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Spatial distribution of otter trawl effort in Icelandic waters: comparison of measures of effort and implications for benthic community effects of trawling activities

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We examined the spatial distribution of trawling effort from logbook data from all Icelandic vessels fishing for demersal fish between 1991 and 1997 with a spatial resolution of 1 degree of latitude and 1 degree of longitude. The trawling effort was widely distributed but was intensive only in small and localised areas. Three measures of effort were compared; tow frequency, tow duration and separate estimates of swept area for otter boards and trawls. In each year, the area swept with otter trawl was 1.7 times greater than the total area in which fishing occurred over the 7 year period. In contrast, the area swept with otter boards was 4% of the total fishing area. Most of the fishing effort was confined to depths shallower than 400 m. With increasing depth, the size of trawls became larger and accordingly, also the area swept per haul. Calculations assuming no variation in the size of the trawl in relation to depth, produced inaccurate swept area estimates. Furthermore, swept area estimates based on depth corrected door spreads were greater than estimates where no such correction was made. Swept area was considered to be a more appropriate measure of effort than tow frequency and tow duration as long as variation in the size of the gear (e.g. in relation to depth) was taken into account. Effort within Icelandic waters was compared in five depth strata within seven zones. Effort was highest off the south and NW coasts and lowest off the north and east coasts. Effort was most intensive at the 100–500 m depth in all zones but in some areas (such as off NW Iceland), effort extended to deeper waters. Knowledge of the distribution of fishing effort is important for predicting larger scale effects of fishing gears on benthic communities.

Keywords: distribution, fishing depth, otter board, otter trawl, swept area, tow duration, tow frequency.

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Introduction

The effects of trawling on the marine ecosystem have been a cause of concern in recent years (e.g. Auster and Langton, 1999; Hall, 1999; Kaiser *et al.*, 2002). Such effects include changes in benthic communities as a result of direct mortality of individuals (e.g. Bergman and Hup, 1992; Collie *et al.*, 1997) and damage of habitats (e.g. Auster *et al.*, 1996; Fosså *et al.*, 2002). Stock depletion in shallow waters coinciding with the development of larger and better equipped vessels has resulted in effort extending into deeper waters (e.g. Koslow *et al.*, 2000). This is a worrying trend as it is widely recognised that deep-sea fauna is often characterised by fragile forms typical of low disturbance regimes, which can be more vulnerable to trawling (e.g. Fosså *et al.*, 2002). Knowledge of fishing effort is vital to estimate the magnitude of trawling impacts. However, data on fishing effort are often poor and sometimes only crude estimates can be provided (Greenstreet *et al.*, 1999). Most studies base the analysis of fishing effort on tow frequency (number of tows), tow duration (hours fishing) and/or days at sea (Lindeboom and de Groot, 1998; Greenstreet *et al.*, 1999; Jennings *et al.*, 1999). However, these measures of effort do not take into account the size of the trawls and therefore cannot provide any information about the size of the area disturbed by demersal fishing gears.

Although the knowledge of local scale effects of trawling on benthos is increasing (e.g. Kaiser and Spencer, 1996), effects on larger scales are harder to estimate and predict (Bergman and van Santbrink, 2000; Craeymeersch *et al.*, 2000; Piet *et al.*, 2000). For such analyses, data on fishing effort at a high spatial resolution (1 nm^2 or less) are of great importance as the distribution of the benthic habitats generally exhibits patchiness on fine scales (Hall, 1994). However, such datasets are rare and most studies have analysed data on fishing effort at a coarse spatial resolution, from 900 nm^2 (30 × 30 nm rectangles) (Churchill, 1989; Greenstreet *et al.*, 1999; Jennings *et al.*, 1999) down to 25 nm^2 (5 × 5 nm rectangles) (Pitcher *et al.*, 2000; Veale *et al.*, 2000). At even finer scales Rijnsdorp *et al.* (1998) analysed data from automated position recordings from 25 vessels, allowing determination of the fishing effort down to a resolution of 0.1 nm^2.

Swept area estimates are widely regarded as an important parameter in calculations of fish stock size (e.g. Pálsson *et al.*, 1989). Thus a good understanding of the underlying factors which can influence the variation in the swept area can be important in improving the accuracy in estimates of fish stocks. The size of the area swept depends greatly on the size of the trawl and the door spread (distance between otter boards during towing). Furthermore, the door spread (and accordingly the swept area) increases with depth due to changes in the trawl geometry (Hagström, 1987; Engås and Godø, 1989; Godø and Engås, 1989; Engås and Ona, 1991; Koeller, 1991). Therefore, calculation of swept area based on fixed door spread may cause errors in swept area estimates (Churchill, 1989; Auster *et al.*, 1996). In addition, the magnitude of trawling impacts on fauna may not only depend on the size of the area swept by the whole trawl, but rather on the size and weight of the specific components of the gear, such as the otter boards, and their pressure on the seabed along the line of the tow (Gilkinson *et al.*, 1998; Fonteyne, 2000).

The most commonly used bottom fishing gear in the N. Atlantic is the otter trawl. Between 1991 and 1997, around 72% of total landings of demersal fish in Icelandic waters were caught with otter trawl. Other types of bottom towed gears used during this period (ranked by total landings) were shrimp trawl, Danish seine, scallop dredge, *Nephrops* trawl and hydraulic dredge. During the first half of the 20th century, the otter trawling fishery around Iceland was confined to relatively shallow waters (<400 m) and targeted cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and ocean perch (*Sebastes marinus*). Deep water fishing (>500 m) developed rapidly in the 1970s, with deep-sea redfish (*Sebastes mentella*) and Greenland halibut (*Reinhardtius hippoglossoides*) as the main target species (Magnússon, 1998).

In this paper we used logbook data to analyse distribution patterns of the otter trawl effort for all Icelandic vessels fishing for demersal fish between 1991 and 1997 at a relatively fine spatial resolution. This enables us to provide an estimate of the total otter trawl effort within Icelandic territorial waters. Firstly, we compared three measures to estimate effort: (1) tow frequency, (2) tow duration (h) and (3) area swept (separately for the trawl and the boards). Secondly, we estimated the swept area based on three different assumptions with regard to the door spread. Thirdly, we assessed how fishing effort around Iceland varies between geographical areas and depths. Finally, the implications of these findings are discussed in the context of the effects of demersal gears on benthic communities and habitats.

Material and methods

The outer boundary of the continental shelf area surrounding Iceland roughly follows the 500 m depth contour. The shelf is narrowest off the south coast, sometimes only extending a few nms offshore and from there the continental slope descends steeply to depths exceeding 1500 m. However, the shelf is relatively broad off the west, north and east coasts extending 60–90 nms from the coast. Within Icelandic territorial waters (764 406 km^2), the area within 500 and 1000 m depths is 221 004 and 319 402 km^2, respectively.

Logbook data on fishing effort of otter trawling for demersal fish were used for the analysis. The data were obtained from the Marine Research Institute (MRI) and the Directorate of Fisheries database. Since 1991, it has been mandatory for Icelandic vessels to keep logbook records on all hauls. The MRI database contains registrations of all individual tows within the Icelandic territorial waters, from 1991, to a spatial resolution of 1′ latitude and 1′ longitude (hereinafter termed a square).

For each haul between 1991 and 1997 (583 573 in total), the following data were extracted from the database; coordinates at the start of tow (latitude and longitude, used to designate a tow to the centre of a square), vessel size (engine power, kW), length of a single bridle (m), weight of a single otter board (kg), trawling depth (m) and tow duration (h). The following formula was used to calculate the surface area of each square (Sq):

$$\mathrm{Sq} = \cos\frac{\mathrm{latitude} \times \pi}{180} \tag{1}$$

The size of squares ranged from 0.38 to 0.49 nm^2, the size being dependent on latitude.

For each square, the total tow frequency and tow duration were averaged over the 7 year period (1991–1997). The average area swept by trawl annually within each square (Figure 1) was calculated according to the following equation:

$$\mathrm{St_j} = \frac{\sum_{i=1}^{\mathrm{Nj}} \mathrm{D} \times \mathrm{T} \times \mathrm{S}}{\mathrm{n}} \tag{2}$$

where, $\mathrm{St_j}$ = area swept by otter trawl in square j, D = door spread (m), T = tow duration (h), S = towing speed (constant: 4 nm h^{-1}), n = number of years and N the total number of hauls in square j.

