In Collaboration with
the Netherlands Institute for Sea Research

Journal of Sea Research 50 (2003) 45–56

JOURNAL OF SEA RESEARCH

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The impact of hydraulic blade dredging on a benthic megafaunal community in the Clyde Sea area, Scotland

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Received 4 December 2002; accepted 13 February 2003

Abstract

A study was made of the impacts on a benthic megafaunal community of a hydraulic blade dredge fishing for razor clams *Ensis* spp. within the Clyde Sea area. Damage caused to the target species and the discard collected by the dredge as well as the fauna dislodged by the dredge but left exposed at the surface of the seabed was quantified. The dredge contents and the dislodged fauna were dominated by the burrowing heart urchin *Echinocardium cordatum*, approximately 60–70% of which survived the fishing process intact. The next most dominant species, the target razor clam species *Ensis siliqua* and *E. arcuatus* as well as the common otter shell *Lutraria lutraria*, did not survive the fishing process as well as *E. cordatum*, with between 20 and 100% of individuals suffering severe damage in any one dredge haul. Additional experiments were conducted to quantify the reburial capacity of dredged fauna that was returned to the seabed as discard. Approximately 85% of razor clams retained the ability to rapidly rebury into both undredged and dredged sand, as did the majority of those heart urchins *Echinocardium cordatum* which did not suffer aerial exposure. Individual *E. cordatum* which were brought to surface in the dredge collecting cage were unable to successfully rebury within three hours of being returned to the seabed. These data were combined to produce a model of the fate of the burrowing megafauna dredged and dislodged in order to collect 10 kg of marketable razor clams.

Keywords: Burrowing organisms; Damage; Discards; Dredges; *Ensis*; Scotland; Clyde Sea

1. Introduction

A fundamental objective of any fishery management strategy must be to accurately quantify the fishing pressure imposed on the target species in order to facilitate the long-term stability of the industry. Additional consideration should also be given to by-catch species of commercial value as well as the conservation of natural habitats and the maintenance of biodiversity (EC Council Communication 143, 2001). Encompassed within this remit is a need to accurately monitor the damage caused to target species, by-catch and discard which will provide a true picture of the 'cost' of any fishery (Jennings and Kaiser, 1998; Hall, 1999; Moore and Jennings, 2000; Gaspar et al., 2002) as well as the effects of scavengers acting on the fishery discard (Ramsay

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doi:10.1016/S1385-1101(03)00045-5

et al., 1996, 1997, 1998; Ramsay and Kaiser, 1998; Fonds and Groenewold, 2000; Groenewold and Fonds, 2000; Veale et al., 2000).

In an attempt to refine assessments of fishery impacts, a number of researchers have acknowledged that not all discarded material from a fishery will die immediately or be scavenged and have sought to incorporate estimates of discard survival into their work. To date, this research has tended to focus upon commercially and ecologically important decapod crustaceans including Norway lobsters *Nephrops norvegicus* (Symonds and Simpson, 1971; Wileman et al., 1999), crabs (Bennett, 1973; Kennelly et al., 1990; Potter et al., 1991; Bergmann and Moore, 2001) and squat lobsters *Munida rugosa* (Bergmann and Moore 2001), as well as other epibenthic invertebrates (Bergmann et al., 2001). Much of this work has focused on the effects of limb autotomy, caused by impact with the fishing gear, on subsequent survival.

The survival of discarded bivalves and other sandy sediment mega-infaunal species is clearly dependent on their ability to rebury into the sediment and escape from the scavengers and predators which invariably move into a fished site (Caddy, 1973; Ramsay et al., 1996; Fonds et al., 1998; Ramsay and Kaiser, 1998; Ramsay et al., 1998). This is especially the case for hydraulic dredge fisheries, which are well established worldwide (Meyer et al., 1981; Ismail, 1985; Pravanovi and Giovanardi, 1994). Hydraulic dredges have the potential to expose deep-burrowing, long-lived bivalves, such as the otter shell *Lutraria lutraria* (Linnaeus, 1758) and the Icelandic cyprine *Arctica islandica* (Linnaeus, 1767), which would otherwise rarely find themselves exposed at the sediment surface. Furthermore, hydraulic dredges use large volumes of seawater to fluidise the sand in order to facilitate extraction of the target species, which can lead to areas of seabed remaining fluidised for extended periods (Tuck et al., 2000). Clearly the generation of tracts of fluidised seabed may impede the successful reburial of infaunal bivalves by preventing their weak pedal muscles, which are relatively atrophied in adults, from being used to create an anchor with which to affect reburial.

The hydraulic dredge fishery for razor clams *Ensis* spp. in Scotland has been pursued on a very small scale for a number of years although improvements in handling, depuration (Younger, 2000) and transportation, combined with increased demand in southern Europe and the Far East has led to growth of interest in the fishery. This interest has intensified, both as fishers seek to diversify and reduce fishing pressure on fin-fish species within the over-fished North Atlantic and North Sea, and also to avoid the recent difficulties in the scallop *Pecten maximus* (Linnaeus, 1758) fishery because of extensive closures caused by shellfish biotoxins.

In light of the increased interest in use of hydraulic gear for harvesting shellfish, as well as potential future changes in legislation, this study sought to quantify the damage caused to the catch and discard generated by a hydraulic dredge fishing on a small razor-clam bed within the Clyde Sea area in Scotland. At the same time, experiments were undertaken to assess the ability of exposed infaunal species to rebury into the sediment and escape subsequent predation. Using these data, a preliminary model of the impacts of hydraulic dredge fishing was generated.

