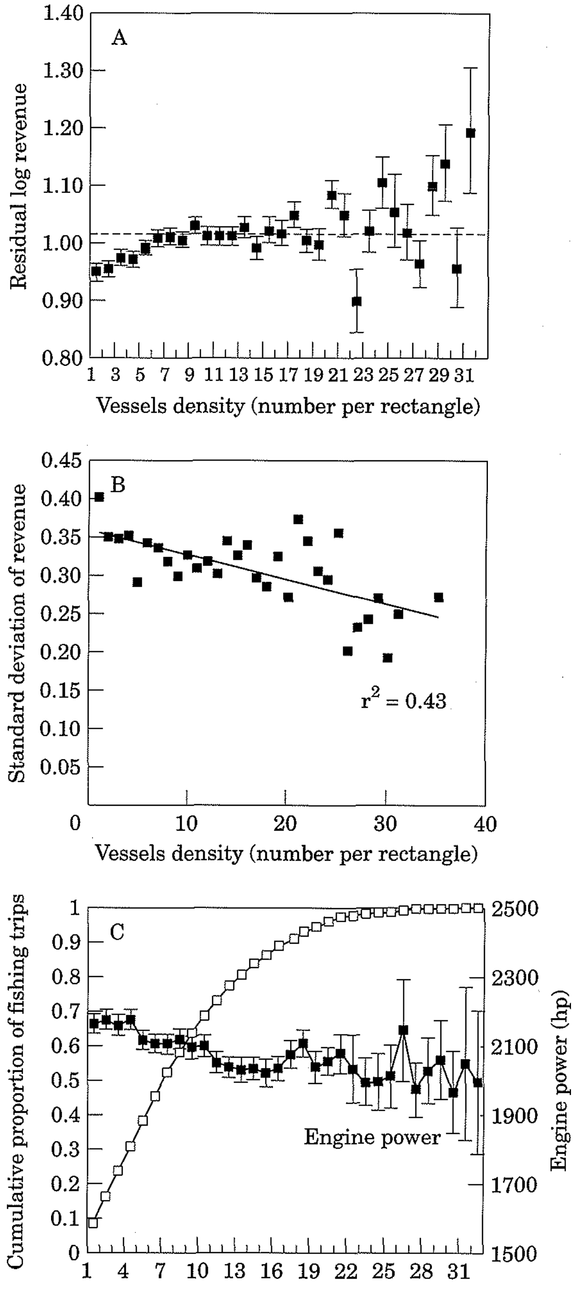

Figure 8. Relationship between vessel density and (a) a mean residual revenue per unit of effort (±2 s.e.). --- line represents the mean residual revenue in rectangles with a density of >=6 vessels. (b) Standard deviation of the residual revenue per unit of effort ($r^2 = 0.43$, $n = 34$, $p < 0.05$). (c) Average engine power (±2 s.e.) (filled symbols) and cumulative proportion of trips (open symbols).

Discussion

We expressed catch rate as the revenue per unit of fishing effort taking account of differences in price between the targeted species. The calculated RPUE is only a crude proxy of the true economic revenue, because differences in market value between size categories, variations in market value over time, and the contribution to the revenue of non-quota species such as turbot, brill, dab, could not be taken into account.

Another complication, which had to be ignored here is the effect of quota management on the fishing patterns of the fleet. Because the flatfish quota is allocated to

Table 5. Mean $\log_e$ RPUE, standard error and number of observations in the experimental week (0) and four weeks before and following the experimental week in the reference area and the experimental area. Pooled data for 1990–1996.

	Experimental area			Reference area		
Week	Mean	SE	N	Mean	SE	N
−4	5.531	0.024	369	5.529	0.024	224
−3	5.531	0.019	407	5.542	0.021	240
−2	5.571	0.017	476	5.859	0.023	248
−1	5.510	0.017	496	5.577	0.020	250
0	5.645	0.033	127	5.543	0.021	228
1	5.493	0.019	440	5.467	0.022	232
2	5.449	0.020	358	5.383	0.022	183
3	5.351	0.021	400	5.263	0.030	210
4	5.300	0.025	398	5.299	0.025	216

individual fishermen (ITQ), the landings do not necessarily reflect the catch. The latter may have affected the data recorded at the end of the quota year as suggested by the rather sudden drop in catch rate in November of 1990 and 1991 which bounced back in the last week of the year (1990) or in the first week of the new year (1991) (Fig. 5). In order to avoid this problem, the analysis was restricted to fishing trips made in the first 10 months of the quota year, when such problems are probably minor.

