J. Mar. Biol. Ass. U.K. (2001), **81**, 85–96
Printed in the United Kingdom

Distribution and damage to the by-catch assemblages of the northern Irish Sea scallop dredge fisheries

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The major by-catch species retained during twice yearly dredge surveys of great scallop, *Pecten maximus*, and queen scallop, *Aequipecten opercularis*, (both Mollusca: Pectinidae) populations on 13 fishing grounds in the northern Irish Sea, over a period of five years, were identified and enumerated. Additionally, the damage sustained by the by-catch was assessed and related to a range of physical parameters recorded during the survey. A number of species captured in the spring-toothed dredges exhibited differences in abundance and damage sustained between years, and also between the start and end of the closed season for great scallop fishing (1 June–31 October). The by-catch assemblage varied geographically, dependent upon the underlying community structure, as well as putative factors including gear efficiency and substratum type. Two clear assemblage types were identified by multivariate analysis, one to the south-west of the Isle of Man, the other covering fishing grounds to the north, east and south of the island. There is a hierarchy of species sensitivity to damage in great and queen scallop dredges, probably related to morphological and behavioural characteristics. This selective mortality of a fraction of the community may have long-term implications at the ecosystem level. The degree of damage sustained by many species is related to both the volume of stones retained in the dredge, and the total volume of the catch (dredge fullness). If these were reduced, the overall magnitude of incidental by-catch mortality would be lower.

INTRODUCTION

The great scallop *Pecten maximus* (L.) has been fished commercially by dredging in the northern Irish Sea for over 60 years (Brand et al., 1991). Additionally, since 1969, the queen scallop *Aequipecten opercularis* (L.) has also been heavily exploited. These species have together dominated (>80% of first-sale value) the Isle of Man fishing and fish processing industries since the collapse of the herring fishery in the late 1970s (Brand & Prudden, 1997).

The great scallop fishery is regulated by various legislation, including a minimum landing size (110 mm shell length) and an annual closed season from 1 June to 31 October inclusive. There is no specific legislation controlling queen scallop fishing, but they are fished mainly in the summer months (Brand et al., 1991). Both great and queen scallop fishing effort is monitored around the Isle of Man through a voluntary logbook scheme which collects catch and effort data from fishermen on an unusually precise spatial scale (5×5 n.m. grid) (Brand & Prudden, 1997), in comparison to the standard International Council for the Exploration of the Sea (ICES) fisheries statistics rectangles which cover 30×30 n.m. (Rijnsdorp et al., 1998).

As both great and queen scallops live on, or recessed in, sandy or gravelly sediments, they are fished using dredges equipped with toothed bars along the leading edge. Typically, individual dredge frames are about 80 cm wide, but they are fished in 'gangs' of up to 16 on each side of the boat. Demersal fisheries using mobile gears inevitably impact on non-target benthic species, both by encounter with the gear on the seabed, and by capture and discarding, which may result in injury or death (Hall, 1996). Most attention has been given to assessing the short-term effects of trawling for finfish, particularly beam trawling (e.g. Evans et al., 1994; Groot & Apeldoorn, 1971; Kaiser & Spencer, 1994; Rumohr & Krost, 1991; Smith & Howell, 1987), but shellfish dredging has also been investigated (e.g. Bradshaw et al., 2000; Currie & Parry, 1996; Eleftheriou & Robertson, 1992; Medcof & Caddy, 1971; Meyer et al., 1981; Roddick & Miller, 1992).

Typically, the by-catches of great and queen scallop dredges are comprised of the larger members of the epibenthos: species that live on, or near, the sediment surface and are sufficiently large to be retained by the steel rings of the dredge 'belly' (Caddy, 1970; DuPaul et al., 1995; Hill et al., 1996; Kaiser et al., 1998). By-catch animals may be killed outright, damaged sufficiently to make subsequent predation inevitable, or survive with minor damage from which they recover at an energetic cost (Beek et al., 1990; Kaiser & Spencer, 1994, 1996; Mensink et al., 2000; Sangster, 1994). For those escaping predation, additional chronic effects associated with the stress of capture may include reduced growth and reproductive rates (Crowder & Murawski, 1998).

Damage may be caused by the initial encounter with the toothbar, impaction or crushing by the steel mesh belly of the dredge or by other components of the catch whilst within the belly of the dredge, or by the sorting process on the deck of the fishing vessel. The extent of damage sustained by the by-catch may vary with the

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composition of the substratum. For instance, a greater proportion of stones and debris in the dredge can lead to greater damage (Medcof & Bourne, 1964; Shepard & Auster, 1991). Differences in the damage sustained by different by-catch species will depend on a number of factors including the fragility of their body (Eleftheriou & Robertson, 1992) and behavioural adaptations (Bergman et al., 1990).

The wider, and longer-term, effects of dredging include population and ecosystem level changes. At the population level, heavily affected by-catch species may undergo changes in population size, size structure or even local extinction (e.g. Philippart, 1998), and impacted ecosystems may change radically as some fractions of the community are selectively removed and trophic interactions are altered (Crowder & Murawski, 1998; Fogarty & Murawski, 1998; Vooys & Meer, 1998).

At the Port Erin Marine Laboratory, by-catch data have been collected regularly since 1992 during twice yearly (June and October) stock assessment surveys of pectinid populations on the main fishing grounds around the Isle of Man. This paper investigates the distribution and abundance of major by-catch species caught during surveys from 1992 to 1996, and assesses the damage sustained by these species during surveys in 1994 and 1995. More detailed data on the abundance and damage sustained by all species retained in the dredges in the October 1994 and June 1995 surveys are used to describe by-catch assemblages on different fishing grounds, and to assess the possible causes of damage. The aims of the study were to examine spatial and temporal variation in by-catch species abundance and the damage caused by the pectinid dredge fisheries. Spatial variation in assemblage structure, potential effects of the closed fishing season for great scallops (beneficial or otherwise), and factors responsible for causing damage to by-catch species were also studied. The results provide an insight into the by-catch sampling programme required to adequately monitor pectinid fisheries, in addition to providing suggestions on gear modifications to reduce by-catch mortality on discard.

MATERIALS AND METHODS

Of the great scallop and queen scallop fishing grounds around the Isle of Man (Figure 1), up to 13 were sampled during each survey, at the start and end of the closed season for great scallop fishing (June and October). Each ground was fished with a gang of four Newhaven spring-toothed great scallop dredges on one side of the RV 'Roagan', and a second gang, modified to retain the smaller queen scallop, with shorter teeth and smaller belly rings, on the other side (Table 1). The dredges used were identical to those used by commercial fishermen in this area and, following common commercial practice, the gear was towed for 2 n.m. (3.7 km) at an approximate speed of 2.5 kn. The gear was adjusted (spring tensions, tooth length etc.) also in accordance with commercial practice. Upon hauling, the contents of all dredges were sorted for the target and major by-catch species. By-catch was sorted to species level, counted and the extent of any damage sustained was recorded on a subjectively

