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Micro-scale distribution of beam trawl e ort 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

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This paper analyses the spatial distribution of fishing e ort in a sample of 25 Dutch commercial beam trawlers fishing for sole and plaice in the period 1993–1996, based on an automated recording system with an accuracy of about 0.1 nautical mile. Intensive fishing occurred along the borders of the closed areas (12 mile zone and the "plaice-box", a protected area in the eastern part of the North Sea) and at certain o -shore grounds in the southern and central North Sea. E ort distribution was studied within 30 × 30 (ICES rectangles), 10 × 10, 3 × 3 and 1 × 1 nautical mile squares and showed a patchy distribution. The degree of patchiness decreased with resolution. Within 3 × 3 mile squares, beam trawling was randomly distributed in some parts of the most heavily fished ICES rectangles but patchily distributed in others. Within 1 × 1 mile squares, the distribution became random within more than 90% of the squares. The micro-distribution showed a remarkable similarity between the 4 years with a mean coe cient of overlap of 0.66, range 0.56–0.76. The micro-distribution of the sampled vessels was raised to the total Dutch fleet in order to estimate the frequency at which the sea bed was trawled. It was estimated that during the four year study period in eight of the most heavily fished rectangles of the North Sea, 5% of the surface area was trawled less than once in 5 years and 29% less than once in a year. The surface area of the sea bed that was trawled between 1 and 2 times in a year was estimated at 30%. The surface area trawled more than five times in a year was estimated at 9%. The relevance of the findings for the study of the impact of beam trawling on the benthic fauna is discussed.

Key words: beam trawling, e ort distribution, ecosystem e ects, benthos.

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Introduction

The possible e ects of fishing activities on the marine ecosystem is a growing concern (Graham, 1955; ICES, 1988, 1994; Messieh *et al.*, 1991; Lindeboom, 1994; Auster *et al.*, 1996). Following the re-introduction in the 1960s of the beam trawl as the main gear employed in the flatfish fishery in the North Sea, attention focused on the e ect of beam trawling on the benthos. The beam trawl is a heavy gear that employs a number of chains that disturb the upper layer of the sediment to activate flatfish. Within the ICES community, a number of experiments on the e ect of the beam trawl on the sea bed were carried out in the early 1970s (de Groot and Apeldoorn, 1971; Houghton *et al.*, 1971; Bridger, 1972; de Clerck and Hovart, 1972; de Groot, 1972; Margetts and Bridger, 1971). The conclusion drawn at that time was that the e ect was not greater than that of other fishing gears, although no assessment of the potential e ects on the benthos community was made (for a review see: de Groot, 1984). The continuous increase in the beam trawl fleets with regard to number of vessels, motor power, weight of the gear and fishing speed, has resulted in renewing the interest

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regarding the possible impact. In 1988, an ICES study group re-addressed this question and concluded that the change in the benthic community from low productive, slowly reproducing organisms to quickly reproducing, opportunistic species could be partly related to the e ect of fishing. However, no firm conclusions could be drawn because (1) the relevant information on the physical e ect of a trawl on the sea bed was missing, and (2) other anthropogenic influences such as pollution and eutrophication could play a role (ICES, 1988).

Restricting ourselves to the impact of beam trawling on the benthic fauna, two key parameters have to be considered: (1) the penetration depth of the beam trawl in relation to the sediment type; (2) the spatial distribution of beam trawl e ort. In the North Sea and adjacent areas, the study of the physical e ect of beam trawl on the sea bed, and its ecological impact, was started in 1989 (Bergman and Hup, 1992; de Groot and Lindeboom, 1994; Kaiser and Spencer, 1996; Kaiser *et al.*, 1996). Information on the spatial distribution of beam trawl e ort, available at a resolution of 30×30 miles, showed that in the heavily fished rectangles every square metre of the sea bed was on average, trawled five to seven times per year (Rauck, 1985). This rather alarming figure together with reports of substantial changes in the benthic community led to a recommendation to close part of the Dutch economic zone for all fishing in order to protect the benthos (Bergman *et al.*, 1991).

The estimated trawling frequencies, however, may be biased because fishing e ort may not be homogeneously distributed within each 30×30 mile rectangle, for example if target fish species show a patchy distribution or if parts of the sea bed are untrawlable (stony grounds, soft bottoms, shipping lanes). A proper evaluation of the possible e ects of beam trawling, therefore, has to take account of the micro-distribution of beam trawl e ort.

Information on the micro-distribution of fishing e ort may also be relevant for other problems. It may form the basis for a study of: (a) the fishing strategies of skippers (Hilborn, 1985), (b) interference between fishing vessels, which may a ect the relationship between the catch per unit of e ort and stock abundance (Gillis *et al.*, 1993), and (c) the small scale distribution and dynamics of spatial distribution of target species (Gulland, 1964).

In this paper we study the spatial distribution of beam trawling by Dutch vessels from EC-logbook data and from automated position recordings from a sample of 25 vessels. The Dutch fleet comprise 50–70% of the total beam trawl e ort in the North Sea. This paper describes the methodology used and analyses the e ort distribution at various levels of resoluton. Finally, the implications of the findings for the study of the impact of beam trawling on the benthic community is discussed.

Material and methods

Spatial distribution of beam trawlers

Data on the spatial distribution of beam trawlers was available from two sources: (a) EC-logbooks of the total Dutch fleet (VIRIS data base); (b) automated position recordings from a sample of 25 Dutch beam trawlers (APR data base).

VIRIS database

In the VIRIS database, the fishing e ort of the total fleet is registered on a spatial scale of 30×30 mile (ICES rectangles) based on the EC-logbook forms. The form contains information on the time of the start and end of the fishing trip, the gear used, the ICES rectangle fished and the landings by fish species. The database is designed for quota management purposes, it is under the responsibility of the Ministry of Agriculture, Nature management and Fisheries, but is available for research purposes.

APR data

Positions were recorded with an automated position recording system (APR) that was connected to the navigator (Decca, GPS, DGPS). The APR device has a separate power supply (24 Volts) and internal clock. The position information from the navigator is stored in a bu er and, after a fixed time interval, decoded and recorded on a removable memory card with an accuracy of 0.1 min ($\pm$ 180 m). The accuracy of the recorded position is less than that of the navigator ($\pm$ 12 to 100 m). Each position fix is based on one reading from the navigator.

All APR devices (MacKotter) and memory cards had a distinct identity number. At the start of each fishing trip, the skipper inserted a new memory card in the device and returned the card to RIVO at the end of the trip. When a memory card is inserted, software specifying, for instance, the registration interval is loaded and the time and first position are recorded. The internal clock was set at installation and checked at least every year.

The memory card was received at the laboratory, and after data control the position recordings were added to the computer database. For each position, the speed of the vessel (S) was calculated from the distance covered to the subsequent position. The speed during fishing $FS = \pm 6$ knots was related to the engine power of the vessel and di ered from the speed during steaming (about 12 knots). Position recordings were classified in