For swept area calculations, we had to allocate the effort to a single global position, which is the centre of the square where the tow started. However, in real fisheries, the swept

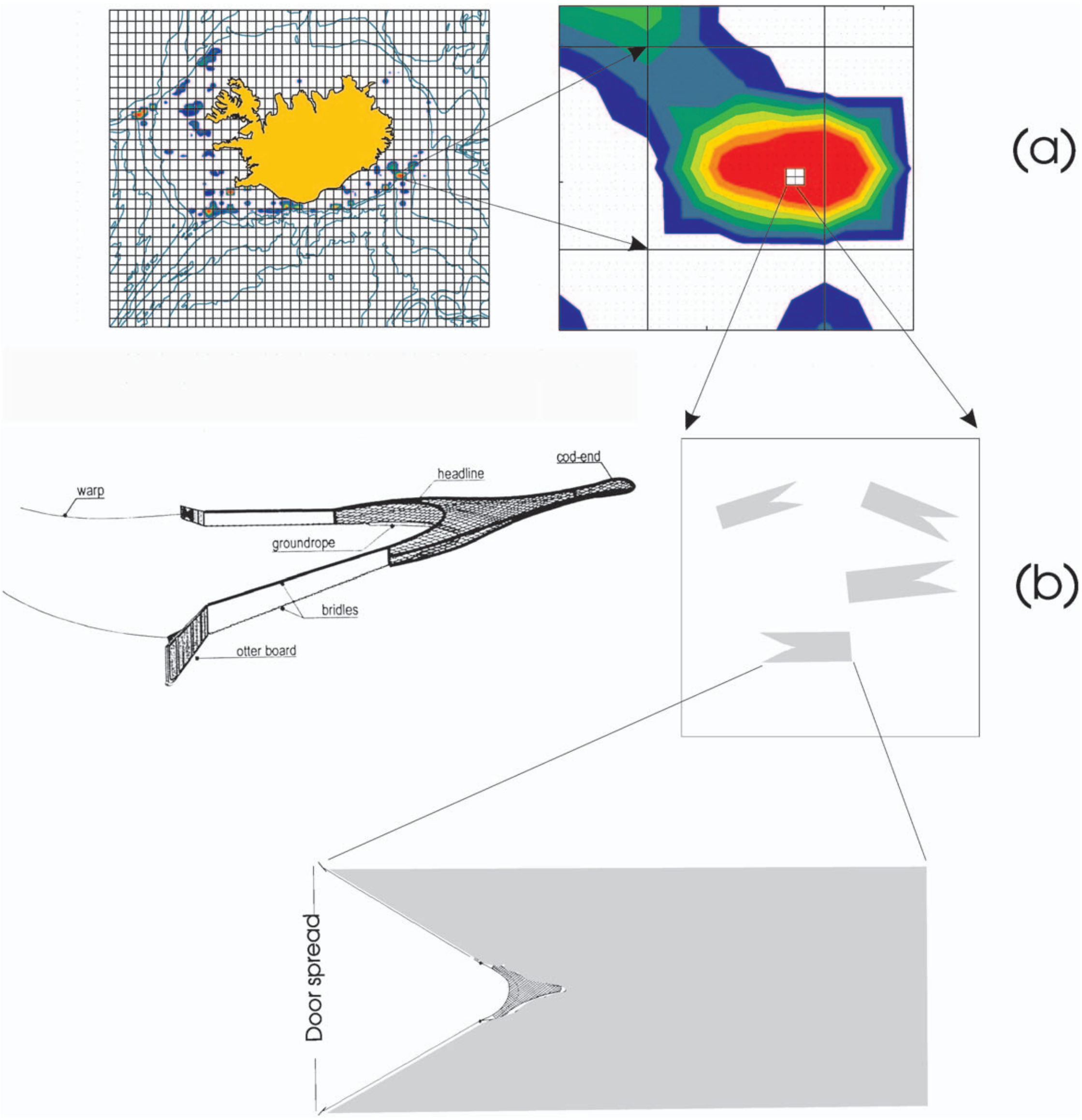

Figure 1. Calculation of swept area. (a) Four squares, each 1′ latitude and 1′ longitude, highlighted (white). (b) Four tows within a single square. The shaded area represents the area swept. Example of a typical otter trawl is shown for explanatory purposes (adapted from Lindeboom and de Groot, 1998).

area is distributed over several squares with each tow ranging between 10 and 20 nm. Within fishing grounds, the starting position of tows and tow direction is likely to be at random, with the exception of a few areas where the physical nature of the seabed (e.g. steep slopes, lava, etc.) restricts trawling. Closer examination of effort data on the behaviour of individual fishers (Steingrímsson, unpubl. res.) shows that fishing vessels towed in the opposite direction to the previous tow, or they remained in the same area but changed the direction of the subsequent tow, but such decisions are based on the catch. While the effort by individual fishing vessels may not be random, it is likely that the pooled effort among all vessels fishing in the area is. For that reason we assume that the direction of towing radiates at random from the centre of each square. By allocating the total swept area of a haul to a single square, we overestimated the effort in that square. However, the overestimated swept area is likely to be levelled out among adjacent squares.

Towing speed was not recorded in the MRI database. Interviews with skippers have revealed that for all boats using otter trawl fishing for demersal fish, the towing speed generally ranges between 3.8 and 4.2 nm h^{-1}. Below 3.5 nm

h^{-1}, the catch is greatly reduced due to decreased efficiency of the gear. For that reason, vessels with low engine power reduce the size or the weight of the trawl to be able to tow faster than 3.5 nm h^{-1}. Large number of factors such as engine power, trawl size, weather, currents, bottom type and the fish species the fishery is targeting influence towing speeds. It would therefore be extremely difficult to predict towing speeds on the basis of the data available to us.

Three measures of D were used in order to compare the effects of different assumptions about door spread on swept area estimates: (1) door spread being equal to the length of a single bridle, (2) fixed door spread (the average bridle length of all hauls recorded in the database) and (3) depth corrected door spread calculated by using the following equation:

$$D = -0.00041d^2 + 0.28d + 51.34 \quad (3)$$

where d = depth, based on direct measurements of door spread using SCANMAR acoustic sensors (SCANMAR AS, Norway) at depths between 50 and 400 m (Pálsson, unpubl. data). To our knowledge, variation in door spread below 400 m has not been investigated. For that reason, no attempts were made to extrapolate the door spread : depth relationship down to greater depths.

The average area swept by otter boards within each square, was calculated according to the following formula:

$$Sb_j = \frac{\sum_{i=1}^{Nj} F \times T \times S}{n} \quad (4)$$

where Sb_j = area swept by otter boards in square j, F = estimated width of furrows made by both otter boards (nm) and n = number of years (T and S as in Formula (2)). To obtain estimates of furrow width (F) the length of the board has to be known. In the database, however, only the weight is given. To circumvent this problem, information about length and weight of otter boards were obtained from the main otter board manufacturer in Iceland (J. Hinrikson Ltd), who equips more than 90% of Icelandic trawlers. Using these data, the length of the otter board was estimated with the following third power polynomial equation:

$$L = 3.55 \times 10^{-11} W^3 - 3.43 \times 10^{-7} W^2 + 1.58 \times 10^{-3} W + 1554 \quad (5)$$

where L = length of an otter board (m) and W = weight (kg).

Over the period 1991–1997, most otter boards used in Icelandic fisheries were oval (J. Hinriksson Ltd, pers. comm.). It was assumed that during towing about one-third of the board penetrates the seabed (J. Hinriksson Ltd, pers. comm.).

Following a conversion of weight into length, the furrow width of both otter boards (F) was estimated according to the following equation:

$$F = (L \times 0.33) \times 2 \quad (6)$$

where L = length of an otter board (m). This value of F was used when estimating the area swept by otter boards (Formula (4)).