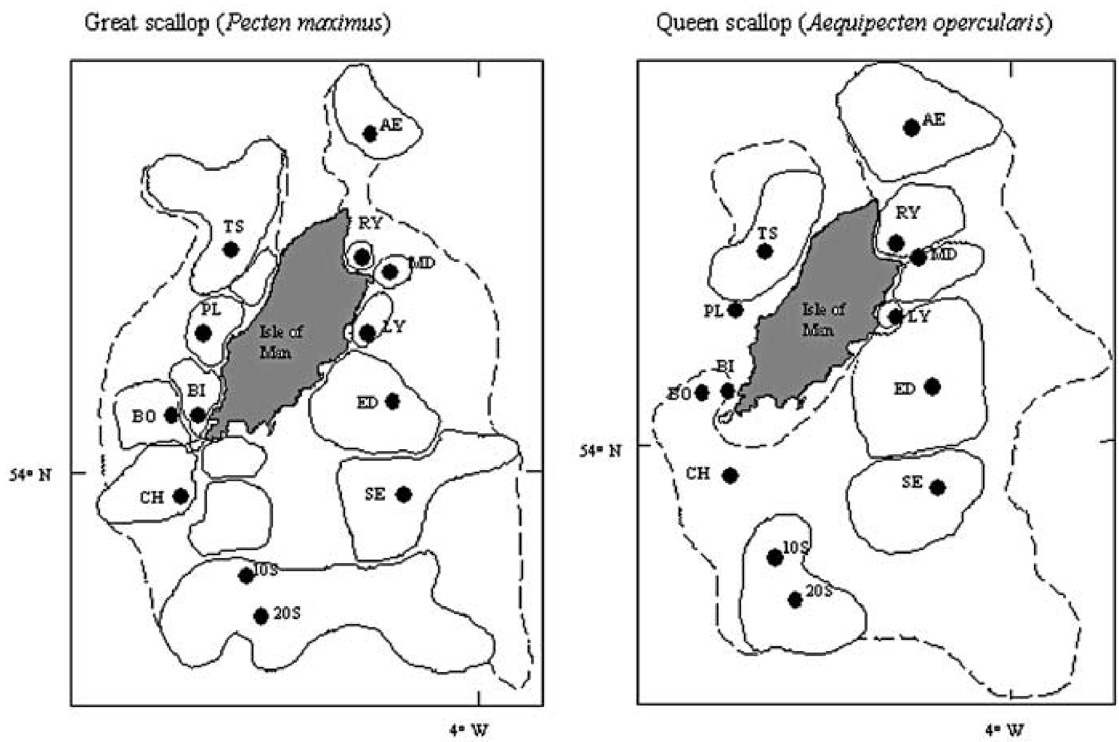

Figure 1. North Irish Sea great scallop and queen scallop fishing grounds around the Isle of Man. Major fishing grounds are bounded by solid lines; a dotted outline indicates where great scallops or queen scallops occur and are occasionally fished. All boundaries are approximate and many fishing grounds are contiguous. Black dots indicate sites surveyed by the RV 'Roagan'. Site labels are as follows: TS, The Targets; PL, Peel Head; BI, Bradda Head; BO, Bradda Offshore/West Calf; CH, The Chickens; 10S, H/I Sector—10 m South; 20S, H/I Sector—20 m South; SE, South East Douglas; ED, East Douglas; LY, Laxey; MD, Maughold; RY, Ramsey; AE, Point of Ayre.

Table 1. *Specifications of Newhaven-type spring-toothed dredges used in surveys of scallop and queen scallop populations.*

Dredge type	No. in gang	Dredge width (m)	No. of teeth	Tooth spacing (cm)	Tooth length (cm)	Belly ring diameter (cm)
Queen	4	0.762	10	7.6	7.6	5.7
Scallop	4	0.762	9	8.6	11.0	8.7

assessed four point scale using criteria appropriate to each taxonomic group (Table 2). Other parameters recorded were: visual estimates of dredge fullness (%) and total volume (l), stone volume (expressed both as a percentage of the total dredge content, and approximately in litres), stone size (as percentages making up small, medium and large size classes), and biota and trash (dead shell, drift weed, gravel etc.) volumes.

The validity of the damage scoring scale was assessed by 72 h post-capture laboratory survival experiments. Representatives of each damage score of each species were returned to the laboratory, and maintained in individual compartments in tanks in the laboratory flow-through seawater system. They were monitored every 12 h and any deaths were recorded and removed.

Additional physical data were collected, when possible, from the on-board navigation software (Microplot—Sea Information Systems, Aberdeen) which records positional data from the differential Global Positioning System (MBX 2, Communications Systems International), along with acoustic data from the echo sounder (Skipper CS 119), including that processed by RoxAnn (Marine Microsystems, Cork, Ireland). RoxAnn is an acoustic post-processor which interprets the strength of the returning first and second echoes, in terms of seabed roughness (echo 1) and hardness (echo 2) (see Magorrian et al. (1995) and Greenstreet et al. (1997) for examples of use).

Data analysis

Total numbers caught per 2 n.m. tow ($0.76\times4\times3704$ m $=11{,}260$ m^2 approximate dredged area) were calculated for each species for each ground during each of the ten surveys (June and October 1992–1996). Individual dredges of the same type were pooled; only grounds that had been sampled on at least eight out of the ten possible occasions were included, and only species which had been recorded in all surveys. A three-way crossed analysis of variance (ANOVA), using a General Linear Modelling approach to account for the unbalanced design and missing values, was then carried out for each species, using year, ground and season (start or end of the closed season for the great scallop) as the factors. A non-parametric ANOVA (Kruskal–Wallis) on ranked data was used, as the assumptions of parametric ANOVA were frequently violated (Cochran's test), despite transformation using the Box–Cox method. Significance levels were adjusted to account for multiple comparisons (eight different species) using the Dunn–Šidák method. Additionally, the powers of the analyses were calculated (Pearson & Hartley, 1951) to assess the likelihood of type II errors occurring, i.e. falsely accepting the null hypothesis of no significant effect of the factor (Peterman & M'Gonigle, 1992).

The by-catch community composition recorded during the October 1994 and June 1995 surveys was examined using the PRIMER suite of programs for multivariate analyses (Clarke & Warwick, 1994), treating the four pooled dredges of each tow as a single replicate. The data were standardized, fourth root transformed and the Bray–Curtis similarity indices calculated between all possible pairs of samples. The relationships between samples were examined by multi-dimensional scaling (MDS) plots, and the analysis of similarities (ANOSIM) routine (Clarke & Warwick, 1994) was used to assess the significance of any differences among the sites (data were grouped into the 13 sites).

To assess variations in the damage sustained by each major by-catch species between years, grounds and season, a three-way crossed ANOVA was again used on the mean damage score data from the June and October surveys in 1994 and 1995, when a consistent damage scoring protocol was used. Again, a non-parametric ANOVA was employed, with significance levels adjusted for multiple comparisons, and power calculated.

Table 2. *Damage scores for biota retained as by-catch during surveys of commercial scallop fishing grounds.*

Score	1	2	3	4
Crabs	No visible damage	Legs missing/ small carapace cracks	Major carapace cracks	Crushed/dead
Starfish	No visible damage	Arms missing	Worn and arms missing/minor disc damage	Major disc damage/dead
Urchins	No visible damage	<50% spine loss	>50% spine loss/minor cracks	Crushed/dead
Whelks	No visible damage	Edge of shell chipped	Shell cracked or punctured	Crushed/dead
Bivalves	No visible damage	Edge of shell chipped	Hinge broken	Crushed/dead
Hermit crabs	No visible damage	Out of shell and intact	Out of shell and damaged	Crushed/dead
Octopus	No visible damage	Minor abrasions to skin/active movement	Major abrasions to skin/weak movement	Crushed/dead

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It was initially assumed that animals assessed as damage score 3 (severely damaged) or 4 (dead) would die on discard, whilst scores 1 and 2 animals would survive. However, this assumption was tested by post-capture laboratory survival studies, over 72 h, and the results used to estimate more accurately the proportion expected to die on discard. This proportion is presented as an index of specific sensitivity to encounter with the two types of scallop dredges, and was calculated as follows;

$$\text{Proportion expected to die} = \frac{\sum_{i=1}^{i=4} an}{N} \qquad (1)$$

where a=proportion of damage grade i dying in the laboratory study, n=number of score i caught, and N=total number of all scores caught.

Considerable variation in the damage sustained by each species was observed between different grounds, and it was assumed that differences in the substrata were largely responsible. The two dredge types collect markedly different volumes of stones, dead shell and biota, and it was suspected that the damage incurred in the two gear types would reflect this. One-way ANOVA was initially used to assess the effect of dredge type on damage sustained by each species, pooled over all grounds (using arcsine transformed proportion data from October 1994 and June 1995), and the results used to decide whether the two gears could be pooled for subsequent analyses. A 'best subsets' regression analysis (Sokal & Rohlf, 1995) was then used to investigate the relationships between the proportion of each species expected to die, and the suite of physical parameters. This analysis calculates the coefficient of determination (R^2, equivalent to 'goodness of fit') of the regression equation between the dependent variable (proportion expected to die over 72 h), and successively larger subsets of the independent, predictor, variables (physical parameters). The combination of physical parameters with the highest R^2 value (adjusted to standardize the degrees of freedom), is considered to best explain the damage sustained. Data were normalized by natural log transformation, except in the case of proportions, which were arcsine transformed. Additionally, correlation coefficients were calculated to examine the relationship between damage and each of the physical parameters individually, and also to determine the direction of any observed relationships.