The analysis showed that the catch rate was substantially affected by the engine power, even after correction for differences in fishing speed (Fig. 4). Another factor which could have contributed to the difference in catch rate is the overall weight of the gear and its effect on the ground contact of the gear. Under conditions of a rough sea the motions of the vessel may lift the trawl from the seabed (van de Nat *et al.*, 1992) allowing fish herded in front of the net to escape (Wardle, 1986). A check of this potential bias in the estimated relationship was conducted by estimating the relationship between catch rate and engine power separately for weeks with calm weather (winds throughout the week $<=4$ m s^{-1}) and weeks with rough weather (wind$>=5$ m s^{-1}) in the first quarter of the period 1990–1996. No difference in the slope of the relationship was observed. The difference in catch rate, therefore, may be interpreted as an indication of a difference in competitive ability among fishing vessels differing in engine power.

In the context of the ideal free distribution, two types of models can be distinguished that result in different distribution patterns of predators in relation to their resources (Tregenza, 1994; Lessels, 1995; van der Meer

Table 6. Mean $\log_e$ RPUE of vessels fishing in the experimental week (0) as well as the reference weeks (−1, 1) and mean vessel density per rectangle within the experimental area where vessel density was reduced substantially and in the reference area.

	Experimental area				Reference area			
	$\log_e$ RPUE			Vessel density	$\log_e$ RPUE			Vessel density
Week	Mean	SE	n	Trips per rectangle	Mean	SE	n	Trips per rectangle
−1	5.570	0.049	23	16.5	5.543	0.025	107	16.5
0	5.659	0.065	23	4.4	5.462	0.020	107	16.1
1	5.563	0.064	23	14.8	5.395	0.025	107	17.0

Table 7. Analysis of covariance of the $\log_e$ RPUE of vessels fishing in the experimental week and reference weeks in rectangles within the experimental area and in the reference area presented in Table 6. Upper panel gives the results according the model: $\log_e$ RPUE=Ship+Year+Week-class+Ship × Year+Area × Week-class, with class variables Ship (60 individual vessels), Year (1990, 1992–1996), Area (reference area, experimental area) and Weekcls (reference weeks t_1, t_{+1} and experimental week t_0). The lower panel gives the parameter estimate of the relative change in $\log_e$ RPUE in the experimental week and experimental area compared to the reference weeks and area.

Source	DF			ChiSquare	Pr>Chi
Ship	58			431.3	0.0001
Year	5			73.60	0.0001
Weekcls	1			5.97	0.0145
Ship × Year	58			88.47	0.0061
Area × Week-class	1			6.99	0.0082
Parameter	DF	Estimate	Std Err	ChiSquare	Pr>Chi
Experiment (Area × Week-class)	1	0.0963	0.0362	7.052	0.0079

and Ens, 1997). In the first type ("continuous input" model), prey is continually put into the system and the catch rate is proportional to the input rate. In the second type, a standing stock of prey is exploited and catch rate will be proportional to the prey density ("standing stock" model). Exploitation will lead to a gradual decrease in standing stock. In both models, competitive interactions may affect the catch rate.

The flatfish species targeted by beam trawlers are characterized by annual recruitment and a gradual growth. Annual fishing mortality rate of the exploited population of plaice and sole is between $F=0.40$ and $F=0.50$ and natural mortality $M=0.10$ (ICES, 1999). This would suggest that on the time scale (one week) and the spatial scale ($\pm 30 \times 30$ nm rectangles) used in this study, these species will provide a non-renewable resource conforming with the "standing stock" model. However, within rectangles flatfish may aggregate in spawning areas or in areas of high food availability, conforming to the "continuous input" model.

The ideal free distribution predicts that ideal free fishermen will have revenues that are independent of vessel density. This prediction was only partly supported by the results. Although in 65% of the fishing trips revenue was independent of vessel density, the standardized revenue increased by 4% when vessel density increased from one to six vessels per rectangle corresponding to 35% of the fishing trips. These results, thus, do not corroborate the IFD model. The deviation may be due to violation of the assumption about the perfect knowledge skippers have about the distribution of their resources. In the real world, no perfect knowledge exist, and vessels may need to explore new fishing grounds continuously. In the rectangles fished by only a few vessels, the variability in revenue was generally higher than in rectangles fished by a larger number of vessels (Fig. 8b). Also, the average engine power of the vessels was slightly higher than in rectangles fished at above average revenue and higher vessel densities (Fig. 8c). When viewed against the result that fishing effort of more powerful vessels was predominantly exerted in rectangles with higher revenues (Fig. 7), this may suggest that larger vessels show more exploration behaviour and encounter a more variable revenue. It can not be excluded that the vessels exploiting rectangles of low vessel density may actually have experienced higher revenues due to the contribution of non-quota species.