Spearman's rank correlation (Zar, 1996) was used to test for significance of correlation between depth, vessel size, door spread, tow duration and furrow width. The non-parametric approach using Spearman rank correlation was preferred as data were not Normally distributed (Zar, 1996).

Fishing effort was compared regionally and bathymetrically by arbitrarily dividing the fishing area into seven roughly equally sized zones (Figure 2a) and five different depth strata (<100, 100–199, 200–499, 500–999 and >1000 m). At each depth stratum, the total seabed area (nm^2), tow frequency (total number of tows), and annual swept area (nm^2, for the whole gear) were estimated.

The variability in the distribution of fishing effort across depth strata and zones was estimated using the coefficient of dispersion (C). The coefficient of dispersion is the ratio between variance and the mean where $C > 1$ indicates a patchy distribution, $C = 1$ random and $C < 1$ uniform distribution (Elliot, 1977). The C was calculated for rectangles of 10′ latitude × 10′ longitude. Each rectangle was divided into 100 sub-units and the total tow frequencies within each sub-unit calculated. Subsequently, the dispersion coefficient (C) was estimated within each rectangle by calculating the mean and variance of the tow frequencies over all sub-units. Finally, to calculate the average C within a depth stratum, the sum of C-values was divided by the number of rectangles within stratum.

Results

Distribution patterns and comparison of effort measures

The otter trawling effort was greatest between 1991 and 1993 but declined steadily thereafter (Table 1). The total number of squares in which at least one tow had been taken between 1991 and 1997 was 85 893, comprising a fished area of 36 547 nm^2. During this period, 80 and 98% of all otter trawl hauls for demersal fish were taken within the 500 and 1000 m depth contours respectively. The trawling effort was highest off the west, south and south-east coasts (Figure 2b–f).

Comparisons of the different measures of the total and average annual effort are shown in Table 2a, and the average effort per haul in Table 2b. The average number of tows per year was 83 367, or nearly one tow per square, if effort had been evenly distributed within the fished area (Table 2a). The total swept area with trawl between 1991 and 1997 was estimated to be 11.8 times greater than the total fished area whereas the average area swept in any one year was 1.7 times greater (Table 2a). The total area swept with otter boards during the period 1991–1997 was 28% of the total fished area over the same period (Table 2a).

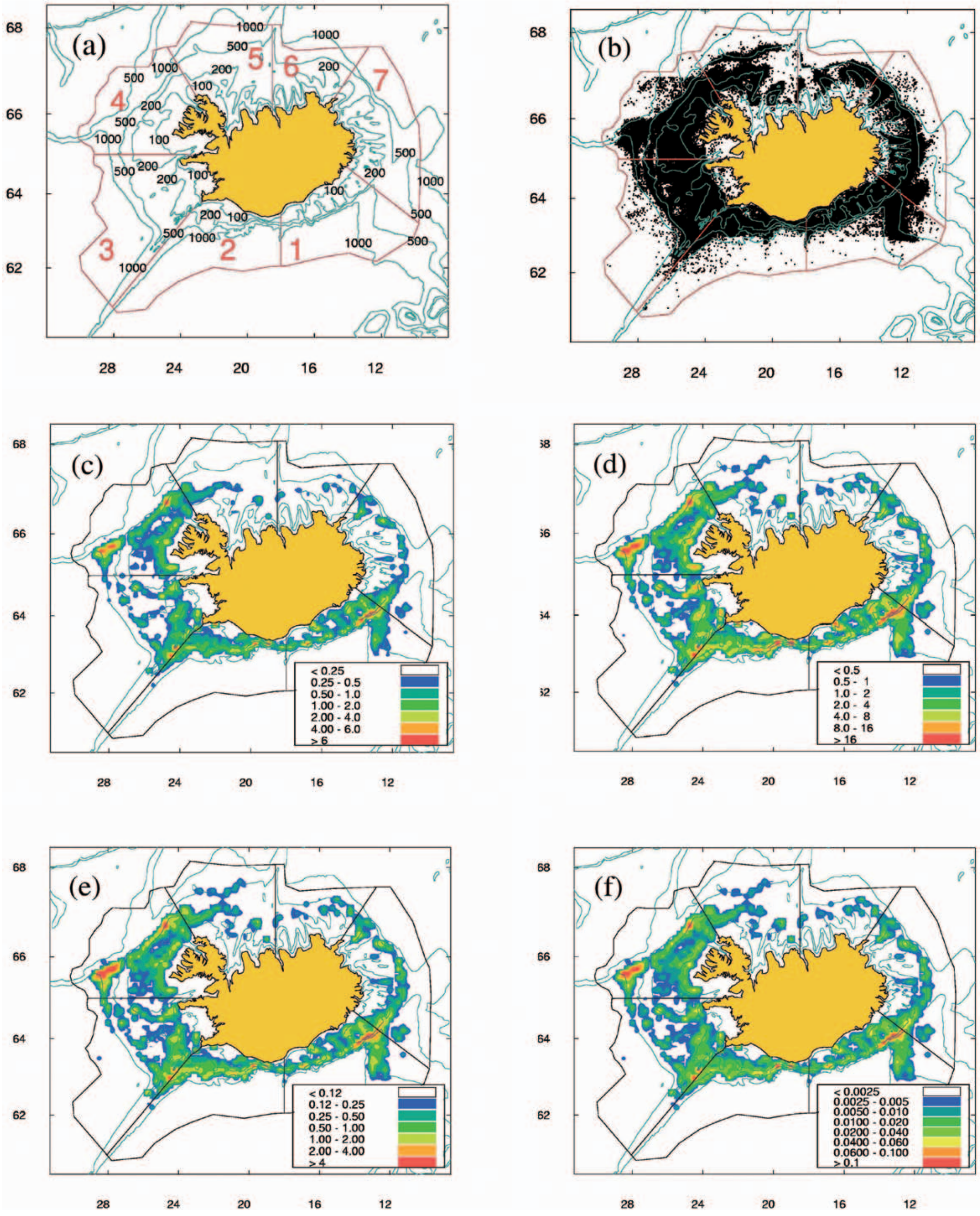

Figure 2. Otter trawling effort for demersal fish in Icelandic waters. (a) The division of Icelandic waters into seven zones and five depth strata (<100, 100–199, 200–499, 500–999 and >1000 m). (b) Distribution of otter trawling effort in Icelandic waters between 1991 and 1997. Each dot denotes one haul. (c–f) Distribution of the annual effort of the total otter trawl fleet calculated for each of the 85 893 squares, (c) mean annual tow frequency, (d) mean annual tow duration (hours fished), (e) mean annual swept area by the otter trawl (nm^2), (f) mean swept area by the otter boards only (nm^2).

Table 1. Otter trawl effort for demersal fish in Icelandic waters over the period 1991–1997.

Year	Number of vessels	Number of hauls	Fishing area (number of squares fished)	Swept area (nm^2)
1991	174	101 605	40 396	63 760
1992	153	105 763	41 710	70 787
1993	148	104 277	39 168	72 077
1994	124	74 185	29 280	54 936
1995	133	71 779	27 804	56 810
1996	130	64 590	26 817	58 125
1997	121	61 374	26 132	55 904

The door spread of the otter trawl was 42.5 times greater than the width of the furrow made by both otter boards. Furthermore, the area swept per haul with otter trawls was about 39 times greater than with otter boards (Table 2b).

On average, 72% of the fishing area was towed less than once per year, 16% once or twice, and about 1% more than 10 times (Figure 3a). The tow duration was less than 2 h yr^{-1} within more than half (58%) of the fished area whereas tow duration exceeded 5 h yr^{-1} in 17% of the fished area (Figure 3b). The area swept annually with trawls exceeded 0.4, 1 and 6 nm^2 in 45, 19 and 1% of the fished area, respectively (Figure 3c). In 34% of the fished area the annual swept area was less than 0.2 nm^2. The area swept annually with otter boards exceeded 0.01, 0.02, and 0.1 nm^2 in 43, 23 and 2% of the total fished area, respectively (Figure 3d). The otter trawling effort in Icelandic waters was randomly (or evenly) dispersed in 54% of the 10′ latitude × 10′ longitude rectangles ($C \leq 1$, Figure 3e). Effort was highly patchy ($C \geq 10$) in 239 rectangles, which is equivalent to 7% of the fished area.