RESULTS

Eight grounds were sampled during at least eight of the possible ten surveys, and were included in the analysis of

Table 3. *Results of non-parametric ANOVA on abundance of major by-catch species collected over five years during twice-yearly surveys (at the start—31 May —and end—1 November—of the closed season for the great scallop) of eight fishing grounds around the Isle of Man, Irish Sea, using great scallop dredges.*

Species	H′	Sig.	Power	Species	H′	Sig.	Power
Aequipecten opercularis				*Eledone cirrhosa*			
Year	6.19	ns	0.95	Year	5.79	ns	0.67
Season	2.62	ns	0.68	Season	0.68	ns	<0.01
Ground	126.49	**	1	Ground	5.21	ns	<0.01
Year *Season	8.98	ns	1	Year *Season	7.31	ns	0.8
Year *Ground	18.33	ns	0.76	Year *Ground	13.55	ns	<0.01
Season *Ground	5.93	ns	0.82	Season *Ground	2.13	ns	<0.01
Asterias rubens				*Echinus esculentus*			
Year	7.30	ns	0.85	Year	2.6	ns	0.62
Season	4.26	ns	0.72	Season	0.53	ns	<0.01
Ground	93.86	**	1	Ground	128.95	**	1
Year *Season	21.65	**	1	Year *Season	4.1	ns	0.86
Year *Ground	28.14	ns	0.72	Year *Ground	13.65	ns	0.76
Season *Ground	7.76	ns	0.72	Season *Ground	3.49	ns	<0.01
Buccinum undatum				*Neptunea antiqua*			
Year	0.73	ns	<0.01	Year	1.37	ns	<0.01
Season	1.63	ns	<0.01	Season	0.72	ns	<0.01
Ground	62.4	**	1	Ground	89.92	**	1
Year *Season	2.97	ns	<0.01	Year *Season	11.09	ns	0.99
Year *Ground	8.42	ns	<0.01	Year *Ground	17.11	ns	0.5
Season *Ground	3.14	ns	<0.01	Season *Ground	5.06	ns	<0.01
Cancer pagurus				*Spatangus purpureus*			
Year	4.21	ns	0.4	Year	1.12	ns	<0.01
Season	12.41	**	1	Season	7.08	ns	1
Ground	96.22	**	1	Ground	13.12	ns	1
Year *Season	6.08	ns	0.67	Year *Season	0.93	ns	<0.01
Year *Ground	13.83	ns	<0.01	Year *Ground	4.63	ns	<0.01
Season *Ground	7.47	ns	0.55	Season *Ground	11.56	ns	1

Sig., statistical significance; H′, Kruskal–Wallis test; *, $P<0.05$; **, $P<0.01$; ns, not significant.

Table 4. *Results of non-parametric ANOVA on abundance of major by-catch species collected over five years during twice-yearly surveys (at the start—31 May—and end—1 November—of the closed season for the great scallop) of eight fishing grounds around the Isle of Man, Irish Sea, using queen scallop dredges. Data for the target species,* Aequipecten opercularis, *are given as a comparison with great scallop dredges.*

Species	H′	Sig.	Power	Species	H′	Sig.	Power
Aequipecten opercularis				*Eledone cirrhosa*			
Year	6.57	ns	1	Year	8.44	ns	0.78
Season	0.07	ns	<0.01	Season	15.39	**	0.99
Ground	170.68	**	1	Ground	10.61	ns	0.74
Year *Season	3.51	ns	0.98	Year *Season	3.64	ns	<0.01
Year *Ground	19.86	ns	1	Year *Ground	21.56	ns	<0.01
Season *Ground	1.97	ns	0.6	Season *Ground	1.74	ns	<0.01
Asterias rubens				*Echinus esculentus*			
Year	22.07	**	1	Year	6.14	ns	1
Season	1.20	ns	<0.01	Season	0.68	ns	<0.01
Ground	93.68	**	1	Ground	126.30	**	1
Year *Season	18.87	**	1	Year *Season	6.34	ns	1
Year *Ground	29.3	ns	0.8	Year *Ground	15.95	ns	0.87
Season *Ground	6.26	ns	0.5	Season *Ground	5.23	ns	0.82
Buccinum undatum				*Neptunea antiqua*			
Year	2.17	ns	0.85	Year	2.81	ns	0.65
Season	0.06	ns	<0.01	Season	1.14	ns	<0.01
Ground	190.39	**	1	Ground	179.51	**	1
Year *Season	2.28	ns	0.86	Year *Season	3.28	ns	0.74
Year *Ground	10.28	ns	0.89	Year *Ground	8.72	ns	<0.01
Season *Ground	4.56	ns	0.96	Season *Ground	3.19	ns	<0.01
Cancer pagurus				*Spatangus purpureus*			
Year	1.56	ns	<0.01	Year	3.68	ns	0.78
Season	10.40	*	1	Season	10.43	*	1
Ground	122.90	**	1	Ground	33.63	**	1
Year *Season	0.65	ns	<0.01	Year *Season	1.18	ns	<0.01
Year *Ground	14.93	ns	<0.01	Year *Ground	12.71	ns	0.55
Season *Ground	12.86	ns	1	Season *Ground	10.00	ns	0.98

H′, Kruskal–Wallis test; Sig., statistical significance; *, $P<0.05$; **, $P<0.01$; ns, not significant.

the abundance data, which was conducted for the two gear types separately. In all, some 87 species of macro-invertebrates and fish were recorded in these surveys (see Veale et al., 2000b, for a full list). Of these, only eight species were recorded consistently over the five year period, and were caught in sufficient numbers to render detailed analysis possible (Tables 3 & 4). This included the queen scallop (*Aequipecten opercularis*), which is often an important by-catch species in great scallop dredges, though it is, of course, the target species for vessels using queen scallop dredges. Only one species, *Asterias rubens* L., showed significant variation from year to year over the study period (but only in the queen scallop dredges), indicating relatively stable populations not subject to large annual fluctuations. Three species exhibited a seasonal variation in abundance: *Cancer pagurus* L. was more abundant in October than June (mean numbers per 2 n.m., October=11.7 ±1.3 SE, June=3.5 ±0.4 SE), in both gear types, and *Eledone cirrhosa* (Lamarck) (June=1.3 ±0.1 SE, October=0.6 ±0.1 SE) and *Spatangus purpureus* O.F. Müller (June=13.3 ±3.2 SE, October=0.9 ±0.5 SE) were more abundant in June, but only in the smaller mesh queen scallop gear. All species varied significantly in abundance, in one or both gears, between grounds, with the exception of *E. cirrhosa*. There were only two significant results within the interaction terms of the ANOVA, those between year and season for *A. rubens* in the two gear types. This implies that the variation between years observed for this species differed between the start and end of the closed season (June and October).

The distributions of the main by-catch species on great and queen scallop fishing grounds around the Isle of Man are shown in Figures 2 & 3. Some species were ubiquitously abundant (e.g. *A. rubens*), some were ubiquitous, but varied in abundance with site (e.g. *Echinus esculentus* L. and *Neptunea antiqua* (L.)), and some were only present on certain grounds (e.g. *Spatangus purpureus*, *Anseropoda placenta* (Pennant) and *Pagurus* spp. Fabricius). The MDS plots of the 1994–1995 season dataset (Figure 4) for great and queen scallop gears separately, both show two distinct groupings, one consisting of the Peel, Bradda Head, Bradda Offshore and Chickens grounds (all grounds to the west of the Isle of Man), and the other containing all remaining grounds (to the south, north and east of the Isle of Man). ANOSIM confirmed that there were highly significant differences between the sites in both datasets (minimum Global R=0.704, $P<0.01$), but the number of multiple comparisons involved (78) meant the location of the differences could not be statistically determined.