These results generally, though not perfectly, corroborated the predictions from the ideal free distribution. Further support of the IFD is given by the analysis of the distribution of the various engine power classes in relation to the profitability of the fishing grounds. The analysis indicated that the less powerful vessels allocated relatively more effort in the poorer rectangles consistent with the prediction of the IFD including differences in competitive abilities (Sutherland and Parker, 1985).

Competitive interactions among vessels are a prerequisite of the IDF. Competitive interactions among beam trawl vessels are not unlikely. More than 50% of the fishing trips occur in ICES rectangles fished by 6 or more vessels (Fig. 8c) and more than 70% of the beam trawl effort was shown to occur in only 20% of the area fished (Rijnsdorp *et al.*, 1998).

The strongest support for competitive interaction among fishing vessels is obtained from the 10% increase in revenue of vessels during the week of prayer when vessel density was reduced to $\pm 25\%$ from 17 vessels per rectangle to four vessels per rectangle. Although these vessel densities only represent the Dutch beam trawl fleet, they will be close to absolute values because in the experimental areas only a few English beam trawlers may be expected to have fished. The evidence presented cannot be considered a strict proof for competitive interactions among vessels because an alternative explanation that the peak in the catch rate in the week of prayer coincides with the seasonal peak in the catch rate irrespective of vessel density can not be excluded. This alternative explanation however is less likely because Figure 5 shows that the timing of the seasonal peak in catch rate varies across years.

There may be several possible mechanisms underlying the observed competitive interactions among vessels: exploitation competition and interference competition. Which one, or both, are involved cannot be evaluated from data at this level of resolution. Knowledge on the nature of the competitive interactions among predators is important because this affects the spatial distribution over their resources (van der Meer and Ens, 1997; van der Meer, 1997). In a study of the dynamics of beam trawl fishing within trips, it was shown that fishing comprized of an exploratory and an exploitation phase. Within the exploitation phase, vessels stayed put and heavily fished local fishing grounds. At the local fishing ground, catch rate declined by $\pm 10\%$ over a 48-h time period. The rate of decline was higher in vessels with less powerful engines, suggesting that interference competition among vessels through a change in behaviour of flatfish in response to fishing disturbance may have contributed to the decline in catch rate (Rijnsdorp *et al.*, 2000).

Competitive interactions among vessels may have important implications for fish stock management. First, they may bias the index of abundance of commercial fish stock sizes estimated by the catch per unit of effort of commercial fisheries (Gillis *et al.*, 1993; Gillis and Peterman, 1998) something which is not always realised (Sampson, 1991). Second, they may affect the catchability coefficient as defined in the equation $F=q \times$ effort. North Sea flatfish stock are now overexploited and fishing mortality has to be reduced (ICES, 1999), a disproportional reduction in fishing effort might be necessary to achieve the fishing mortality target. Although other factors such as changes in the distribution area of fish populations in relation to stock abundance (Gulland, 1964; Paloheimo and Dickie, 1964; MacCall, 1990; Swain and Sinclair, 1994) may also influence the relationship between effort and fishing mortality rate, this study highlights that the fisheries management should take into account the potential effects of competitive interactions among vessels. For example, a reduction in the number of vessels, resulting in a reduction in competitive interactions and an increase in q, may have a different impact on the fishing mortality than a reduction of effort in which competitive interactions are not reduced or even increased (closed seasons, closed areas). The study of vessel interactions and their implications seems to have been largely neglected. We hope to have shown that careful studies of competitive interactions among vessels and studies on the implications of various models are urgently needed to provide a sound basis for management advice on the reducing fishing effort levels.

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References

Abrahams, M. V., and Healy, M. C. 1990. Variation in the competitive abilities of fishermen and its influence on the spatial distribution of the British Columbia salmon troll fleet. Canadian Journal of Fisheries and Aquatic Sciences, 47: 1116–1121.

Abrahams, M. V., and Healy, M. C. 1993. Some consequences of variation in vessel density: a manipulative field experiment. Fisheries Research, 15: 315–322.

Daan, N. 1997. TAC management in North Sea flatfish fisheries. Journal of Sea Research, 37: 321–341.

Fretwell, S. D., and Lucas, H. L. 1970. On territorial behavior and other factors influencing habitat distribution in birds. I. Theoretical development. Acta Biotheoretica, 19: 16–36.

Gillis, D. M., Peterman, R. M., and Tyler, A. V. 1993. Movement dynamics in a fishery: application of the ideal free distribution to spatial allocation of effort. Canadian Journal of Fisheries and Aquatic Sciences, 50: 323–333.