Table 2. Summary of effort by the Icelandic otter trawl fleet (targeting demersal fish) over the period 1991–1997. Note that for (b) the furrow width and swept area by otter boards are calculated for the combined width of both boards and the range consists of 90% of tows.

(a) Total and average annual effort	Total effort	Annual effort
Tow frequency	583 573	83 367
Tow duration (h)	2 001 977	285 996
Swept area (trawl) (nm^2)	432 399	61 771
Swept area (otter boards) (nm^2)	10 367	1480

(b) Average effort per haul	Average	Range	SD
Tow duration (h)	3.5	1.8–5.1	1.1
Otter trawl			
Door spread (m)	101.9	53.7–137.1	31.8
Swept area per haul (nm^2)	0.8	0.3–1.3	0.4
Otter boards			
Furrow width (m)	2.4	1.8–2.7	0.3
Swept area per haul (nm^2)	0.018	0.009–0.028	0.006

Depth and effort

About 70% of the fishing effort occurred within 400 m depth (Figure 4a). Vessel size was correlated with all variables, with the exception of tow duration (Table 3). Furthermore, there were obvious differences in the average depth of fishing, swept area and door spread between vessel sizes (Table 4). As an example, the total area swept (1991–1997) by large vessels was 37% greater than that swept by small vessels, even though the total number of hauls by small vessels was 48% higher (Table 4).

The trawl opening (door spread estimates based on bridle length) was positively correlated with depth whereas tow duration was poorly correlated (Table 3). Therefore, variation in door spread explained most of the variation in area swept. As an example, the average area swept at 800–999 m depth was about two times greater than within 200 m, whereas the average tow duration was only 1.2 times greater (Figure 4b). Similarly, while 40% of tows taken within 200 m depth accounted only for 32% of the total area swept, 6% of tows taken deeper than 800 m accounted for 10% of the total area swept (Figure 4a).

Swept area calculations based on fixed door spread (average bridle length = 101.9 m; see Table 2) overestimated the swept area in shallow waters but underestimated the swept area in deeper waters. As an example, estimates based on fixed door spread were 16% higher within 200 m depth but 24% lower within the 800–999 m depth range (Figure 5). Swept area estimates based on depth corrected door spreads were 54% greater at the 200–399 m depth range compared to estimates based on bridle length (Figure 5).

Comparison of effort across zones and depths

Fishing effort was considerably less off the north and east coasts of Iceland (zones 5–7) compared to areas off the south and west coasts (zones 1–4), (Table 5, Figure 6a). The effort was highest off the NW coast (zone 4) where the area swept annually was equivalent to 27% of the total area of seabed in that zone. The effort was lowest off the NE coast (zone 6) where the area swept was equivalent to only 3% of the total surface area of zone 6.

The fishing effort was generally most intense in the 100–499 m depth range in all zones (Figure 6a). The effort was, however, highest in the 200–499 m depth range off south-west Iceland (zone 2), comprising an annual swept area equivalent to 79% of the total surface area of that depth stratum (Table 5).

Within the 500–999 depth stratum, the effort was most intensive off the SE and NW coasts (zones 1 and 4) with an area swept annually equivalent to 20 and 25% of the total seabed area, respectively. Fishing below 1000 m depth was

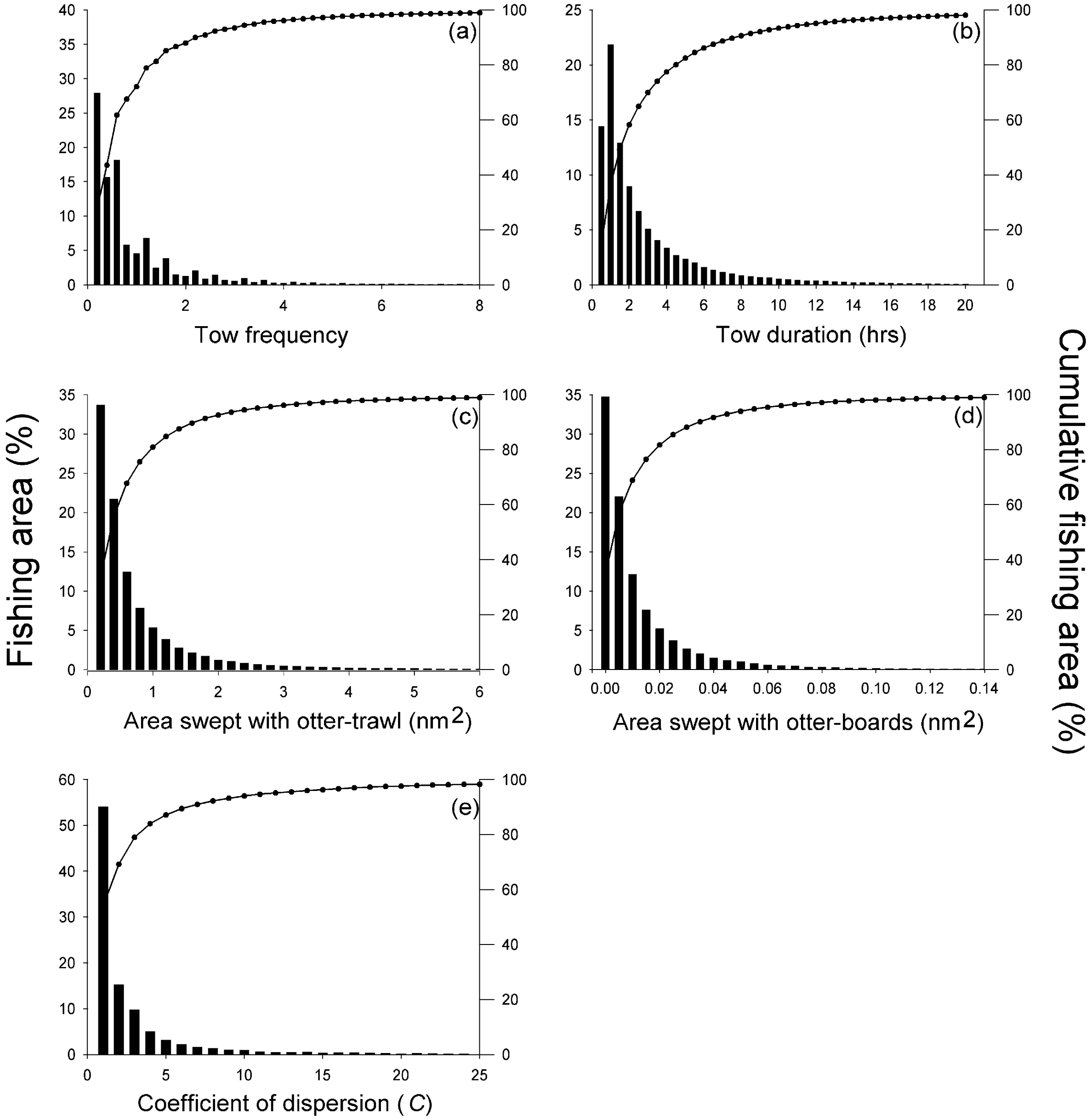

Figure 3. Frequency distributions (bars) of the annual fishing effort within the fishing area (proportion of squares, %) in terms of (a) tow frequency, (b) tow duration (h), (c) swept area of the whole gear (nm^2), (d) swept area of the otter boards (nm^2) as proportion (%) of the total fishing area and (e) frequency distribution of the coefficient of dispersion (C) calculated for each of the 2200 rectangles (10′ latitude × 10′ longitude). In all figures the cumulative proportion of the fishing area (dotted line) is shown on the right y-axis.

predominantly confined to the area off NW Iceland (zone 4), where 982 nm^2 were swept annually (equivalent to 17% of the total surface area of that depth stratum). In contrast, the combined swept area below 1000 m for all other areas was 292 nm^2 (Table 5).