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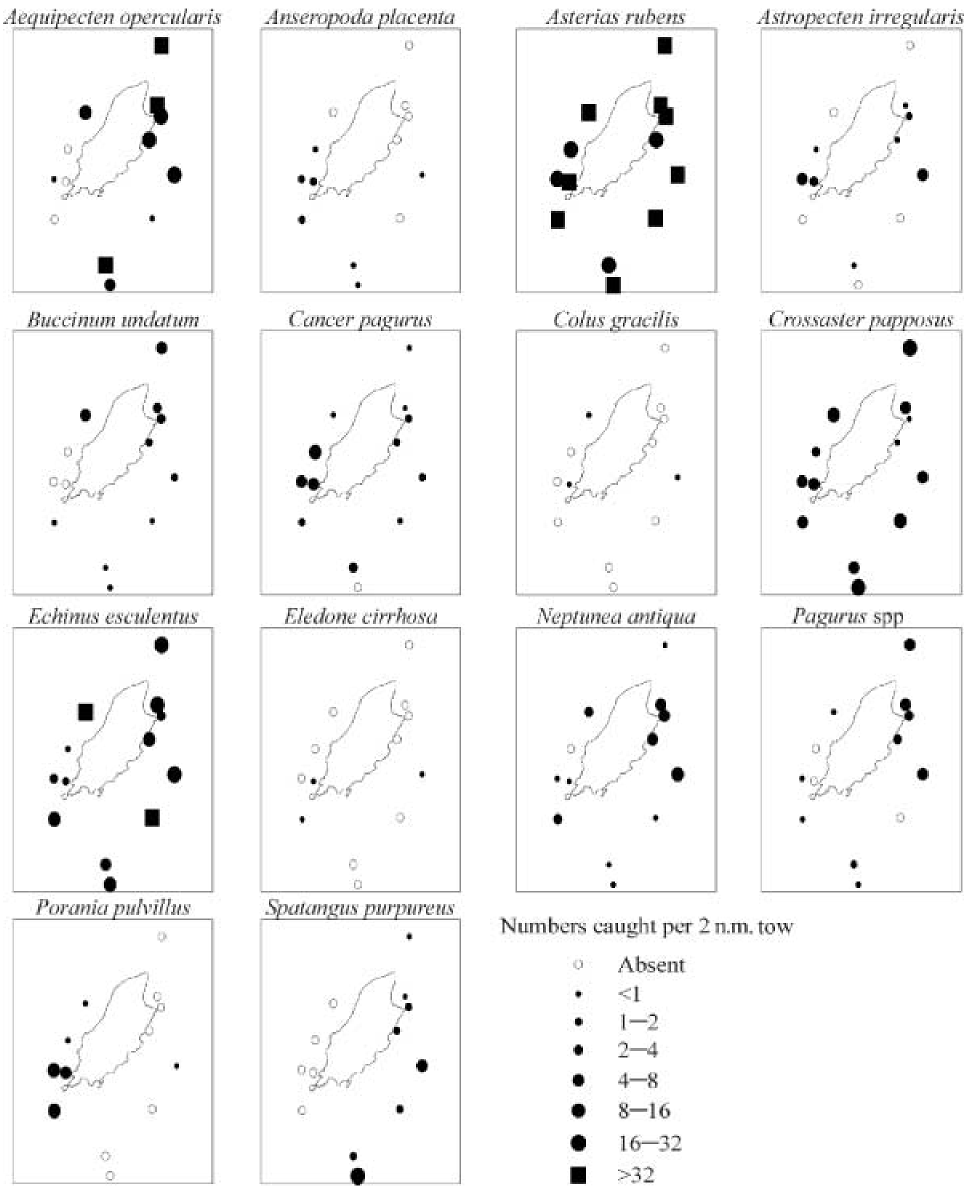

Figure 2. Numbers of major by-catch species per 2 n.m. tow, sampled by great scallop fishing gear on grounds around the Isle of Man, during the 1994–1995 fishing season.

The analysis of mean damage scores was limited to the 1994 and 1995 datasets, when the most complete suite of species was assessed for damage on the four point scale. This reduced sample size meant that many of the analyses lacked sufficient replication and power to draw meaningful conclusions, but a number of results were notable. Damage to *Asterias rubens* varied significantly between grounds in both gears (great scallop gear: $H'=30.8$, $P<0.01$, queen scallop gear: $H'=46.1$, $P<0.01$), and damage to *Cancer pagurus* and *Echinus esculentus* also varied between grounds, but only in the queen scallop gear ($H'=16.7$, $P<0.05$ and $H'=27.4$, $P<0.5$ respectively). Unfortunately, the tests for the effect of season all lacked sufficient power.

The post-capture laboratory experiments showed that, for most species, the majority of severely injured (damage score 3) animals died within 72 h, while animals with lesser injuries (scores 1 and 2) survived (Table 5). However, there were a number of exceptions e.g. only 18% of severely injured (score 3) *C. pagurus* died, while 47% of apparently unharmed (score 1) *Eledone cirrhosa* died. Estimates of the proportions of discarded animals expected to die were calculated, over all grounds investigated, as an index of sensitivity to capture in great and queen scallop dredges separately (Table 6). These should be considered to be minimum values, as injured animals returned to the seabed would be subject to increased predation (Veale et al., 2000a). *Spatangus purpureus* and *Anseropoda placenta* both exhibited high sensitivity to capture in the dredge, with virtually all individuals caught expected to die within 72 h of capture and discard. *Cancer pagurus*, *Echinus esculentus*, *Buccinum undatum* L., *Pagurus* spp., *Crossaster papposus* (L.), *Aequipecten opercularis*, and *Astropecten irregularis* (Pennant) all displayed some sensitivity, but *Asterias rubens* and *Porania pulvillus* (O.F. Müller) appeared to suffer very little damage with less than 10% dying on discard.

There were no significant differences (ANOVA—pooled data over all grounds) for any species, in the damage sustained between individuals caught in great and queen scallop dredges. This eliminated gear type as a factor directly contributing to damage levels in