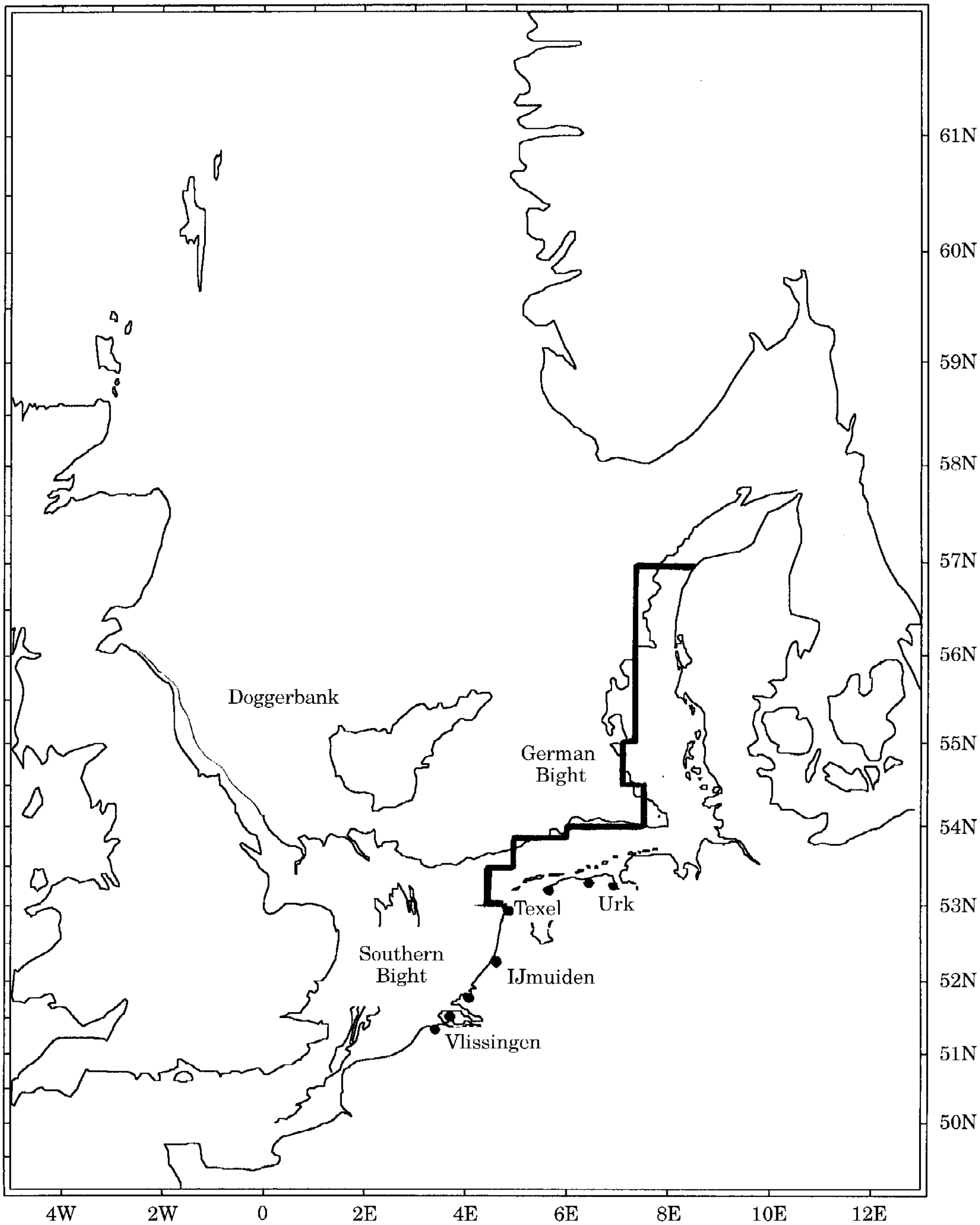

Figure 1. Map of the North Sea with the "Plaice Box", the 40 m depth contour and topographic names referred to in the text.

one of three classes (fishing, steaming, floating) based on the speed of the vessel. Hence fishing positions: $FS-2<=S<=FS+2$; steaming positions: $S>(FS+2)$; floating positions: $S<(FS-2)$.

The validity of this interpretation is illustrated by a comparison of the APR recordings and information recorded by the fishing skipper on the time of shooting and hauling the gear (Fig. 2). Periods of steaming to and from the fishing grounds at the beginning and end of the trip, as well as the intermediate change of fishing grounds on day 3, are clearly reflected in the calculated speeds from the APR recordings. Also, the regular pattern during 2 and 3 successive recordings of a low speed corresponds to the times of hauling the gear, which typically takes about 15 min. Erratic recordings of a high speed were found to occur in the regular pattern

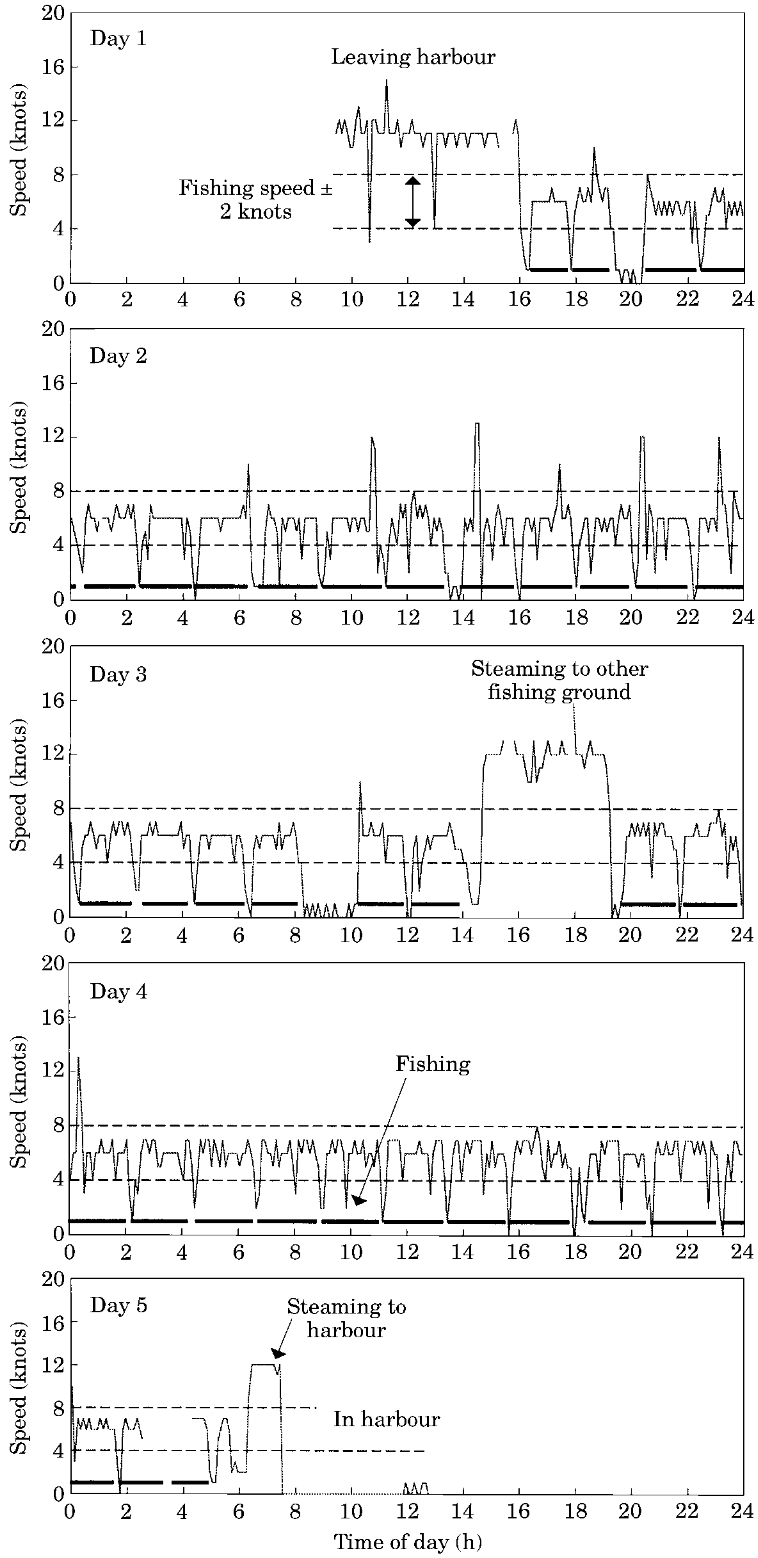

Figure 2. Speed during a single 5-day fishing trip. The speed was calculated from the distance between two successive position fixes and shows the steaming (± 12 knots), fishing (± 6 knots), and the moments of hauling the gear (0–4 knots). The fixes between the two dashed lines (fishing speed ± 2 knots) are interpreted as fishing positions. The black bars show the hauls from the logbook of the skipper. On the third day the vessel steamed to another fishing ground.

Table 1. Composition of (a) the Dutch beam trawl fleet by fishing harbour and size class (data for late 1993 from LEI-DLO: J. W. de Wilde pers. comm.) and (b) the APR sample.

	HP-class				
Harbour	301–1100	1101–1700	1701–2000	>2000	Total
(a) Dutch beam trawl fleet:					
Urk	4	18	35	25	82
Den Helder/Texel	0	8	18	16	42
IJmuiden/Stellendam	0	10	24	16	50
Vlissingen/Breskens	0	0	2	14	16
Total	4	36	79	71	190
(b) APR sample:*					
Urk	0	1	5	3	9
Den Helder/Texel	0	1	1	3	5
IJmuiden/Stellendam	0	0	5	2	7
Vlissingen/Breskens	0	1	1	2	4
Total	0	3	12	10	25

of fishing and hauling and are due to a single error in the position recording. The erratic occurrence of low speeds may be due to the change in the direction of the vessel, which will reduce the distance covered between two successive fixes during a tow. This may result in a number of fishing positions being erroneously considered to be non-fishing positions. On the other hand, some positions will be interpreted to be fishing positions when in actual fact they were non-fishing positions. This may occur close to the harbour where the vessel may not steam at maximum speed.