The distribution of fishing effort was more patchy off the SE to NW coasts (zones 1–4) (Table 5, Figure 7b–e) compared to NNW to E coasts of Iceland (zones 5–7) (Table 5, Figure 7f–h). Effort tended to be most patchy in the 100–499 m depth range, with the exception of zone 2 (SW) where the average C increased with depth (Figure 6b). Below 1000 m depth, the effort was uniformly to randomly distributed. The patchy distribution of otter trawling occurred primarily at the steep slope area off South Iceland (Figure 7b, c), on the Reykjanes Ridge (Figure 7d) and at the NW slope of the Denmark Strait (Figure 7e).

Discussion

Spatial distribution of otter trawl effort

The otter trawling effort for demersal fish within Icelandic waters was patchy, with areas of high effort confined to

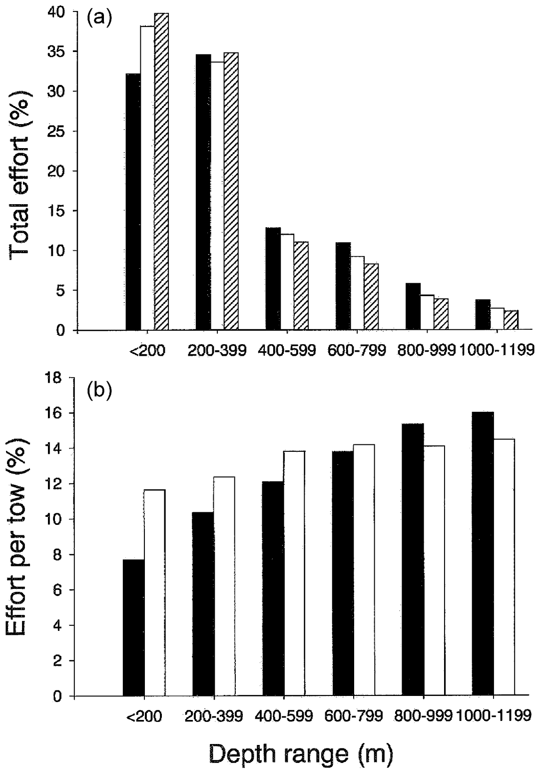

Figure 4. Frequency distribution (%) of the total (a) and average (b) fishing effort in relation to depth (m). Swept area (solid bar), tow duration (open bar) and tow frequency (hatched bar).

small and localised areas, primarily on the slope off the S, SW and NW coasts of Iceland (zones 1–4). Therefore, large areas around Iceland were scarcely fished or not at all by otter trawls. Such patchiness arises, of course, since trawlers tend to target fishing grounds which have a history of high catches or that the suitability of the seabed for trawling differs among locations. The bottom topography of the Reykjanes Ridge (SW off Iceland, Figure 7c, d) is very complex with numerous peaks and rifts (Copley *et al.*, 1996) which are likely to occupy habitats attractive for demersal fish. Many fishermen avoid trawling in such areas as the rough seabed can easily damage the net of the otter trawl (Magnússon and Magnússon, 1995). This probably explains why the trawling effort around Reykjanes Ridge is so patchy. Similarly, the slope areas off the south coast of Iceland are very steep, with depths descending from around 400 m to more than 1500 m within few nautical miles, and parts of the slope areas are considered difficult for trawling.

Table 3. Spearman's rank order correlation matrix. The Spearman correlations coefficient (r_s) is shown and significant correlation ($p < 0.00005$) are marked with asterisk. Note that correlations with very low correlation coefficients were significant, due to large sample sizes. Interpretation of results from tests should therefore be treated with caution.

	Depth (m)	Vessel size (kW)	Door spread (m)	Tow duration (h)
Vessel size (kW)	0.46*	–	–	–
Door spread (nm)	0.43*	0.75*	–	–
Tow duration (h)	0.12*	−0.044	−0.00025	–
Furrow width (nm)	0.47*	0.88*	0.78*	−0.0093

Table 4. Comparison of effort between three size classes of vessels, small (<1000 kW), medium (1000–2000 kW) and large (>2000 kW) over the period 1991–1997.

	Small	Medium	Large
Total number of vessels	122	71	31
Total number of hauls	161 762	312 263	109 548
Total fishing area (nm^2)	36 542	66 084	35 537
Total swept area (nm^2)	80 594	241 423	110 382
Average area swept per haul (nm^2)	0.5	0.7	1.0
Average door spread per haul (m)	64.3	106.6	131.4
Average depth of fishing (m)	174.3	315.9	431.0
Average tow duration per haul (h)	3.6	3.3	3.5

It is of interest to know how effort is distributed over the area fished. To address that, we used the method described in Rijnsdorp *et al.* (1998) where the relationship between cumulative effort was plotted against the fished area. Comparison of the relationships from Icelandic waters and the southern North Sea revealed that they were surprisingly similar (Figure 8). As an example, 70% of the effort took place in 19% of the fishing area in the

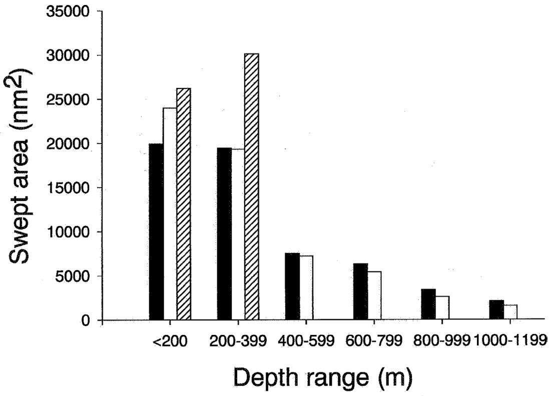

Figure 5. Comparison on three approaches to calculate swept area; door spread being equal to bridle length (solid bar), constant door spread (average bridle length of all hauls) (open bar) and on depth corrected door spread (hatched bar). Data for depth corrected door spread were only available for the depth range 50–400 m, and no attempts were made to extrapolate the depth:door spread relationship to greater depths.

Table 5. Comparison of swept area and distribution of fishing effort between five depth strata in seven zones (see Figure 7a). The surface area (nm^2) of each depth stratum is given. Annual swept area (nm^2) and the swept area as a proportion of the size of depth stratum (%) is shown in brackets. The total number of rectangles (10′ latitude × 10′ longitude) within each depth stratum and the average coefficient of dispersion (C) is shown. The average C of each depth stratum was calculated as the sum of all dispersion estimates (calculated separately for each rectangle) divided by number of rectangles.

Zone	Depth stratum (m)	Size of a zone (nm^2)	Annual swept area	No. of rectangles	Average C
1 SE	<100	4471	761 (17%)	45	5.5
	100–199	11 311	5030 (44.5%)	77	9.6
	200–499	14 068	3990 (28.4%)	82	6.7
	500–999	17 100	3482 (20.4%)	111	5.3
	>1000	30 071	66 (0.2%)	207	0.9
2 SW	<100	4331	1000 (23.1%)	41	9.1
	100–199	5804	1915 (33%)	42	10.9
	200–499	6463	5128 (79.3%)	40	13.3
	500–999	11 581	1646 (14.2%)	67	23.7
	>1000	53 661	86 (0.2%)	368	0.8
3 W	<100	5324	235 (4.4%)	45	2.1
	100–199	11 717	2990 (25.5%)	84	9.2
	200–499	23 240	6062 (26.1%)	151	6.2
	500–999	15 498	1600 (10.3%)	100	3.5
	>1000	45 706	126 (0.3%)	314	0.5
4 NW	<100	14 300	2987 (20.9%)	128	3.6
	100–199	13 582	4178 (30.8%)	97	3.7
	200–499	7017	2913 (41.5%)	52	6.9
	500–999	25 845	6531 (25.3%)	200	2.2
	>1000	5692	982 (17.2%)	47	1.1
5 NNW	<100	6677	38 (0.6%)	78	0.5
	100–199	9736	867 (8.9%)	71	1.8
	200–499	21 454	1628 (7.6%)	159	1.8
	500–999	11 545	241 (2.1%)	98	0.5
	>1000	0	0	0	0
6 NE	<100	3624	12 (0.3%)	43	0.4
	100–199	6820	160 (2.3%)	51	1.2
	200–499	10 934	608 (5.6%)	80	2.3
	500–999	7542	140 (1.8%)	72	0.6
	>1000	0	0	0	0
7 E	<100	3355	26 (0.8%)	30	0.7
	100–199	13 546	1776 (13.1%)	104	2.6
	200–499	25 025	3640 (14.5%)	164	2.4
	500–999	13 515	848 (6.3%)	58	2.9
	>1000	15 687	15 (0.1%)	122	0.5

present study compared to 20% of the fished area in the southern North Sea. This finding indicates that even though there are considerable differences between these two regions, fishers from both areas concentrated their effort in similar manners. The North Sea study was based on beam trawl effort where most of the fishing grounds consist of flat sandy bottoms (Basford *et al.*, 1993) and the fishery was predominately targeting flatfish species (e.g. Rijnsdorp *et al.*, 1998). In contrast, Icelandic otter trawlers were primarily targeting roundfish (e.g. Anon., 1997) and the fishing occurred over a greater range of substrate types and depths. The similarity in the relationship between effort and area fished, despite the obvious differences between the two regions, merits a further study on whether such relationships exist for other marine ecosystems.