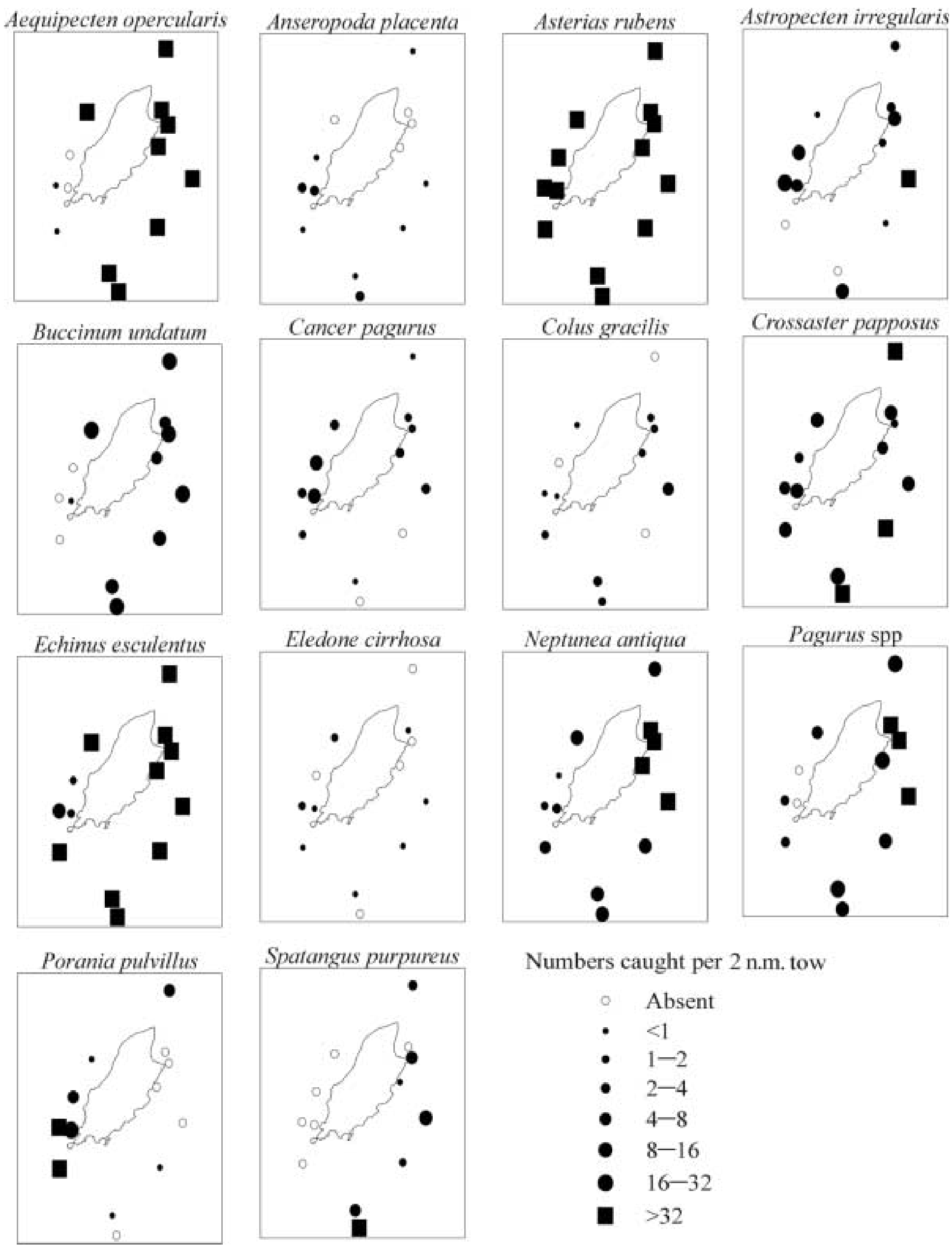

Figure 3. Numbers of major by-catch species per 2 n.m. tow, sampled by queen scallop fishing gear on grounds around the Isle of Man, during the 1994–1995 fishing season. The target species, *Aequipecten opercularis*, is also shown.

subsequent correlation calculations. However, gear type is clearly indirectly involved, as the two dredges collect very different volumes of stones, shell and biota, because of their differing teeth lengths and belly ring sizes.

For none of the species examined did a single subset of physical parameters stand-out as best explaining the proportion of individuals expected to die. Generally, the addition of a further parameter increased R^2 marginally, with no combination of parameters presenting itself clearly as the best subset. R^2 values varied considerably between species (range in the maximum adjusted R^2 values; 29.8–82.4%), as did the number of parameters contributing to the best subset (2–10) (Table 7). The whelks, *Neptunea antiqua* and *Buccinum undatum*, both exhibited R^2 values of over 75%, demonstrating that much of the variability in the proportion dying can be explained in terms of interactions between the physical parameters. Conversely, other species such as *Aequipecten opercularis*, *Asterias rubens* and *Cancer pagurus*, exhibited low R^2 values, suggesting that other unmeasured factors may be contributing to mortality.

Examined singly, a number of the physical parameters correlated significantly with the proportion of each species expected to die (Table 8). Again these varied between species, and they did not always correspond to the parameters isolated by best-subsets regression analysis. Some species are not included in Table 8 because all, or none, were expected to die, giving no variation in this parameter. Seven of the physical parameters correlated significantly with *Asterias rubens* damage, but none with *Neptunea antiqua*. The latter result is in direct contrast with the findings from best subsets regression where 75% of variability in whelk damage was explained: this may highlight the importance of the interaction between

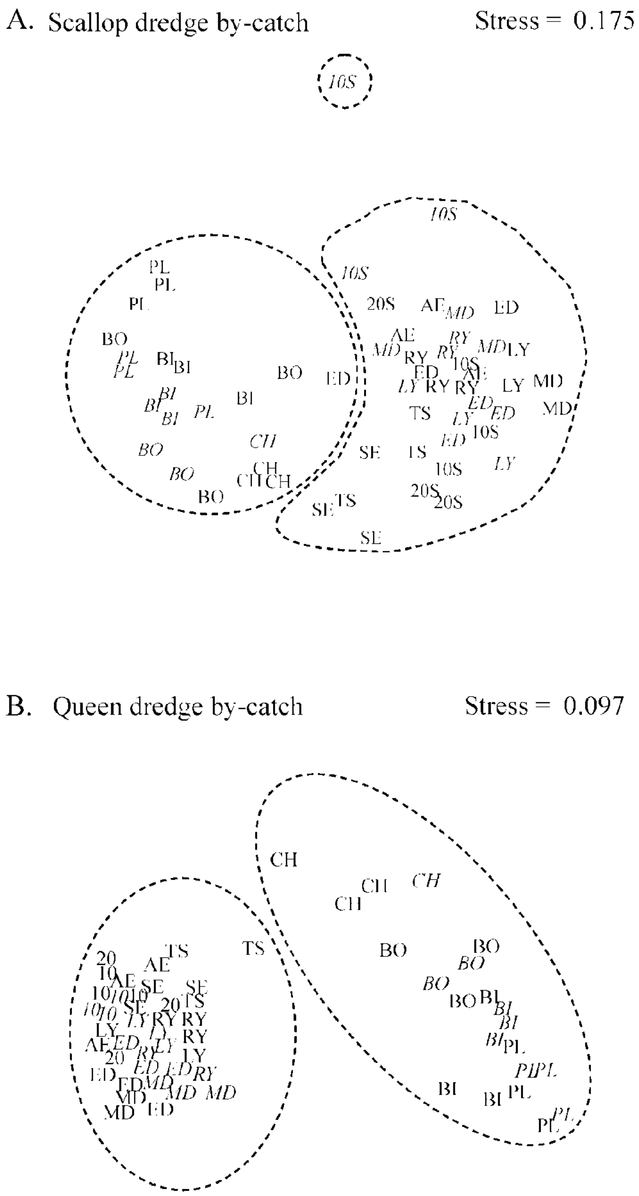

Figure 4. Multidimensional scaling plots based on the Bray–Curtis similarities between by-catch samples collected from a number of commercial fishing grounds, by (A) great scallop and (B) queen scallop dredging gear, during October 1994 (italics) and June 1995 (normal). Dotted lines indicate clusters which are distinct at the 50% similarity level (from cluster analysis—not shown). Site labels are as follows: TS, The Targets; PL, Peel Head; BI, Bradda Head; BO, Bradda Offshore/West Calf; CH, The Chickens; 10S, H/I Sector—10 m South; 20S, H/I Sector—20 m South; SE, South East Douglas; ED, East Douglas; LY, Laxey; MD, Maughold; RY, Ramsey; AE, Point of Ayre.

physical factors, for example, a *higher* percentage of stones may interact with a *lower* total volume (greater movement within the dredge possible) to induce more damage to brittle shelled animals. Depth, stone volume (% and litres), total volume and dredge fullness all correlated significantly with the proportion expected to die in more than one species.

Table 5. *Percentage mortality over 72 h in post-capture laboratory survival studies (sample sizes in brackets). Blanks indicate that no representatives of the given damage score were examined. All damage score 4 animals were dead on deck.*

Species	Score 1	Score 2	Score 3
Cancer pagurus	0 (24)	9 (23)	18 (27)
Asterias rubens	0 (40)	10 (31)	50 (30)
Aequipecten opercularis	0 (10)	10 (10)	80 (10)
Buccinum undatum	7 (28)	11 (28)	38 (16)
Neptunea antiqua	0 (32)	5 (40)	28 (18)
Echinus esculentus	0 (36)	12 (44)	46 (35)
Spatangus purpureus		100 (10)	100 (13)
Eledone cirrhosa	47 (19)	44 (9)	0 (2)
Crossaster papposus	12 (59)	41 (29)	77 (26)
Astropecten irregularis	9 (32)	16 (44)	75 (8)
Porania pulvillus	2 (42)		
Pagurus spp.	0 (21)	20 (25)	100 (10)
Anseropoda placenta		82 (11)	100 (10)

Table 6. *Sensitivity scales for the major by-catch species caught in scallop and queen dredges in the northern Irish Sea. Values are the arithmetic means of the proportion expected to die within 72 h of capture, over all grounds surveyed, ranked in order of sensitivity to each gear type.*

Scallop gear		Queen gear	
Spatangus purpureus	1.00 ±0.00	*Spatangus purpureus*	0.98 ±0.02
Anseropoda placenta	0.59 ±0.16	*Anseropoda placenta*	0.90 ±0.02
Echinus esculentus	0.34 ±0.03	*Eledone cirrhosa*	0.68 ±0.10
Crossaster papposus	0.30 ±0.02	*Echinus esculentus*	0.31 ±0.03
Cancer pagurus	0.26 ±0.06	*Cancer pagurus*	0.25 ±0.05
Buccinum undatum	0.25 ±0.04	*Crossaster papposus*	0.24 ±0.01
Pagurus spp.	0.22 ±0.07	*Pagurus* spp.	0.23 ±0.03
Astropecten irregularis	0.19 ±0.03	*Astropecten irregularis*	0.15 ±0.01
Aequipecten opercularis	0.14 ±0.03	*Buccinum undatum*	0.15 ±0.01
Neptunea antiqua	0.14 ±0.05	*Aequipecten opercularis*	0.14 ±0.02
Asterias rubens	0.07 ±0.01	*Asterias rubens*	0.10 ±0.01
Porania pulvillus	0.02 ±0.00	*Neptunea antiqua*	0.05 ±0.01
		Porania pulvillus	0.02 ±0.00