Sample of a beam trawl fleet

The sample, comprising 25 beam trawlers >300 HP (about 10% of the Dutch fleet), was stratified by fishing harbour and HP classes (Table 1). The sample included three vessels employing chain mats as generally used in the southern harbours of Vlissingen and Breskens (Fig. 1). In addition, one vessel of 300 HP was studied but the results are excluded from this report.

Vessels were selected from a list of potential participants compiled by local representatives of the fishing unions. The large majority of Dutch beam trawlers are skipper owned. The sample contained two vessels from the same company. Participation was on a voluntary basis.

The smaller HP-classes of 301–1100 and 1101–1700 were under-represented at the start of the project. However, during the project the smaller and generally older vessels became reduced in number as they were replaced by new larger vessels. Of the 25 vessels studied, 4 were replaced by other vessels from the same stratum during the course of the study.

APR registrations are available for 75% of the fishing trips. The missing data were mainly due to technical failures of the equipment (power failure, damaged memory card, etc.). A check of the first recorded position on the memory card, reflecting insertion of the card, showed no relationship with either the imposed restriction of the beam trawl fishery in space (closed areas) or in time (closed seasons). The project started in 1993 and is still ongoing.

Measure of patchiness

The spatial distribution of e ort can be characterized by the degree of patchiness (Pielou, 1977). If beam trawling takes place at random, the distribution of the registrations over the spatial units will follow a Poisson distribution where the mean fishing intensity (m) equals the variance (s^2). As measure of patchiness, hereafter denoted as C, we simply used the coe cient of dispersion (s^2/m). C-values larger than 1 indicate an increasingly patchy distribution, whereas C values <1 reflect increasingly uniform distributions. A value of $C=0$ reflects a fully uniform distribution. At $C=1$ the distribution is random.

Analysis of the micro-distribution

The spatial distribution of beam trawl e ort will be approached from di erent perspectives: (a) e ect of scale on the level of patchiness; (b) micro-distribution of individual vessels; (c) trawling frequency of the sea bed; (d) the level of overlap in micro-distribution among vessels and among years.

Micro-distribution within spatial windows

The question addressed here is how the spatial distribution varied at di erent levels of spatial resolution. Spatial windows were sub-divided into 100 sub-units and the coe cent of dispersion was calculated from the mean and variance of the number of beam trawl

Table 2. Summary of the micro-distribution of beam trawling of individual vessels: Sum is the total number of beam trawl fixes in the period 1993–1996: m is the mean number of beam trawl fixes per 3 × 3 nautical mile square per year: s.d. is the standard deviation: C is the index of patchiness: n is the number of 3 × 3 nautical mile squares fished in the period 1993–1996.

Vessel	Sum	m	s.d.	C	n
6	152 520	18.6	47.09	119	1556
11	58 629	41.8	72.11	124	782
21	73 242	48.6	85.65	151	898
22	113 210	38.6	81.23	171	1621
31	36 289	52.0	96.42	179	556
41	43 223	40.8	63.19	98	659
42	32 006	25.7	45.88	82	1014
43	15 735	15.7	19.75	25	732
44	75 417	44.1	72.05	118	957
45	56 440	41.5	86.66	181	705
46	51 230	37.5	53.68	77	686
47	74 482	117.1	224.86	432	252
48	47 178	19.2	36.19	68	1720
49	81 012	39.2	73.55	138	929
50	54 489	91.6	115.49	146	298
51	53 559	99.7	117.99	140	259
52	14 625	26.0	45.36	79	562
61	14 577	158.4	160.05	162	92
62	16 580	35.3	61.92	108	469
82	73 219	17.7	25.48	37	2120
83	110 097	79.7	140.99	249	659
84	192 124	43.4	68.41	108	933
85	105 139	25.1	42.96	74	1903
86	22 326	16.5	30.58	57	1151
87	91 340	34.8	74.06	158	1304
88	64 379	30.9	51.32	85	1202
89	46 628	31.4	45.23	65	831
90	77 555	30.1	45.47	69	1422
91	27 220	16.8	25.61	39	1494
Mean	64 637	45.4	72.7	121.9	957.4
s.d.	41 367	33.4	44.8	78.6	517.3

fixes over the 100 sub-units. Four levels of resolution corresponding to the spatial windows, indicated in the following text table, were considered.

Window size	Resolution
30′ latitude × 60′ longitude (±30 × 30 mile)	±3 mile
10′ latitude × 20′ longitude (±10 × 10 mile)	±1 mile
3′ latitude × 6′ longitude (±3 × 3 mile)	±0.3 mile
1′ latitude × 2′ longitude (±1 × 1 mile)	±0.1 mile

The largest window corresponds to the ICES rectangle. The ±0.1 nautical mile resolution reflects the highest level of resolution possible given the accuracy of the data.

Micro-distribution of individual vessels

From the perspective of the individual vessel, the micro-distribution is the result of the fishing strategy employed by the skipper where he balances the exploitation of local fish patches found and the search for these local concentrations. The coe cient of patchiness was calculated over those spatial units where one or more position fixes were recorded.

Estimate of the trawling frequency of the sea bed

The frequency with which the sea bed is trawled annually was estimated in a two-step procedure. In the first step, the total number of fishing days in each ICES rectangle was calculated for the total Dutch beam trawl fleet from the VIRIS database. In the second step, the micro-distribution of the fleet within each ICES rectangle was raised to the fishing days of the total fleet.

The trawling frequency per spatial unit i within ICES rectangle j, (Fij) can be calculated according to $Fij = Rij \times (Tj/Nj) \times Aij^{-1}$ where Rij is the number of APR fishing position recordings in sub-unit i of rectangle j; Tj = the total number of fishing days of the total fleet in ICES rectangle j; Nj = fishing days of the sampled fleet in ICES rectangle j; Aij = the number of APR recordings corresponding to a beam trawl intensity of once every year. In calculating Nj it was

Table 3. Summary of the micro-distribution of beam trawling of the sampled vessels by year and the number of days at sea of the total Dutch beam trawl fleet from the VIRIS data base. Sum is the total number of beam trawl fixes; m is the mean number of beam trawl fixes per 3 × 3 nautical mile square; s.d. is the standard deviation; C is the index of patchiness; n is the number of 3 × 3 nautical mile squares.

Year	Sum APR	m	s.d.	C	n	Days at sea total fleet (VIRIS)
1993	361 031	97.8	152.1	236	3690	36 079
1994	512 665	117.1	172.8	255	4379	37 981
1995	540 931	139.5	286.0	586	3877	37 762
1996	459 843	107.6	175.9	287	4273	31 166
1993–1996	1 874 470	341.3	593.8	1033	5493	142 988

assumed that one fishing day corresponds to 20 fishing hours.

Aij was calculated from the surface area trawled between sucessive APR recordings and the surface area of the spatial unit fished. For the Dutch beam trawl fleet, fishing speed is on average 6 knots, beam trawl width is 12 m and the number of beam trawls is two. Thus, one APR registration (6 min) corresponds to a surface area trawled of 0.02667 km^2. At 53°N, the surface area of a sub-unit of 1′ latitude × 2′ longitude equals to $1.852 \times 2 \times 1.852 \times \cos(\text{latitude}) = 4.13\ km^2$. Hence, at $4.13/0.02667 = 155$ APR registrations a 1′ latitude × 2′ longitude sub-unit is trawled on average 1 time per year.

Coe cient of overlap

The degree of overlap between micro-distributions in two sub-sets (among vessels and among years) was calculated using the overlap coe cient of Horn (1966):

$$O = 2\sum_j (p_{aj}p_{bj}) \Big/ \left(\sum_j p_{aj}^2 + \sum_j p_{bj}^2 \right)$$

where p_{aj} = the proportion of registrations in spatial unit j of ship a.

The overlap coe cient ranges between 0 and 1. A coe cient of 0 implies that both vessels are fishing in completely di erent spatial units, whereas a coe cent of 1 reflects that both vessels have fished in exactly the same spatial units at similar relative intensities.