Gillis, D. M., and Peterman, R. M. 1998. The implications of interference and the ideal free distribution to the interpretation of CPUE. Canadian Journal of Fisheries and Aquatic Sciences, 55: 37–46.

Gulland, J. A. 1964. The reliability of the catch per unit of effort as a measure of abundance in North Sea trawl fisheries. Rapport et Proces Verbaux des Réunions Conseil international de l'Exploration de la Mer, 155: 99–102.

Healey, M. C., and Morris, J. F. T. 1992. The relationship between the dispersion of salmon fishing vessels and their catch. Fisheries Research, 15: 135–145.

Hilborn, R. 1985. Fleet dynamics and individual variation: why do some people catch more fish than others. Canadian Journal of Fisheries and Aquatic Sciences, 42: 2–13.

Hilborn, R., and Ledbetter, M. 1979. Analysis of the British Columbia salmon purse seine fleet: dynamics of movement. Journal of the Fisheries Research Board of Canada, 36: 384–391.

Hilborn, R., and Walters, C. J. 1992. Quantitative Fisheries Stock Assessments: Choice, Dynamics and Uncertainty. Chapman and Hall, New York. 570 pp.

ICES. 1999. Report of the working group on the assessments of demersal stocks in the North Sea and Skagerrak. ICES C.M. 1999/ACFM:8.

Kennedy, M., and Gray, R. D. 1993. Can ecological theory predict the distribution of foraging animals? A critical analysis of experiments on the ideal free distribution. Oikos, 68: 158–166.

Lessells, C. M. 1995. Putting resource dynamics into continuous input ideal free distribution models. Animal Behaviour, 49: 487–494.

Lindeboom, H. J., and Groot, S. J. de. (eds) 1998. IMPACT-II. The effects of different types of fisheries in the North Sea and Irish Sea benthic ecosystems. NIOZ-Rapport 1998-1. RIVO-DLO Report C003/98.

MacCall, A. D. 1990. Dynamic Geography of Marine Fish Populations. Washington Sea Grant Program. University of Washington Press, Seattle. 153 pp.

Meer, J. van der, and Ens, B. 1997. Models of interference and their consequences for the spatial distribution of ideal free predators. Journal of Animal Ecology, 66: 846–858.

Meer, J. van der 1997. Ideal free distribution for unequal predators. Oikos, 80: 301–310.

Milinski, M., and Parker, G. A. 1991. Competition for resources. *In* Behavioural Ecology: an evolutionary approach, pp. 137–168. Ed. by J. R. Krebs, and N. B. Davies. Blackwell Scientific Publications, Oxford.

Nat, C. G. J. M. van der, Marlen, B. van, and Klein Woud, J. 1992. The effect of shipmotions on the dynamic behaviour of a beam trawl. ICES CM 1992/B:18, 14 pp.

Paloheimo, J. E., and Dickie, L. M. 1964. Abundance and fishing success. Rapport et Proces Verbaux des Réunions Conseil international de l'Exploration de la Mer, 155: 152–163.

Rijnsdorp, A. D., Buys, A. M., Storbeck, F., and Visser, E. G. 1998. Micro-scale distribution of beam trawl effort in the southern North Sea between 1993 and 1996 in relation to the trawling frequency of the sea bed and the impact on benthic organisms. ICES Journal of Marine Science, 55: 403–419.

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

SAS. 1993. SAS Technical report P-243. SAS/STAT Software: the GENMOD procedure. SAS Institute Inc., Cary, USA. 88 pp.

Salz, P. 1996. ITQs in The Netherlands: 20 years of experience. ICES CM 1996/P:18.

Sampson, D. B. 1991. Fishing tactics and fish abundance, and their influence on catch rates. ICES Journal of Marine Science, 48: 291–301.

Swain, D. P., and Sinclair, A. F. 1994. Fish distribution and catchability: what is the appropriate measure of distribution? Canadian Journal of Fisheries and Aquatic Sciences, 51: 1046–1054.

Sutherland, W. J. 1983. Aggregation and the "ideal free" distribution. Journal of Animal Ecology, 52: 821–828.

Sutherland, W. J., and Parker, G. A. 1985. Distribution of unequal competitors. *In* Behavioural ecology. Ecological consequences of adaptive behaviour, pp. 255–273. Ed. by R. M. Sibley, and R. H. Smith. Blackwell Scientific Publications, Oxford.

Tregenza, T. 1994. Common misconceptions in applying the ideal free distribution. Animal Behaviour, 47: 485–487.

Wardle, C. S. 1986. Fish behaviour and fishing gear. *In* Behaviour of teleost fishes, pp. 463–495. Ed. by T. J. Pitcher. Chapman and Hall, London.