Table 7. *Results of best-subsets regression analysis.* R^2 *is the adjusted coefficient of determination for the regression equation between the proportion of each species (with sufficient data) expected to die (over 72 h) and subsets of the physical parameters.*

Species	Maximum R^2 value	Number of parameters in best subset
Aequipecten opercularis	30.2	3 (e, h, i)
Asterias rubens	38.4	5 (a, c, h, k, l)
Astropecten irregularis	61.1	7 (e, f, h, i, j, k, l)
Buccinum undatum	82.4	8 (c, d, e, g, h, i, k, l)
Cancer pagurus	29.2	5 (a, f, g, j, k)
Crossaster papposus	48.6	3 (c, f, h)
Echinus esculentus	52.3	5 (c, h, i, k, l)
Neptunea antiqua	79.7	9 (a, b, d, e, f, g, j, k, l)
Pagurus spp.	37.2	2 (a, b)

Parameters: a, depth; b, E1; c, E2; d, stone volume (l); e, % large stones; f,% medium stones; g, % small stones; h, trash volume; i, biota volume; j, total volume; k, dredge fullness (%); l, stones as a % of the catch.

https://doi.org/10.1017/S0025315401003435 Published online by Cambridge University Press

Table 8. *Significant results of Spearman-rank correlation tests to determine the relationships between the proportion of each species expected to die and physical parameters.*

Species	Depth	E1	E2	Stone volume	% large stones	% medium stones	% small stones	Trash volume	Biota volume	Total volume	% dredge fullness	% stones volume
Aequipecten opercularis					* (−)		* (+)					
Asterias rubens		* (+)	* (+)	** (+)					** (+)	* (+)	** (+)	** (+)
Buccinum undatum											* (+)	* (+)
Cancer pagurus	* (−)											
Crossaster papposus	** (+)											
Echinus esculentus				** (+)								** (+)
Neptunea antiqua												
Pagurus spp.	* (+)							** (+)		* (+)		

*, significant at 5% level; **, significant at 1% level; (+), positive correlation; (−), negative correlation.

DISCUSSION

This study provides an assessment of pectinid dredge by-catches in the north Irish Sea over a temporal scale of up to five years, and over a spatial scale of individual fishing grounds within a fishery. The study had the advantage of being conducted on a research vessel, so that sampling sites were accurately revisited and tow parameters kept constant, but it is possible that the fishing methods varied slightly from commercial practices. Also, the assessment of damage was based purely on external characteristics, whereas significant internal damage, stress and increased risk of predation may serve to reduce the likelihood of an animal surviving discard (Chopin & Arimoto, 1995; Crowder & Murawski, 1998).

Great and queen scallop dredge by-catches are characterized by a suite of large-bodied epifaunal species, although representatives of a number of smaller-bodied groups are also retained as the dredges fill up. The use of spring-toothed dredges in recent years has allowed the exploitation of rougher grounds (Brand et al., 1991), and hence extended the impact of the dredge fisheries to a greater variety of species. These areas, with coarser sediments and a greater proportion of stones and dead shell on the surface, harbour more diverse communities with a greater number of sessile colonial species utilizing the more permanent substrata (Kaiser et al., 1998). In areas like the Irish Sea, where the seabed type is very heterogeneous (Bradshaw et al., 2000), it is clearly very important to assess the impact of fishing on all the ground types where fishing occurs. Great and queen scallops together inhabit a wide range of seabed types, from fine sand to coarse gravel, dead shell and maerl. This study has attempted to describe the by-catch on the full range of seabed types fished for both species around the Isle of Man.

The multivariate analysis showed two distinct groupings of by-catch assemblage: one centred off the south-west coast of the Isle of Man, and the other on the remaining fishing grounds to the north, south and east of the island. These observations broadly correspond to the generalized benthic community types described for this area by Mackie (1990). There are obviously many possible reasons for the formation of discrete assemblages, including differences in substrata and hydrography. For example, the sediments on the grounds to the south-west generally contain more sand and less gravel than the other grounds (Holt et al., 1990). There is also a seasonal gyre in the western Irish Sea (Hill et al., 1997) which may retain the planktonic larvae of a number of benthic species and contribute to the maintenance of the observed differences in benthic assemblages. Differential exposure to intense commercial dredging may also play a key role in structuring these assemblages (Veale et al., 2000b): the great scallop grounds around the south-west of the Isle of Man have been heavily exploited since 1937, while other grounds have a shorter, and less intensive, history of exploitation (Brand et al., 1991).

The distribution of a number of the by-catch species considered individually also broadly fit into one of the two groups proposed above: e.g. *Porania pulvillus, Cancer pagurus,* and *Anseropoda placenta* are abundant off the south-west coast of the island, and *Buccinum undatum, Pagurus* spp., and *Spatangus purpureus* are more abundant around the rest of the coast. It is clear from these findings that to obtain an accurate description of by-catch species and numbers, the spatial and temporal scale of sampling is very important. The observed heterogeneity in by-catch assemblage in the northern Irish Sea pectinid fishery demonstrates the need for regular sampling on each of the discrete assemblage types present within the fishery, on a time scale that can account for major variations in annual recruitment. When planning by-catch monitoring programmes, fisheries managers should first seek out existing benthic datasets in an attempt to identify any distinct seabed communities within the area of the fishery. In the absence of such existing datasets, a comprehensive initial by-catch survey should be carried out instead. This information can then be used to target by-catch surveys to adequately sample all benthic assemblages affected by the fishery (Veale et al., 2000b).

The differences in numbers of *Eledone cirrhosa* and *Cancer pagurus* recorded in the surveys at the beginning and end of the closed season for great scallop fishing may be due to seasonal variation in behaviour. For example, the seasonal abundance of *C. pagurus* in the by-catch is strongly dependent on their annual inshore/offshore migration pattern (Edwards, 1979), which has been recently demonstrated on some of these grounds by Pennington (1999).

https://doi.org/10.1017/S0025315401003435 Published online by Cambridge University Press

Fishing patterns in the north Irish Sea change during the closed season for great scallops, as the boats revert to fishing for queen scallops. Great and queen scallops co-exist in commercially viable densities on some grounds, but grounds are generally fished for one or the other species. This shift in the spatial distribution of fishing effort will change the vulnerability of by-catch populations to fishing disturbance: populations on great scallop grounds may benefit from the summer closed season, while those on queen scallop grounds will suffer increased mortality. There was, however, no evidence in our study of any beneficial effect of the closed season, on the species studied. Notable among the results of the abundance analyses was the lack of any significant interaction term between season and ground, despite a number of the tests having sufficient power to detect a difference, had it been present. If the closed season had a beneficial effect on the populations of by-catch species on great scallop grounds and the opposite effect on queen scallop grounds, then we might have expected this term to be significant. However, the species tested here are all relatively slow-growing and long-lived, so the potential increase in population abundance over a five month period would not be very large, although the annual mortality rate of these species may be reduced. Small, short-lived, fast-growing species are most likely to benefit from the cessation of dredge disturbance over the closed season on great scallop grounds, but since such species are not retained in the dredges in any number, they were not included in this study. There was a significant reduction in *Spatangus purpureus* abundance between June and October, suggesting that the mandatory great scallop closed season may have a short-term negative effect on this species, as fishing effort is switched to the grounds that this species shares with the queen scallop. If reduction of by-catch mortality is a desirable function of a closed season, then it seems apparent that the closure must be for all mobile demersal gears.