Results

Micro-distribution of individual vessels

Individual vessels tend to concentrate their e ort in a relatively small part of the potentially available area. The number of 3 × 3 nautical mile squares trawled by individual vessels was on average 957 (Table 2), corresponding to 17% of the total number of 3 × 3 nautical mile squares trawled by the sampled vessels (5493, Table 3), but varied substantially among vessels (Table 2). One vessel (#61) concentrated its fishing activity on only 92 3 × 3 nautical mile squares. Vessel #82 on the other hand fished almost 40% (2120) of all the 3 × 3 nautical mile squares fished by the sampled vessels during the 4 year study. The mean number of beam trawl fixes in a 3 × 3 nautical mile square was 45 (range 16–158). The coe cient of patchiness (C_{mean} = 122, range 25–432) showed that the distribution of beam trawl e ort was highly patchy for all of the vessels studied (Table 2). The total area fished in the 4 years of study was, on average, 4055 squares of 3 × 3 miles (range 3690–4379, Table 3). Over the 4-yr period the area fished was only 35% larger (5493 squares).

The overlap in the micro-distribution of individual vessels was studied by taking account of the harbour or origin: I – Vlissingen, Breskens, Arnemuiden (VLI, BR, ARM); II – Stellendam (GO, OD); III – Den Helder, Texel (HD, TX) and IV – Urk (UK). The single vessel from IJmuiden showed a very distinct spatial distribution and was omitted from the analysis. Comparison of the overlap coe cients between individual vessels showed a large variation. Some vessels show overlap percentages as high as 0.5, whereas others show no or hardly any overlap (Fig. 3). Overlap coe cients are generally higher within groups than among groups (Table 4). The overlap coe cients between di erent groups declined with increasing distance between harbours.

Comparing the within group coe cients showed that these were higher in the southern harbours (I and II) than in the more northern harbours (III and IV). This may be related to the larger sea area available at similar distances for the northern harbours.

With the exception of Vlissingen, the overlap in the micro-distribution between vessels increased when analysed for ICES rectangles separately, especially when vessels of di erent groups were compared (Table 5). This indicates that when fishing in the same ICES rectangle,

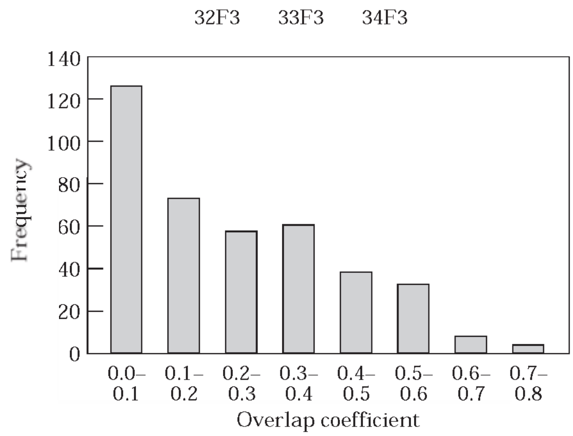

Figure 3. Frequency distribution of the coe cient of overlap between vessels fishing in the same rectangle.

individual vessels choose the same fishing grounds irrespective of their harbour of origin. The slightly lower overlap between the vessels of group I with those of other groups may be due to the use of chain mats in group I, which will allow them to fish rougher fishing grounds.

Overlap in micro-distribution between years and season

The micro-distribution of the sampled vessels shows that beam trawling is concentrated in the southern and south-eastern North Sea (Fig. 4). The pattern in the 4 years of study showed a strong similarity with an average coe cient of overlap of 0.66 (S.D.=0.069, n=6, Table 6). In the coastal areas, e ort is concentrated along the borders of the closed areas (Plaice Box, 12 mile zone; Fig. 4). In these areas beam trawling was not permitted for vessels exceeding 300 HP. The maps also show tracks of registrations in coastal areas, which reflect steaming at low speed to and from the fishing harbours.

Micro-distribution at di erent levels of resolution

Analyses carried out on a 3 × 3 mile scale indicates that beam trawling appears to have a patchy distribution. A

Table 5. Mean coe cient of overlap in the micro-distribution of individual vessels within a group and with vessels of other groups. In this analysis the overlap was calculated for individual ICES rectangles.

	Overlap	
	Vessels within group	Vessels of other groups
I – Vlissingen	0.231	0.103
II – Stellendam	0.324	0.178
III – Den Helder	0.341	0.174
IV – Urk	0.247	0.180

plot of the cumulative number of beam trawl registrations vs. the rank of the beam trawl intensity of the 3 × 3 mile square, shows that most of the beam trawling is carried out in only a part of the area that has been fished (Fig. 5). The graph, for instance, shows that 70% of the e ort occurred in only 20% of the total area fished.

The patchy distribution of beam trawling is observed on the scale of the North Sea, but also on the scale of individual ICES rectangles (Fig. 4). The question is, at which resolution does the e ort distribution become random? To study this question, the micro-distribution within the 11 most heavily fished rectangles was analysed on an increasingly higher level of resolution. In these ICES rectangles about 50% of the beam trawl e ort of the Dutch fleet (>300 HP) was exerted in 1993.

Figure 6 gives cumulative plots of ranked C-values for a resolution of 10 × 10, 3 × 3 and 1 × 1 mile for one ICES rectangle. Plots for the other rectangles gave similar results. At the highest level of resolution (window size 1 × 1 mile), the ranked C-values show that within the majority of 1 × 1 mile squares e ort has a random distribution with a coe cient of patchiness of about 1. Only in a small number of 1 × 1 mile squares beam trawling is patchy (C>1). At a window size of 3 × 3 mile, the proportion of windows with a random distribution decreases. At a window size of 10 × 10 mile, the distribution of beam trawling becomes increasingly patchy. However, at a window size of 30 × 30 mile (ICES rectangle) the distribution becomes less patchy (Table 7). The spatial distribution of the 3 × 3 mile

Table 4. Mean coe cient of overlap in the micro-distribution of individual vessels (resolution 3 nautical mile) from di erent harbours (I to IV).

	I Vlissingen	II Stellendam	III Den Helder	IV Urk
I – Vlissingen	0.282	0.028	0.000	0.002
II – Stellendam	0.028	0.305	0.069	0.019
III – Den Helder	0.000	0.069	0.173	0.072
IV – Urk	0.002	0.019	0.072	0.156