It would be of interest to investigate whether this effort:fished area relationship is similar for other areas. However, such relationships will always be influenced by the spatial resolution of the data (Rijnsdorp *et al.*, 1998). As an example, 50% of the effort occurred within 7 and 11% of the fishing area at the 3 × 3 nm and 1 × 1 nm resolution, respectively. Comparison of effort : fishing area relationships from a wide range of marine ecosystems may therefore reveal whether there are general patterns in fishing effort.

Comparison of effort measures across zones and depths

In Icelandic waters, most fishing takes place at depths between 100 and 500 m, where the fishery primarily targets cod (*G. morhua*), haddock (*M. aeglefinus*), saithe (*Pollachius virens*) and ocean perch (*S. marinus*). However, there were large differences in effort between zones. As an example, 27% of the total surface of zone 4 was swept annually whereas in zone 6, fishing effort concentrates within only 3% of its total available surface area. Vessels trawling in deep water (>500 m) were mainly targeting Greenland halibut (*R. hippoglossoides*) and deep-sea redfish (*S. mentella*). Considerably more deep water fishing was carried out in zones 1 and 4 compared to other areas.

This study shows that effort of larger vessels tended to extend into deeper waters. Gear size was positively correlated with vessel size and depth and for that reason the swept area per haul was greater in deeper waters compared to smaller vessels. However, tow duration did not vary much with size of gear or depth. The duration of a tow is likely to depend more on the amount of fish in the area and what target species are being caught than on the size of the gear or depth. Therefore, tow duration alone can be regarded as an inappropriate measure of effort as it does not take into account variation in the size of the trawl (Greenstreet *et al.*, 1999; Jennings *et al.*, 1999). Studies in the North Sea have also demonstrated increase in the size of vessels with distance from land (Lindeboom and de Groot, 1998; Rijnsdorp *et al.*, 2000) and a positive correlation between vessel size and area swept per haul (Prawitt *et al.*, 1996).

We compared swept area calculations based on three different assumptions on door spread. Assuming fixed door spread, the swept area became increasingly underestimated with depth compared to estimates based on bridle length alone. In contrast, calculations using depth : door spread relationships obtained from the Icelandic groundfish survey (Pálsson, unpubl. data) to calculate depth corrected door spread produced the highest swept area estimates. As an example, at 300 m depth, the swept area estimate based on depth corrected door spread was 1.5 times greater compared to estimates based on bridle length. Analysing our data using another depth : door spread relationship

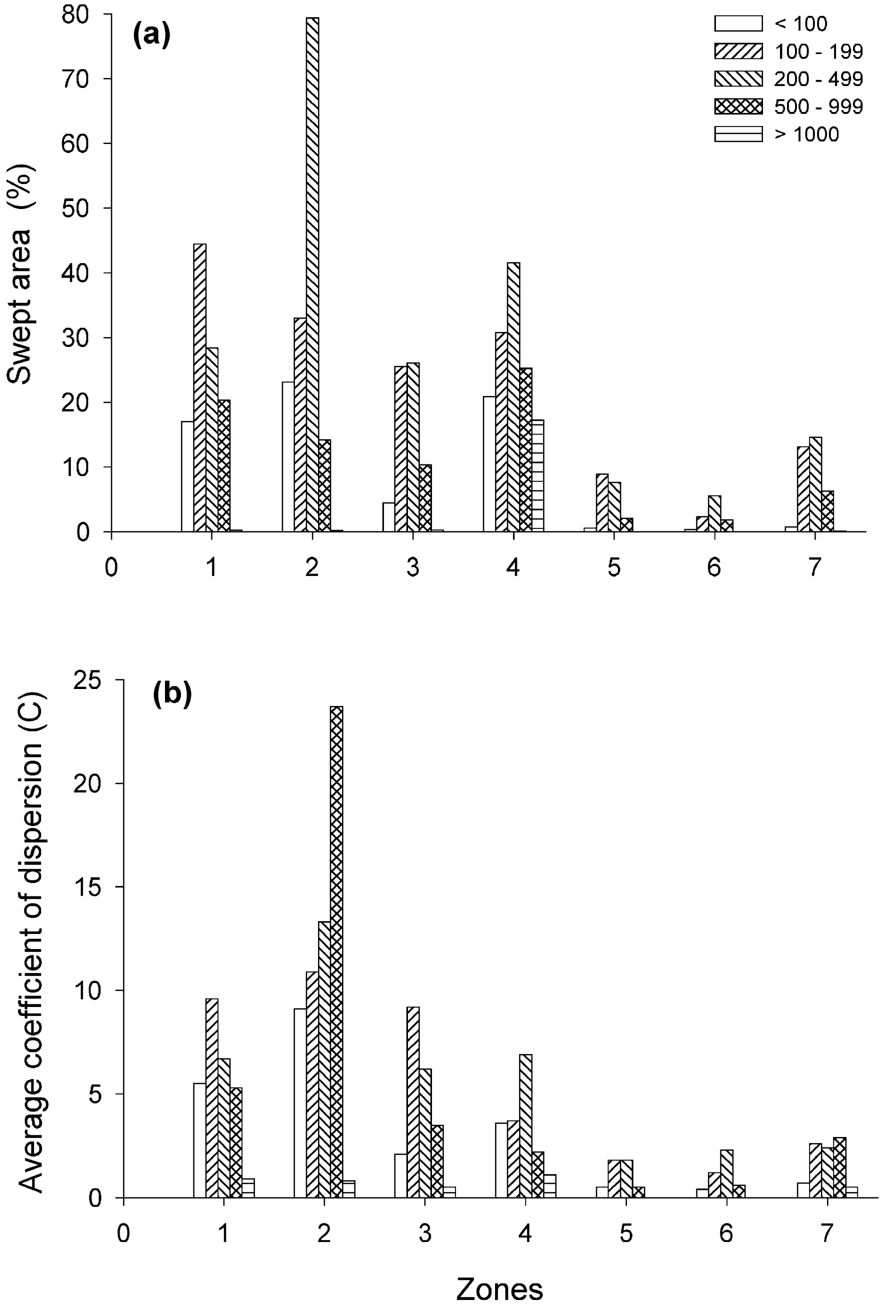

Figure 6. Comparison of swept area and contagion in spatial distribution patterns of the fishing effort in five depth strata within seven zones. (a) Histogram showing swept area as a proportion of the total surface area of each depth strata. (b) Histogram showing the average C per each depth strata.

provided by Koeller (1991) produced similar results, with swept area being 1.7 times greater at 300 m depth. These findings indicate that such relationships could be used for estimating trawl opening at a given depth for a range of otter trawls. Little is known about variation in door spread below 400 m depth. However, variation in door spread and wingspread (which has been estimated down to 600 m depth; Godø and Engås, 1989) is highly correlated (Koeller, 1991). Using this finding for extrapolating the door spread:depth relationship for the 400–599 m depth range, the swept area estimate based on bridle length (7223 nm^2) would be raised to 11 700 nm^2.