The only significant differences in damage sustained between sampling sites were observed for *Asterias rubens*, *C. pagurus* and *Echinus esculentus*. Differences between grounds were expected as the substratum and content of the dredges varies considerably between sites. It is clear that some species are much more sensitive to capture in the dredge than others. The fragile test of *S. purpureus*, and the thin body of *Anseropoda placenta* make both these species particularly susceptible to damage, although another echinoid, *E. esculentus*, is slightly more robust. The edible crab, *C. pagurus,* is surprisingly robust to capture in the dredge, given the tendency of the legs to become enmeshed in the belly rings and netting back of the dredge. The percentage of whelks, *Buccinum undatum*, estimated to survive in the present study (75–85%, the inverse of the proportion expected to die) is somewhat higher than that from the North Sea 12 m beam trawl fishery (40%) (Mensink et al., 2000). This may be partly due to the extended study period in the latter, but also to differences in the gear and seabed type. The tough compact body of *Asterias rubens*, *Porania pulvillus* and the shell of *Neptunea antiqua* undoubtedly render them hardy to dredging. The index of sensitivity provides a clear indication of which by-catch species should be monitored in order to assess the impact of the fishery, and could be used to highlight areas of conservation value on the grounds of the sensitive species they harbour. If some assumptions about the generality of application over different seabed types are made, the index can be used by fisheries scientists, in conjunction with fishing effort data, to convert by-catch data to estimates of numbers and biomass killed by a commercial fleet.

As might be expected, there is a hierarchy of sensitivity to dredge capture among different species, and this may lead to long-term alterations in community structure, as more sensitive species are removed from the community, and robust species capable of utilizing discard material (such as *Asterias rubens*) may thrive. Additionally, the relocation of animals by discarding, and the spatial distribution (over different fishing grounds) of fishing effort, may play roles in restructuring communities. Possible long-term changes in the north Irish Sea benthic communities resulting from dredging are discussed in Hill et al. (1999) and Veale et al. (2000b).

For some species (e.g. *Buccinum undatum*), up to 80% of the variation in damage sustained can be attributed to some combination of the physical parameters recorded. In contrast, for other species (e.g. *C. pagurus*) this figure is as low as 30%. This suggests that other factors, not recorded in this study, must play a role in determining the damage sustained. In the case of *C. pagurus*, this may include the seasonal reproductive cycle, as the distension of the abdomen in ovigerous females makes severe damage much more likely. Similarly, the damage sustained by *A. rubens* in the October surveys may differ from that sustained in June because the condition of the animals varies. After a summer of warm temperature and higher feeding rates (Jangoux, 1982), *A. rubens* become large and swollen, and appear to be more vulnerable to limb loss and crushing.

The correlation coefficients between damage and the physical parameters examined singly were also generally low, and no common suite of explanatory parameters was readily apparent, although different species might be expected to be damaged in different ways. It was anticipated that the volume of stones in the catch would prove to be strongly correlated with damage, and possibly that emptier dredges may allow more damaging movement of the whole catch. The percentage of stones in the catch was correlated with damage for *A. rubens, B. undatum* and *E. esculentus*. The brittle test or shell of the latter two species sustain damage on sharp impact with stones in the catch, and *A. rubens* suffers crushing and grinding. Dredge fullness or total volume was positively correlated with damage for *A. rubens, B. undatum* and *Pagurus* spp., suggesting that some damage is caused by crushing for these species. Correlations with depth may be due to indirect effects attributable to physical differences in the animals themselves. For example, ovigerous female *C. pagurus* are known to migrate into shallower inshore waters as hatching time approaches, and moulting may occur soon after (Edwards, 1979). Also, local differences in shell morphology in response to a number of factors, including depth, are well known in gastropods such as *B. undatum* (Thomas & Himmelman, 1988). It is clear that a reduction in both the total volume of material retained by the dredges, and in the proportion of stones caught, may significantly reduce damage to the by-catch, and improve the survival rates of discarded animals. These goals could be achieved through modifications of the gear (such as altered tooth design) to improve selectivity for the target species, particularly for queen scallop dredges, or to reduce the number of stones entering the dredge. Such modifications are currently under investigation by the EU project Ecodredge (FAIR CT98-4465). A reduced tow length would also be of benefit by minimizing the time spent in the dredge sustaining damage from the 'churning' contents, but this measure would be unpopular with fishermen as it would reduce efficiency.

The numbers of by-catch animals captured per unit area obviously varies from ground to ground with the density of each species on the seabed, but will also vary with the substratum as gear efficiency is related to this parameter. The numbers of animals affected by dredging are therefore likely to be greatly underestimated from by-catch studies, especially given the relatively low efficiency of dredges at catching the target species (6–41% for great scallop dredges) (Dare et al., 1993) and the high size selectivity that allows many of the smaller species to avoid capture. Future work should therefore be directed at obtaining a more complete description of the communities present on commercial fishing grounds, including an evaluation of those animals killed by the passage of the gear, but not retained. Sufficient data will then be available to assess the impact of dredging on the benthos at the scale of the ecosystem, and to determine whether a by-catch management programme is required.

The authors would like to thank the crew of the RV 'Roagan', and all the volunteers who help out on the biannual by-catch surveys, especially Matthew Mosley. This study was funded by the Ministry of Agriculture, Fisheries and Food as part of contract no. CSA 2332. This work also drew on the resources and data provided by the Isle of Man Department of Agriculture, Fisheries and Forestry scallop fishery research project.

REFERENCES

Beek, F.A. van, Leeuwen, P.I. van & Rijnsdorp, A.D., 1990. On the survival of plaice and sole discards in the otter-trawl and beam-trawl fisheries in the North Sea. *Netherlands Journal of Sea Research*, **26**, 151–160.

Bergman, M.J.N., Fonds, M., Hup, M. & Stam, A., 1990. Direct effects of beam trawl fishing on benthic fauna in the North Sea. *International Council for the Exploration of the Sea (CM Papers and Reports)*, CM 1990/mini:11, 19 pp.

Bradshaw, C., Veale, L.O., Hill, A.S. & Brand, A.R., 2000. The effects of scallop dredging on gravelly sea-bed communities. In *Effects of fishing on non-target species and habitats* (ed. M.J. Kaiser and S.J. de Groot), pp. 83–104. Oxford: Blackwell Science.

Brand, A.R., Allison, E.H. & Murphy, E.J., 1991. North Irish Sea scallop fisheries: a review of changes. In *An international compendium of scallop biology and culture* (ed. S.E. Shumway and P.A. Sandifer), pp. 204–218. Baton Rouge: World Aquaculture Society.

Brand, A.R. & Prudden, K.L., 1997. The Isle of Man scallop and queen fisheries: past, present and future. *University of Liverpool, Report to the Isle of Man Department of Agriculture, Fisheries and Forestry*, 101 pp.

Caddy, J.F., 1970. Records of associated fauna in scallop dredge hauls from the Bay of Fundy. *Technical Report. Fisheries Research Board of Canada*, **225**, 1–11.

Chopin, F.S. & Arimoto, T., 1995. The condition of fish escaping from fishing gears—a review. *Fisheries Research*, **21**, 315–327.

Clarke, K.R. & Warwick, R.M., 1994. *Change in marine communities: an approach to statistical analysis and interpretation*. Swindon: Natural Environment Research Council.

Crowder, L.B. & Murawski, S.A., 1998. Fisheries bycatch: implications for management. *Fisheries*, **23**, 8–17.

Currie, D.R. & Parry, G.D., 1996. Effects of scallop dredging on a soft-sediment community: a large-scale experimental study. *Marine Ecology Progress Series*, **134**, 131–150.

Dare, P.J., Key, D., Darby, C.D. & Connor, P.M., 1993. The efficiency of spring-loaded dredges used in the western English Channel fishery for scallops, *Pecten maximus* (L.). *Ministry of Agriculture, Fisheries and Food, Directorate of Fisheries Report*, 16 pp.

DuPaul, W.D., Brust, J.C. & Kirkley, J.E., 1995. Bycatch in the United States and Canadian sea scallop fisheries. In *Solving bycatch workshop: considerations for today and tomorrow* (ed. T. Wray), pp. 175–182. Seattle: Alaska Sea Grant College Program.

Edwards, E., 1979. *The edible crab and its fishery in British waters*. Farnham, Surrey: Fishing News Books.

Eleftheriou, A. & Robertson, M.R., 1992. The effects of experimental scallop dredging on the fauna and physical environment of a shallow sandy community. *Netherlands Journal of Sea Research*, **30**, 289–299.