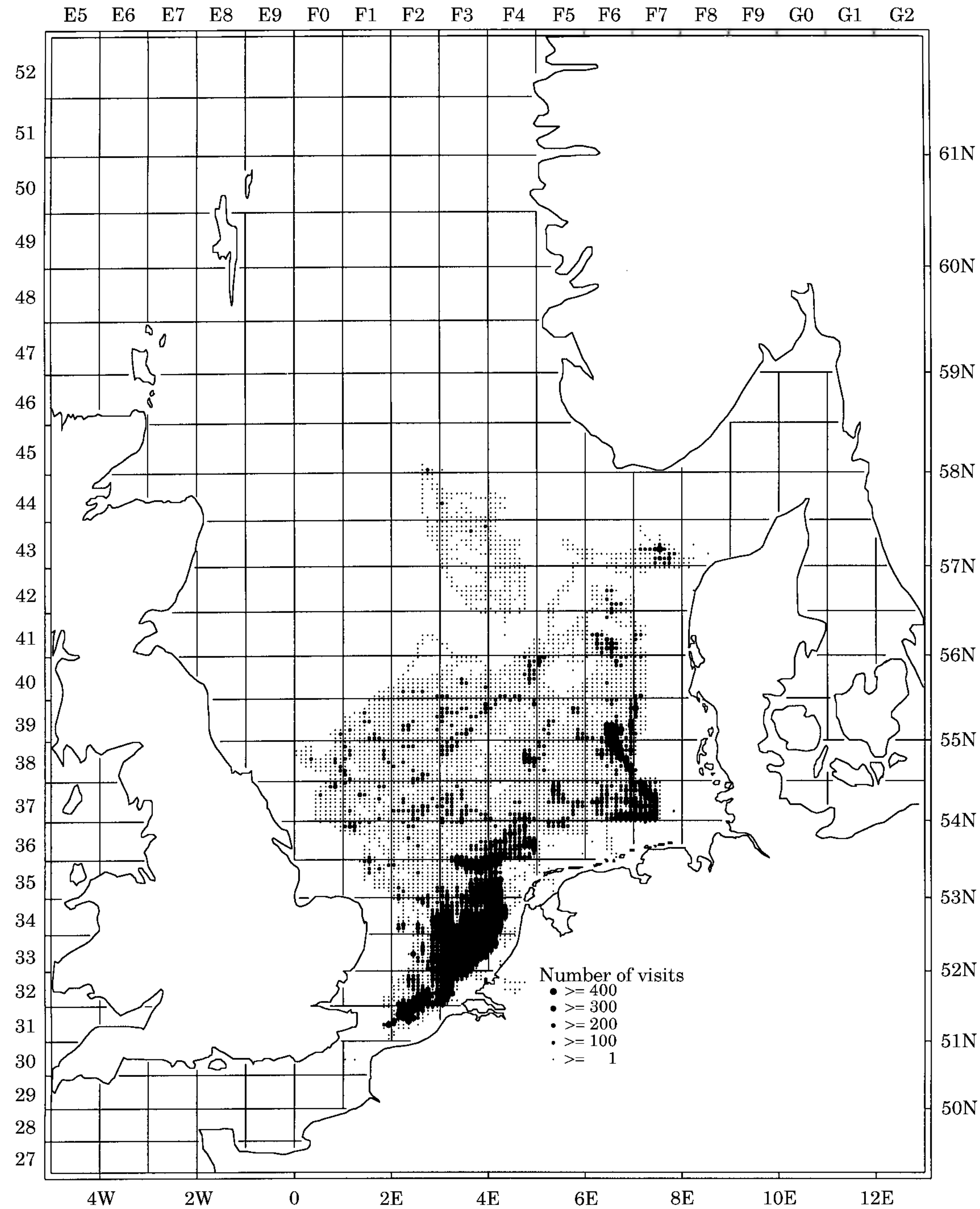

Figure 4. The micro-distribution of beam trawling of a sample of 25 beam trawl vessels (>300 hp) in 1995. The dots show the number of fish position registrations. The trace of dots within the coastal zone reflect steaming positions of the vessels to and fro the harbours (see text).

windows where fishing was random (C<2) is shown in Figure 7. Random trawling occurred in 3 × 3 mile squares in the o shore waters south of the Doggerbank, whereas patchy trawling occurred in the Southern Bight, German Bight and in the coastal areas.

Trawling frequency of the sea bed

Figure 8 shows a map of the average trawling frequency of the sea bed by the fleet of Dutch beam trawlers on a 1 × 1 mile scale during the 4-year study period. The area

Table 6. Coe cient of overlap between the micro-distribution (scale 3 × 3 mile) in the 4 years of the study.

	1994	1995	1996
1993	0.758	0.627	0.556
1994	—	0.710	0.652
1995	—	—	0.669

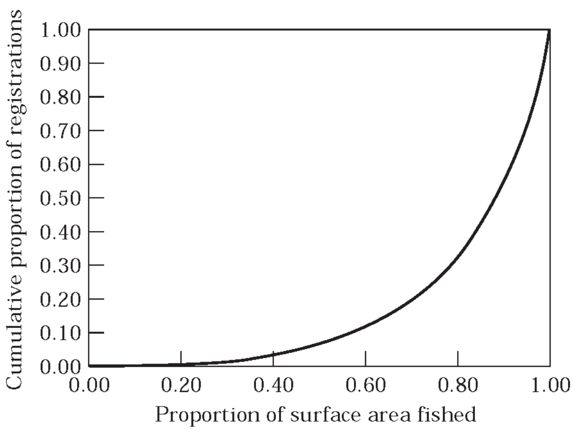

Figure 5. The relationship between the cumulative proportion of beam trawl registrations and the proportion of the surface area fished.

that is trawled more than once a year extends from the Southern Bight along the continental coast into the German Bight.

Particularly intensive trawling occurs along the borders of the 12 miles zone and the "Plaice Box", where beam trawling is not allowed for vessels beyond 300 HP. However, the "Plaice Box" regulation allowed fishing by large beam trawlers during part of the study period and as a result of this Figure 8 still shows a low trawling frequency within the box. Within the intensively trawled area in the south-eastern North Sea some parts are trawled less than once a year. In the deeper o shore areas of the central North Sea, the beam trawl intensity is generally less than once a year, with localized spots of heavy trawling.

We also estimated the trawling frequency for the eight most heavily fished ICES rectangles where fishing was not restricted by closed areas. This analysis showed that 47–71% (mean=62%) of the surface area was trawled 1–5 times per year; 9–44% (mean=29%) was trawled less than once every year, and 0–4% (mean=1%) was trawled between 10–50 times a year (Table 8, Fig. 9). The trawling frequency in the ICES rectangles where fishing was restricted by closed areas, indicated in Table 8 by asterisks, shows a similar distribution to the other rectangles except for the larger untrawled area.

Discussion

Representatives of APR sample

In extrapolating the micro-distribution patterns of the sampled vessels to the total Dutch fleet, we have to ascertain that the sampled vessels form a representative sample of the total fleet. The relative proportion of fishing e ort of the sampled vessels shows a high degree of similarity with that of the total fleet (Fig. 10). Comparison of the distribution of APR recordings over the ICES rectangles with the fishing days registered in VIRIS gave a coe cient of overlap of 0.92.

Another test of the representativeness of the sampled vessels was done by analysing the e ect of sample size on the trawling frequency–surface area relationship. This was done by drawing 500 random samples of 1 to 25 vessels from the sampled APR vessels for the eight most heavily fished rectangles. Selection was done with replacement. Figure 11 shows the estimated surface area for various levels of trawling frequency and the approximate 95% confidence intervals. The estimated surface area stabilizes at a sample size of 10 vessels. Increasing the number of vessels hardly a ects the estimated relationship, although the confidence interval becomes smaller. From these results it can be concluded that the sample of 25 beam trawlers allows us to extrapolate the trawling frequency of the total Dutch fleet.

Factors a ecting the micro-distribution of beam trawling

The spatial distribution of beam trawl e ort will be a ected by a variety of factors. The most important ones are: (1) the abundance of the main target species in relation to the distance to the harbour; (2) fishery management regulations (closed areas, quota); (3) suitability of the sea bed for beam trawling; (4) the occurrence of physical obstacles such as oil rigs; (5) shipping lanes.

The beam trawl fishery in the North Sea mainly targets at sole *Solea solea* L. and plaice *Pleuronectes platessa* L. Sole occurs in the southern North Sea and shows a seasonal migration towards the coastal spawning areas in spring and an o shore migration in autumn (ICES, 1965; de Veen, 1978). Plaice shows a northbound migration towards the feeding grounds in the central North Sea in early spring and a return to the spawning areas in the southern and south-eastern North Sea in late autumn (de Veen, 1978; Rijnsdorp and Pastoors, 1995). The seasonal pattern in distribution of plaice and sole is reflected in the o shore–inshore movement of the beam trawl e ort. The concentration of beam trawl e ort along the borders of the closed areas (12 mile zone and plaice box) can be interpreted as a response to the o shore movement of recruiting flatfish in autumn and a

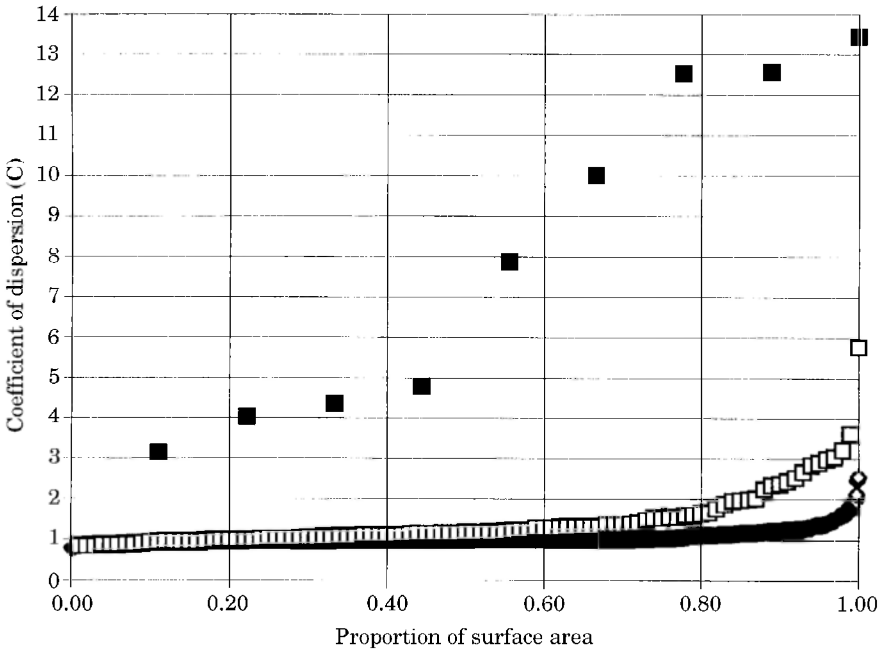

Figure 6. The relationship between the surface area fished and the ranked coe cients of dispersion. Data for ICES rectangle 35F6. 1 × 1 mile (◌); 3 × 3 mile (□); 10 × 10 mile (■).