A number of factors other than depth can influence door spread, such as towing speed, bottom type (Main and

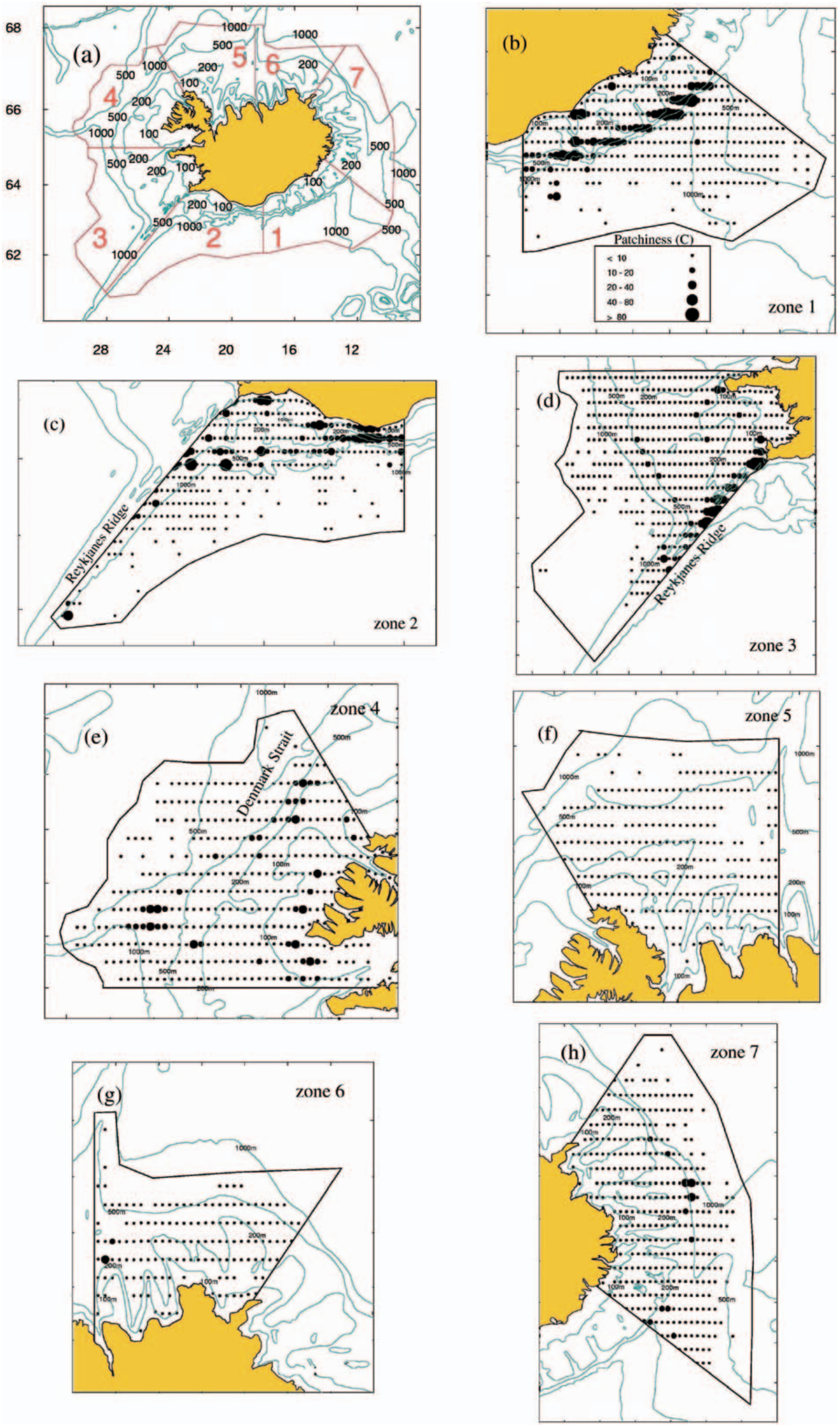

Figure 7. Patchiness of otter trawling effort in Icelandic waters. (a) The division of Icelandic waters into seven zones and five depth strata (<100, 100–199, 200–499, 500–999 and >1000 m). (b–h) Patchiness of otter-trawl effort within 10′ latitude × 10′ longitude rectangles. The size of dots denotes the magnitude of the coefficient of dispersion (C) and depth contour lines indicate levels of depth strata. When C ≤ 1 the effort is random to uniform but when C >1 the effort is patchily distributed.

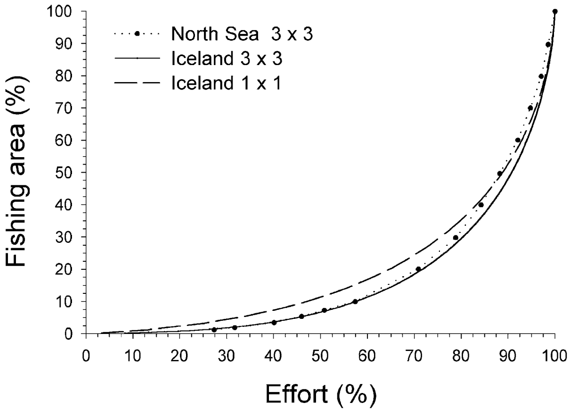

Figure 8. The relationship between the cumulative effort and the cumulative fishing area for Icelandic waters at a spatial resolution of 3 × 3 nm (solid line) and 1 × 1 nm (dashed line). North Sea data (dotted line) were obtained by directly reading values (denoted as circles) from the graph in Figure 5 in Rijnsdorp *et al.* (1998) paper. They compared the cumulative proportion of beam trawls registration in relation to the proportion of fishing area on the spatial resolution of 3 × 3 nm. For Icelandic data, the cumulative tow frequency was used as a measure of effort.

Sangster, 1979) and bridle lengths (Hagström, 1987; Engås and Godø, 1989). However, it is unrealistic to include these factors in swept area calculations as such information can be difficult to obtain. We conclude that swept area is a more appropriate measure of effort compared to tow frequency and tow duration but we stress, however, the importance of taking into account variation in door spread when calculating the swept area.

We estimated that the area swept annually with otter boards was about 42 times smaller compared to the area swept with the whole trawl. These findings indicate that 57 tows are required to cover the whole surface area of 1 nm^2 of seabed with otter board furrows (based on data on average tow duration and furrow width given in Table 2b). Considering flat soft bottoms, it is generally accepted that otter boards have a greater impact per unit area, compared to other components of the gear (e.g. Krost *et al.*, 1990; Gilkinson *et al.*, 1998) as these can penetrate the seabed down to 5–15 cm below the sediment surface and form furrows 50–100 cm in width (Caddy, 1973; Krost *et al.*, 1990; Werner *et al.*, 1990; Gilkinson *et al.*, 1998). If benthos is only affected within the area penetrated by the otter boards, it is clear that a very high trawling intensity is required to result in detectable effects on benthic communities. While this may be true for small sized fauna in mobile sediments where the hydrodynamic régime is intensive, other components of the trawl (such as bridles and groundrope) are likely to have an impact in less rigorous benthic habitats.

Due to lack of data on towing speeds, we were forced to apply a constant speed for all swept area calculations (4 nm h^{-1}). However, the towing speeds generally only range between 3.5 and 4.5 nm h^{-1} (information from fishermen). At these two extreme towing speeds the swept area per haul would be 0.67 and 0.86 nm^2, respectively. Therefore, assuming constant towing speed may not impose significant inaccuracy to our swept area estimates.

Importance of high resolution effort data in order to predict the larger scale impacts of fishing activities

Over the recent years there has been increasing evidence that fishing gears have an impact on benthic communities (e.g. Kaiser *et al.*, 2002; Thrush and Dayton, 2002). The majority of studies have investigated the effects of trawling with manipulative field experiments. Inherently, these studies only provide information on the effects of trawling where the study took place, i.e. we cannot extrapolate results from a single study to generalise about impacts on large spatial scales. The ultimate goal of trawl impact studies should be to predict effects of fishing on a large spatial scale and outcomes for a range of fisheries management regimes. To fulfil this goal it is important to obtain quantitative information on the magnitude of fishing impacts across a range of habitats, locations and benthic communities and between different gear types (e.g. Collie *et al.*, 2000). In order to assess with some accuracy the large scale impacts of fishing, a combination of high resolution data on distribution patterns of fauna, habitats and effort is required. At present, such datasets are only available for very few areas, such as part of the southern North Sea (Craeymeersch *et al.*, 2000). However, better data are to be expected in the near future with advanced remote sensing technology for mapping fishing effort (e.g. Marrs *et al.*, 2002), seabed topography (bathymetry and sediments, (e.g. Scheirer *et al.*, 2000) and habitat types (e.g. Kostylev *et al.*, 2001). The next step is to locate these habitats which have high conservation value and have been shown to be vulnerable to trawl impacts (Fosså *et al.*, 2002) and/or are important as fish habitats (Benaka, 1999).