Evans, S.M., Hunter, J.E., Elizal, A. & Wahju, R.I., 1994. Composition and fate of the catch and bycatch in the Farne-Deep (North-Sea) Nephrops Fishery. *ICES Journal of Marine Science*, **51**, 155–168.

Fogarty, M.J. & Murawski, S.A., 1998. Large-scale disturbance and the structure of marine system: fishery impacts on Georges Bank. *Ecological Applications*, **8**, S6–S22.

Greenstreet, S.P.R., Ruck, I.D., Grewar, G.N., Armstrong, E., Reid, D.G. & Wright, P.J., 1997. An assessment of the acoustic survey technique, RoxAnn, as a means of mapping seabed habitat. *ICES Journal of Marine Science*, **54**, 939–959.

Groot, S.J. de & Apeldoorn, J., 1971. Some experiments on the influence of the beam trawl on the bottom fauna. *International Council for the Exploration of the Sea (CM Papers and Reports)*, CM 1971/B:2, 5 pp.

Hall, M.A., 1996. On bycatches. *Reviews in Fish Biology and Fisheries*, **6**, 319–352.

Hill, A.E., Brown, J. & Fernand, L., 1997. The summer gyre in the western Irish Sea: shelf sea paradigms and management implications. *Estuarine, Coastal and Shelf Science*, **44**, 83–95.

Hill, A.S., Brand, A.R., Wilson, U.A.W., Veale, L.O. & Hawkins, S.J., 1996. Estimation of by-catch composition and the numbers of by-catch animals killed annually on Manx scallop fishing grounds. In *Aquatic predators and their prey* (ed. S.P.R. Greenstreet and M.L. Tasker), pp. 111–115. Oxford: Blackwell Scientific.

Hill, A.S., Veale, L.O., Pennington, D., Whyte, S.G., Brand, A.R. & Hartnoll, R.G., 1999. Changes in Irish Sea benthos: possible effects of 40 years of dredging. *Estuarine, Coastal and Shelf Science*, **48**, 739–750.

Holt, R., Fisher, E. & Graham, C., 1990. Coastal resources of the Irish Sea. In *The Irish Sea: an environmental review.* Part 1. *Nature conservation* (ed. Irish Sea Study Group), pp. 5–38. Liverpool: Liverpool University Press.

Jangoux, M., 1982. Food and feeding mechanisms: Asteroidea. In *Echinoderm nutrition* (ed. M. Jangoux and J.M. Lawrence), pp. 117–159. Rotterdam: A.A. Balkema.

Kaiser, M.J., Armstrong, P.J., Dare, P.J. & Flatt, R.P., 1998. Benthic communities associated with a heavily fished scallop ground in the English Channel. *Journal of the Marine Biological Association of the United Kingdom*, **78**, 1045–1059.

Kaiser, M.J. & Spencer, B.E., 1994. A preliminary assessment of the effect of beam trawling on a benthic community in the Irish Sea. In *Environmental impact of bottom gears on benthic fauna in relation to natural resources management and protection of the North Sea* (ed. S.J. de Groot and H.J. Lindeboom), pp. 87–94. Texel: Netherlands Institute for Sea Research.

Kaiser, M.J. & Spencer, B.E., 1996. Behavioural responses of scavengers to beam trawl disturbance. In *Aquatic predators and their prey* (ed. S.P.R. Greenstreet and M.L. Tasker), pp. 116–123. Oxford: Blackwell Scientific.

Mackie, A.S.Y., 1990. Offshore benthic communities of the Irish Sea. In *The Irish Sea: an environmental review.* Part 1. *Nature conservation* (ed. Irish Sea Study Group), pp. 169–218. Liverpool: Liverpool University Press.

Magorrian, G.H., Service, M. & Clarke, W., 1995. An acoustic bottom classification survey of Strangford Lough, Northern Ireland. *Journal of the Marine Biological Association of the United Kingdom*, **75**, 987–992.

Medcof, J.C. & Bourne, N., 1964. Causes of mortality of the sea scallop, *Placopecten magellanicus*. *Proceedings. National Shellfisheries Association*, **53**, 33–50.

Medcof, J.C. & Caddy, J.F., 1971. Underwater observations on performance of clam dredges of three types. *International Council for the Exploration of the Sea (Gear and Behaviour Committee)*, CM 1971/B:10, 261–267 pp.

Mensink, B.P., Fischer, C.V., Cadee, G.C., Fonds, M., Ten Hallers-Tjabbes, C.C. & Boon, J.P., 2000. Shell damage and mortality in the common whelk *Buccinum undatum* caused by beam trawl fishery. *Journal of Sea Research*, **43**, 53–64.

Meyer, T.L., Cooper, R.A. & Pecci, K.J., 1981. The performance and environmental effects of a hydraulic clam dredge. *Marine Fisheries Review*, **43**, 14–22.

Pearson, E.S. & Hartley, H.O., 1951. Charts for the power function for analysis of variance tests, derived from the non-central F-distribution. *Biometrika*, **38**, 112–130.

Pennington, D., 1999. *Studies of aspects of predation on the Manx scallop,* Pecten maximus *(L.), populations*. PhD thesis, University of Liverpool, Liverpool.

Peterman, R. & M'Gonigle, M., 1992. Statistical power analysis and the precautionary principle. *Marine Pollution Bulletin*, **24**, 231–234.

Philippart, C.J.M., 1998. Long-term impact of bottom fisheries on several by-catch species of demersal fish and benthic invertebrates in the south-eastern North Sea. *ICES Journal of Marine Science*, **55**, 342–352.

Rijnsdorp, A.D., Buys, A.M., Storbeck, F. & 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.

Roddick, D.L. & Miller, R.J., 1992. Spatial and temporal overlap of the American lobster (*Homarus americanus*) and sea scallop (*Placopecten magellanicus*) as related to the impact of inshore scallop dragging. *Canadian Journal of Fisheries and Aquatic Sciences*, **49**, 1486–1492.

Rumohr, H. & Krost, P., 1991. Experimental evidence of damage to benthos by bottom trawling with special reference to *Arctica islandica*. *Meeresforschung—Reports on Marine Research*, **33**, 340–345.

Sangster, G.I., 1994. A review of the survival of fish escaping from fishing gears. *International Council for the Exploration of the Sea (Report of the sub-group on methodology of fish survival experiments)*, CM 1994/B:8, 46 pp.

Sheader, M., 1986. The effects of intensive dredging on benthic community structure. *Nature Conservancy Council*, CSD Report no. 679, 60 pp.

Shepard, A.N. & Auster, P.J., 1991. Incidental (non-capture) damage to scallops caused by dragging on rock and sand substrates. In *An international compendium of scallop biology and culture* (ed. S.E. Shumway and P.A. Sandifer), pp. 219–230. Baton Rouge: World Aquaculture Society.

Smith, E.M. & Howell, P.T., 1987. The effects of bottom trawling on American lobsters, *Homarus americanus*, in Long Island Sound. *Fisheries Bulletin*, **85**, 737–744.

Sokal, R.R. & Rohlf, F.J., 1995. *Biometry.* New York: W.H. Freeman & Co.

Thomas, M.L.H. & Himmelman, J.H., 1988. Influence of predation on shell morphology of *Buccinum undatum* L. on Atlantic coast of Canada. *Journal of Experimental Marine Biology and Ecology*, **115**, 221–236.

Veale, L.O., Hill, A.S. & Brand, A.R., 2000a. An *in situ* study of predator aggregations on scallop (*Pecten maximus* (L.)) dredge discards using a static time-lapse camera system. *Journal of Experimental Marine Biology and Ecology*, **255**, 111–129.

Veale, L.O., Hill, A.S., Hawkins, S.J. & Brand, A.R., 2000b. Effects of long-term physical disturbance by commercial scallop fishing on subtidal epifaunal assemblages and habitats. *Marine Biology*, **137**, 325–337.

Vooys, C.G.N. de & Meer, J. van der, 1998. Changes between 1931 and 1990 in by-catches of 27 animal species from the southern North Sea. *Netherlands Journal of Sea Research*, **39**, 291–298.

Submitted 4 September 2000. Accepted 20 October 2000.