Table 7. Patchiness of beam trawl e ort for various level of resolution in 1994. The patchiness was calculated over 100 sub-units within spatial windows (scale) of 1 × 1, 3 × 3, 10 × 10 and 30 × 30 nautical mile. C gives the mean coe cient of patchiness calculated over all windows within each ICES rectangle. C_{min} and C_{max} give the minimum and maximum C-value observed with a single sub-unit. An asterisk indicates ICES rectangles in which beam trawling is only allowed in part of the rectangle.

Scale (miles)	1 × 1		3 × 3		10 × 10		30 × 30
Resolution (miles)	0.1		0.3		1		3
Number windows	900		100		9		1
ICES code	C	C_{min}–C_{max}	C	C_{min}–C_{max}	C	C_{min}–C_{max}	C
32F2	1.1	0.7–1.2	2.4	0.9–11.1	18.7	6.4–36.4	1.7
34F3	1.2	0.7–3.1	2.4	0.7–7.9	15.1	11.9–21.2	1.1
35F3	0.7	0.7–2.0	2.1	0.7–5.1	14.1	5.6–22.0	1.2
36F4	1.1	0.7–2.2	1.8	0.7–5.6	13.8	4.7–25.8	2.2
37F4	1.0	0.8–3.0	1.3	0.8–2.7	6.0	1.9–18.7	0.5
37F5	1.0	0.7–2.5	1.3	0.8–3.2	7.0	2.2–11.2	0.8
37F6	1.1	0.7–4.1	1.8	0.8–9.5	10.3	2.3–29.9	1.3
38F6	1.1	0.8–6.4	2.9	0.8–18.6	24.1	2.4–49.8	1.5
33F3*	1.1	0.7–3.0	2.3	0.9–7.9	17.0	6.8–38.2	1.2
35F4*	1.3	0.9–31.0	3.0	0.9–31.0	16.0	2.0–58.3	3.1
37F7*	1.2	0.7–2.5	2.6	0.9–12.2	34.4	8.9–95.0	4.5

response to the inshore movement of mature sole in spring. The local concentrations in beam trawling in the central North Sea are mainly targeted at adult plaice.

The lower coe cient of overlap observed in 1995 and 1996 as compared to previous years may reflect the decreasing abundance of plaice relative to sole which resulted in a relative decrease in fishing e ort in the o -shore grounds in the central North Sea (Pastoors *et al.*, 1997).

The importance of the distance to the harbour is reflected in the band of intensively trawled areas along the coast. Beam trawl e ort mainly occurs within 60–90 miles from the harbour, which results in a higher overlap in micro-distribution between vessels of the same harbour or of neighbouring harbours (Tables 4 and 5).

The technical management regulations, which prohibit the larger beam trawlers from fishing the coastal grounds, have clearly a ected the spatial distribution of

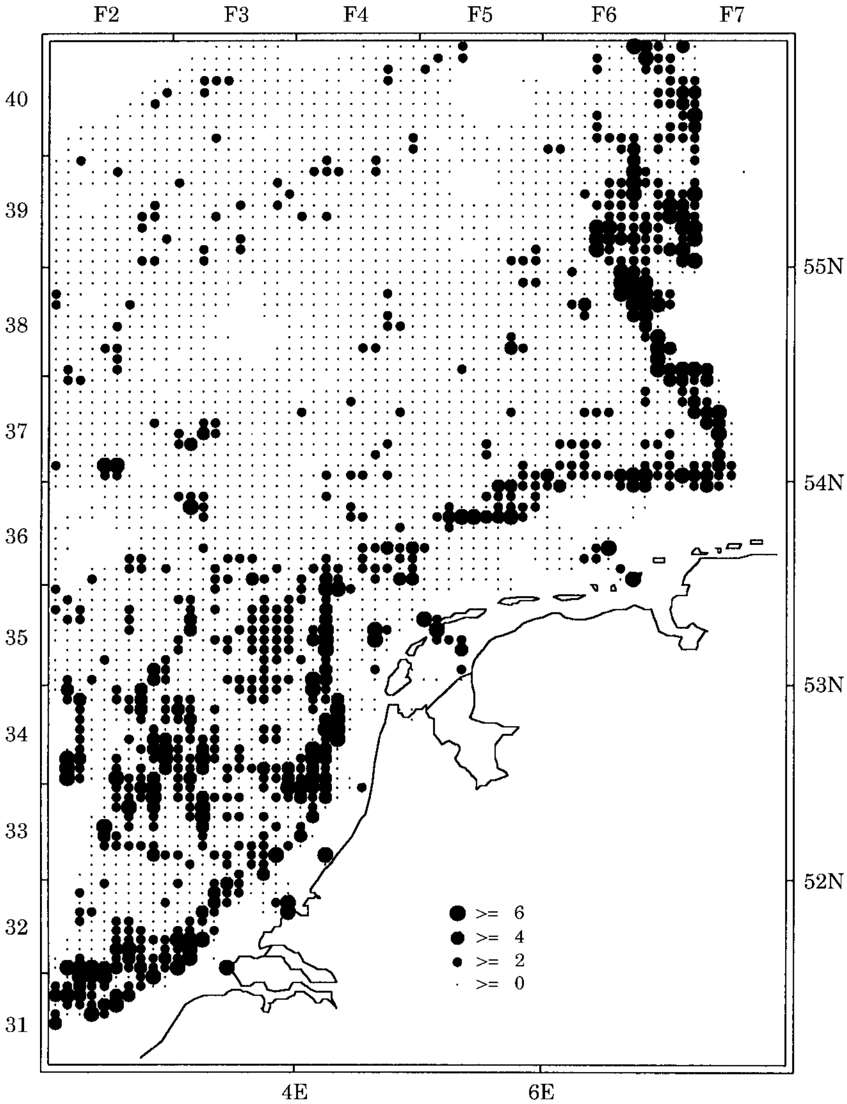

Figure 7. Map of the patchiness of beam trawling within 3 × 3 nautical mile squares. The dots show the coe cient of dispersion C. At C-values <2 beam trawling is more or less at random, whereas at C-values >=2 beam trawling becomes increasingly patchy.

beam trawl e ort. This is particularly pronounced in the German Bight where intensive beam trawling occurs along the borders of the "plaice box" (Fig. 4). This area was established to reduce discarding of undersized flatfish (ICES, 1987) and was closed for the larger beam trawlers in the second and third quarter of the year. In 1994, the regulation was extended to the fourth quarter and in 1995 to the first quarter.

The distribution of beam trawling will also be a ected by the suitability of the sea bed for beam trawling (stones, muddy areas), the occurrence of physical obstacles such as wrecks and oil rigs, and of shipping lanes. Beam trawling is patchily distributed in stony areas (o Sylt and Borkum) even at a resolution of 3 × 3 miles (Fig. 7). In the Southern Bight, the heterogeneous nature of the sea bed forming a mosaic of hard grounds (gravel and sand dunes) is reflected in the patchy distribution of beam trawling. It is only in the o shore areas north of 53°30′N that beam trawling has a random distribution at a 3 × 3 mile scale. It is striking that this random character is maintained on the Dogger Bank despite the more heterogeneous depth profile.