Manipulative field experiments which have been carried out in shallow (<100 m) waters on sedimentary bottoms have reported minor impacts of otter trawling (e.g. Lindegarth *et al.*, 2000a, b; Sanchez *et al.*, 2000; Drabsch *et al.*, 2001; Kenchington *et al.*, 2001). Many of these were carried out in high energy environments where it could be expected that storm-induced sediment suspended loads exceeded those of trawling (Churchill, 1989). The infauna in such areas may, therefore, be resilient towards physical disturbances and trawling is only expected to have minor impacts (e.g. Oliver *et al.*, 1980). However, effects of storms on communities may only be limited to shallow waters on sedimentary bottoms, probably generally less than 50 m depth (Amos and Judge, 1991; Hall, 1994; Schwinghamer *et al.*, 1998). In Icelandic waters, most of the effort was below a depth at which storms are thought to affect benthic communities, with only 0.4 and 13% of all otter trawl tows occurring at <50 and <100 m depths, respectively.

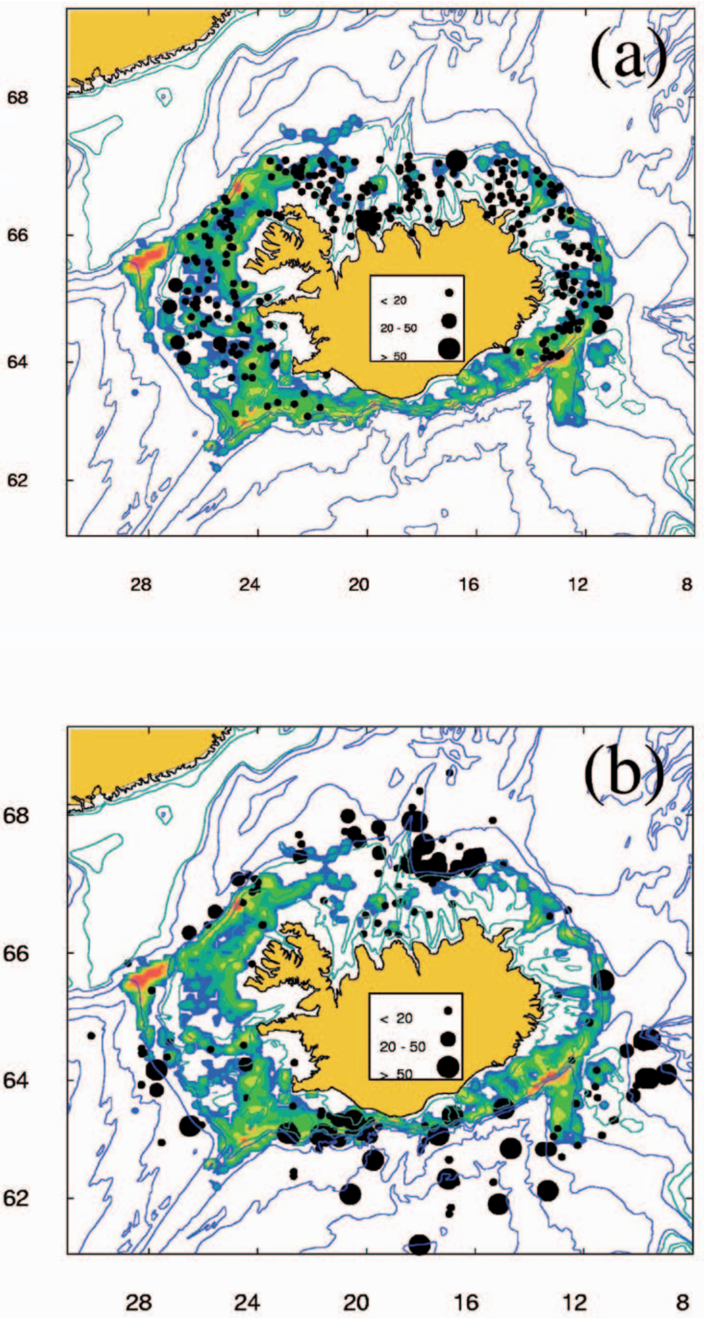

Figure 9. Examples of benthic animals that are potentially vulnerable to physical disturbances caused by trawling and their distribution in Icelandic waters in relation to otter trawling effort. (a) Total biomass (kg h^{-1}) of sponges (Porifera) caught with otter trawl during MRI groundfish survey 2002 (Steingrímsson and Tendal; unpubl. res.). (b) Total number of octocorals collected in the BIOICE project (Steingrímsson and López-Conzález; unpubl. res.).

However, while the small bodied infauna in high energy environments may be adapted to frequent sediment transport, larger species are at more risk of being damaged or killed following a direct contact with a trawl. As an example, while Kenchington *et al.* (2001) reported minor effects of trawling on infauna, Prena *et al.* (1999) reported considerable impact on epifauna in the same location. Cryer *et al.* (2002) showed that large surface-dwelling species on muddy bottoms between 200 and 600 m depth were all negatively associated with fishing activities, but about 50% of the effort in Icelandic waters occurred within this depth range. Finally, the time scale for the recovery of deep-sea megafauna on soft bottoms where trawling has taken place can be very long (Roberts *et al.*, 2000; Bluhm, 2001; Rodrigues *et al.*, 2001).

Several studies have been carried out in areas where habitat complexity is high, such as boulder grounds, corals and seapen communities. These habitats are known to be vulnerable to physical disturbances caused by trawling (Auster *et al.*, 1996; Turner *et al.*, 1999; Fosså *et al.*, 2002) and for biogenic structures in general the natural recovery following impact can be very long, especially in deep waters (Mortensen and Rapp, 1998; Turner *et al.*, 1999; Fosså *et al.*, 2002). In such habitats, the bridles and groundrope of the trawl can easily break down fragile structures rising above the seabed and only a few tows may be required to cause significant impacts. In contrast, on homogeneous soft bottoms the otter boards are likely to be the only component of the trawl causing an impact on the infauna.

Data on the distribution of taxa known to be sensitive to physical disturbances and the information on otter trawl fishing effort are useful to identify those areas where benthic communities are impacted by fishing activities. In Figure 9, we show preliminary data on the distribution of sponge biomass and octocoral abundances superimposed over fishing effort. Solely based on visual estimation, there are indications that sponges and octocorals were less common in areas where effort was intensive. However, inferring trends solely on the basis of effort should be carried out with caution, as a large number of other factors such as seabed characteristics, hydrographic régimes and fishing effort by fleets using other demersal gears than otter trawls contribute to the distribution of sponges and octocorals.

Over the last decade there has been a substantial increase in our knowledge on the effects of fishing gears. However, there are still some major gaps. Future studies should especially focus on investigating impacts on a wider range of habitats and in deeper waters. Our analysis demonstrated that in Icelandic waters large vessels were fishing in deep waters using bigger and heavier gear than employed in shallow waters. Trawling is therefore, likely to have a stronger impact on benthic communities in deeper waters than activities by small vessels in shallow coastal areas. It is of concern that in many parts of the world, the fleet consists of increasingly larger and better equipped vessels which are able to fish in deeper waters, often in areas where fragile benthic communities are found (e.g. Koslow *et al.*, 2000). In Icelandic waters, the average size of the otter trawlers (brutto tonnes) fishing below 500 m depth rose by 10% over the period 1991–1997 (Ragnarsson; unpubl. res.). Although this may seem like a moderate increase, it has to be stressed that most development of the deep-sea fisheries took place from 1970s onwards (Magnússon *et al.*, 2000).

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