In the German Bight and Southern Bight, some of the patchy fished rectangles may be related to the shipping lanes where fishing is prohibited. The patchily trawled areas north-west of Texel are probably related to the occurrence of oil rigs. Patchily trawled squares along the border of the "plaice box" are related to mismatch

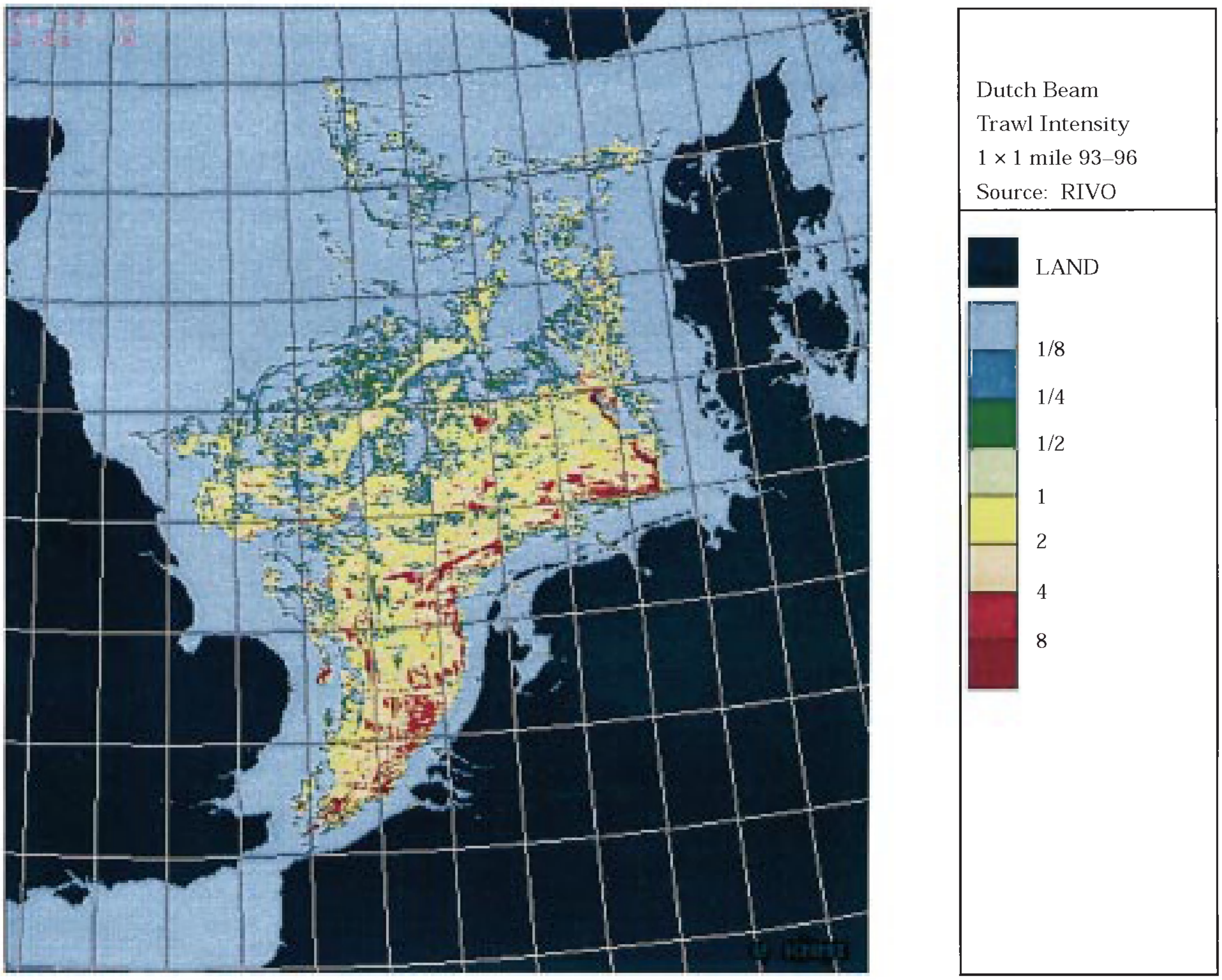

Figure 8. Map of the average annual trawling frequency of the sea bed by the total Dutch beam trawl fleet in the 4-year period between 1993 and 1996 as estimated on a 1 × 1 nautical mile scale from the APR recordings of 25 vessels (>300 hp) raised for each ICES rectangle to the e ort of the total Dutch fleet.

between the borders of the closed area and the borders of the 3 × 3 mile squares used in the analysis. The occurrence of single 3 × 3 mile squares which are patchily trawled may be related to shipwrecks. How the micro-distribution of e ort is related to the micro-distribution of sole and plaice remains to be studied. The observation that beam trawling in the area south of the Dogger Bank is highly patchy, whereas the distribution within each 3 × 3 mile square is random, suggests that the concentrations of beam trawl activity reflect the occurrence of local concentrations of target fish species, which may move in time, and not the suitability of the sea bed for beam trawling.

The impact of beam trawling on benthos

How does this heavy trawling a ect the benthos? Beam trawls are not selective and catch substantial amounts of undersized fish and epibenthic invertebrates and infauna (van Beek, 1990; de Groot and Lindeboom, 1994; Kaiser and Spencer, 1996; Kaiser *et al.*, 1996). Although survival experiments have shown mortality rates as high as 50–95% (van Beek *et al.*, 1990; Bergman and Santbrink, 1994; Santbrink and Bergman, 1994) these cannot be taken as estimates of the mortality generated at the population level. At the population level, the impact of beam trawling is a function of the overlap in distribution between beam trawl e ort and organisms, both vertically and horizontally, and will depend on the fragility of the organisms considered. Because the data on the horizontal and vertical distribution of the main benthic organisms are not yet available on the appropriate spatial scales to relate to the distribution of beam trawling, quantification of its impact is impossible.

Duineveld *et al.* (1991) showed that the benthos in the southern North Sea could be divided into three di erent

Table 8. Proportion of surface area of ICES rectangles trawled at a certain frequency (number of times one square meter is trawled annualy). The frequency was estimated from the micro-distribution (resolution 1 × 1 nautical mile) and the number of fishing days (e ort) of the total Dutch fleet from EU-logbooks in the period 1993–1996. In part of the ICES rectangles 33F3, 35F4 and 37F7 trawling is not allowed for vessels exceeding 300 HP

	0 ×	<0.1 ×	0.1 × – <0.2 ×	0.2 × – <0.5 ×	0.5 × – <1 ×	1 × – <2 ×	2 × – <5 ×	5 × – <10 ×	10 × – <20 ×	20 × – <50 ×
32F2	12.2	8.4	2.6	4.6	10.3	21.8	35.2	4.1	0.8	0.0
34F3	0.0	0.8	1.1	6.1	17.7	38.2	31.4	4.7	0.0	0.0
35F3	0.0	0.1	1.1	9.2	14.7	23.8	41.4	9.3	0.3	0.0
36F4	0.2	0.6	1.2	7.6	14.6	24.7	40.3	9.7	1.2	0.0
37F4	0.6	1.0	2.1	6.3	17.8	32.4	34.0	5.4	0.3	0.0
37F5	0.1	0.2	1.8	10.6	25.9	33.9	22.3	5.2	0.0	0.0
37F6	0.0	0.1	0.1	1.1	8.1	28.9	42.3	16.9	2.2	0.2
38F6	0.6	1.8	1.3	5.0	35.0	34.0	13.1	5.8	2.9	0.6
Mean	1.7	1.6	1.4	6.3	18.0	29.7	32.5	7.6	1.0	0.1
33F3*	7.0	0.0	0.6	0.4	0.3	5.7	70.0	15.3	0.7	0.0
35F4*	50.1	0.0	3.2	5.1	9.4	5.0	19.4	6.9	0.8	0.0
37F7*	40.6	0.0	1.9	3.2	3.9	12.1	23.0	9.2	5.6	0.6
Mean	32.6	0.0	1.9	2.9	4.6	7.6	37.5	10.5	2.3	0.2

benthic clusters which were related to sediment characteristics. In shallow (<30 m) coastal waters and in the Southern Bight, the benthos is characterized by relatively small, highly productive organisms in shallow coarse sand or shallow fine sand, which are particularly resilient to physical disturbance. In these areas, physical disturbance is a natural feature due to strong tidal currents and the e ect of storm surges. The deeper o shore waters (>30–40 m), coinciding with muddy sand, were characterized by a more sensitive cluster, including larger animals such as *Arctica islandica*. It is likely that beam trawling will have a relatively stronger e ect in the latter areas.

An interesting observation was made by Witbaard and Klein (1994) who studied (fishery-) scars in the shells of *A. islandica* collected at a location in the German Bight. They showed that scar frequencies increased over time in agreement with the increase in beam trawl e ort, reaching a level of about 40% around 1990. In comparison, the micro-distribution data indicated a beam trawl frequency at this location of 4–8 × per year in the period 1993–1996. A combination of both methods o ers a powerful tool to quantify e ects of local trawl disturbance.

It is possible that the benthic communities described by Duineveld *et al.* (1991) have already been a ected by the impact of beam trawling, as our analysis showed that the location of the heavily trawled areas were similar in the four years studied. It has been shown that physical disturbance may lead to a change in the benthic community. Studies of Pearson and Rosenberg (1976) and Rhoads *et al.* (1978) showed that dumping or pollution had a negative e ect on longer lived species but a positive e ect on small opportunistic species such as polychaetes. The observed increase in growth rate of

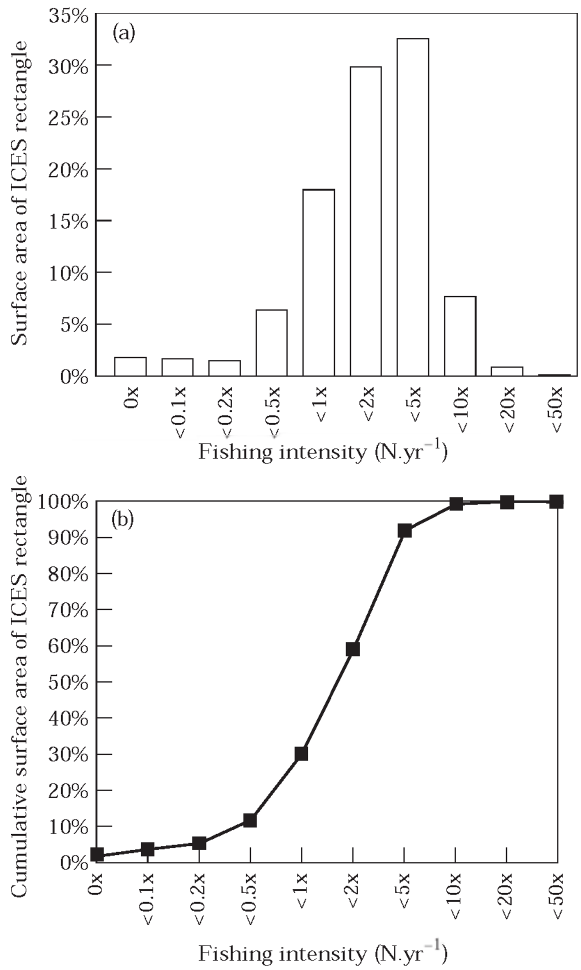

Figure 9. Relationship between the surface area trawled at di erent levels of fishing intensity as estimated for the eight most heavily trawled ICES rectangles.

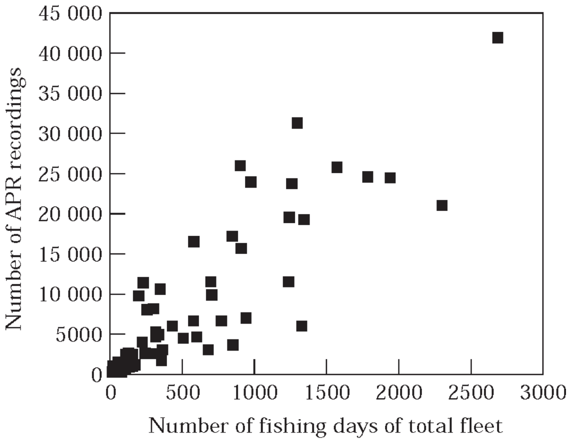

Figure 10. Relationship between the number of fishing position recordings of the APR sample of 25 beam trawlers and the number of fishing days of the total Dutch fleet per ICES rectangle.

both sole and plaice species, which prey mainly upon the smaller opportunistic benthic species, may be a result of the increased productivity of suitable benthic food in the heavily trawled areas (de Veen, 1976; Rijnsdorp and van Beek, 1991; Rijnsdorp and van Leeuwen, 1996).

The micro-distribution data indicated that, within the most heavily trawled ICES rectangles, on average 15% of the surface area is trawled less than once a year, and 4% is estimated to be trawled less than once in every 5 years. This could imply that sensitive organisms may survive in these areas if the micro-distribution of the beam trawling does not change substantially between years. The coe cient of overlap in the micro-distribution (0.66) between the 4 years suggested that this is indeed the case. Nevertheless, because the population turn-over time of more sensitive benthic organisms is likely to be substantially more than 4 years, it is necessary to study the micro-distribution of e ort over longer time periods.

The main criticism of the above inference is that beam trawling could be micro-habitat specific. Hence, some specific habitats, and therefore specific benthic communities, are exposed to intensive trawling each year. In the near future, we plan to analyse the beam trawl intensity in relation to both micro-habitat (depth, sediment) and benthic community structure. Such a study could also provide information whether more sensitive organisms

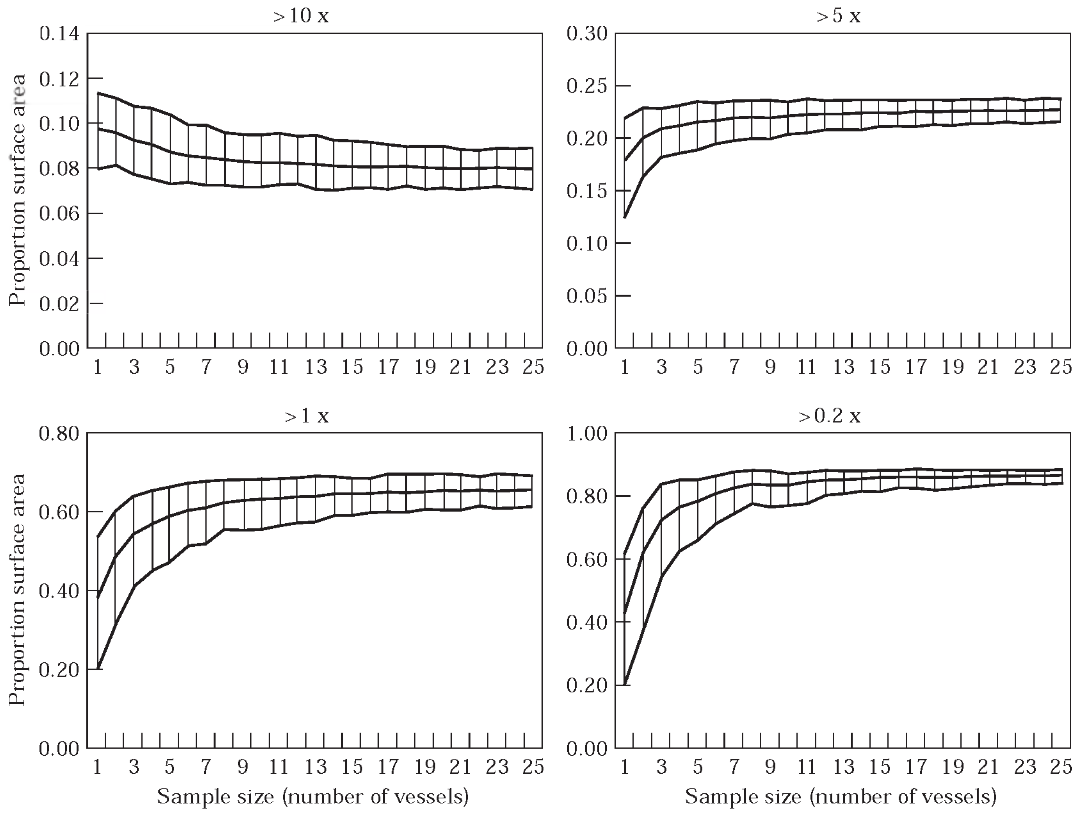

Figure 11. The estimated surface area ($\pm$95% confidence limits) trawled at a particular level of fishing intensity ($>10 \times year^{-1}$; $>5 \times year^{-1}$; $>1 \times year^{-1}$; $>0.2 \times year^{-1}$) as a function of the sample size. The relationships were estimated by drawing 500 random samples with replacement from the micro-distribution of individual APR vessels at a scale of 1 × 1 nautical mile in 1994.

may have a chance to survive in less heavily trawled local areas. The data collected so far do suggest that the claim by Rauck (1985) that beam trawling has a detrimental e ect on the benthos is untenable. The areas of intensive beam trawling shown in the present study, have already been trawled intensively for several years and still provide profitable fishing grounds. Without ample benthic food for plaice and sole, these fishing grounds would have lost their profitability for fishing.

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