2. Methods

2.1. The hydraulic blade dredge

Details of the UMBSM hydraulic blade dredge used in this work have been presented elsewhere (Hauton et al., 2003). Preliminary experiments, which compared the catch collected by the dredge with an independent quadrat-based assessment of the density of *Ensis* spp., showed that the dredge removed ~ 90% of the razor-clam biomass from a central 0.4-m swath of sediment (Hauton et al., 2002). This was in good agreement with an estimate of 91% previously calculated for a hydraulic dredge fishing for surf clams *Spisula solidissima* (Dillwyn) in America (Meyer et al., 1981).

2.2. Damage caused to the catch, discards and those individuals dislodged by the dredge but left on the seabed

A total of ten dredge hauls were made on five separate dates between February 2001 and December 2001 at Hunterston Sands (HU, 55.73°N, 04.88°W) within the Clyde Sea area. Each dredge haul was sorted on deck and the target razor clams *Ensis siliqua*

(Linnaeus, 1758) and *E. arcuatus* (Jeffreys, 1865) were separated into three damage classes: intact, lightly damaged and severely damaged, according to the criteria shown in Table 1. A distinction was also made between clams of different sizes because, under current legislation, only clams above 10 cm could be landed commercially. In addition the most abundant by-catch species were collected and graded according to the same damage criteria. For every species the number of individuals per damage category was counted and the whole wet weight of each category recorded. Finally the qualitative abundance of all other species found in the dredge was recorded.

For every haul, SCUBA divers followed behind the dredge during fishing and collected all of the megafauna which were dislodged by the dredge but which were left lying exposed on the surface of the dredge track. At the end of the dredge haul, the divers used a tape measure to record the total length of the track. By treating the dredge contents and the material collected from the dredge track identically it was possible to combine the data to produce an overall assessment of the damage caused to the target species and the discard.

2.3. Reburial capacity of dredged fauna

The reburial capacity of dredged or dislodged megafauna, which were otherwise intact or suffering only light damage, was assessed using a separate experiment done over a four-day period during August 2001. The aim of this investigation was to determine (a) the ability of dredged fauna to rebury when returned to the seabed and (b) to compare the reburial success of razor clams on a dredged/fluidised seabed with that on a 'pristine' seabed.

On each day of the experiment, dislodged material was collected from a dredge haul at Hunterston Sands.

Table 1
Summary of criteria for assessing damage to megafauna

Class of animal	Intact	Light damage	Severe damage
Gastropoda and Bivalvia	Externally, no visible signs of damage	Shell chipped or with surface cracks	Shell with deep cracks revealing soft tissue, or broken shells
Echinoidea	As above	Test intact, spines missing	Punctured or crushed test

Once hauled, the dredge contents were quickly sorted and a range of intact animals collected. The shell of each razor clam was marked at the siphonal opening with white Tipp-Ex™ correction fluid, which increased the colour contrast of the shell against the sediment and facilitated accurate determination of the time at which the clam disappeared below the surface of the seabed. All of the animals used were held on deck under running seawater until they were returned to the seabed in order to minimise the stress imposed by aerial exposure and the maximum time on deck was limited to 40 min.

On the first two days of the experiment RV 'Aora' simply anchored fore and aft, whilst on each of the last two days a short dredge track was created with the hydraulic dredge to produce a strip of fluidised sand and then the vessel anchored fore and aft over the dredge track. With the vessel at anchor a weighted frame was lowered over the stern and onto the seabed. This frame was covered in 0.25-mm^2 plastic Netlon™ mesh to prevent any potential interference from scavengers and predators and to create an enclosure in which the dislodged animals could be laid out on the seabed. With the frame in place, divers entered the water and laid out all of the dislodged material within the enclosure.

Reburial activity was recorded under natural light using a Kongsberg Simrad™ Osprey OE 1362 low-light sensitive colour camera with a fixed focal length, which was attached to the frame. The video output from the camera was recorded via umbilical using a Panasonic™ AG 5700 VHS video recorder on RV 'Aora' and activity was recorded for 3 h.

During this field experiment certain anomalies in the behaviour of the burrowing heart urchin *Echinocardium cordatum* were noted and, as a result, divers made additional observations on the reburial activity of this species in situ, as described in Section 3.3.

2.4. Data analysis

2.4.1. Damage to catch, discard and dislodged individuals left in the dredge track

Before analysing the data, a distinction was made between the catch, by-catch and discards as defined by Alverson et al. (1994). The catch included the intact and lightly damaged target *Ensis* spp. which were above the minimum landing size (MLS) and which could marketed.

Discards comprised non-commercial species as well as the severely damaged and undersized *Ensis* spp. To remove any confounding effect associated with the differing track lengths all of the data have been standardised to a unit area of 1 m^2, using the track length measurements recorded by the divers and the standard fished width of 0.45 m determined empirically for the UMBSM dredge (Hauton et al., 2002).

2.4.2. Analysis of reburial capacity

The video records of reburial activity were analysed to produce the following data set.

i) The proportion of animals of each species that completely reburied within the duration of the experiment (3 h).
ii) The time taken for each animal to commence reburial activity (lag).
iii) The time each animal took to complete reburial, recorded as the time from when the animal first started to rebury until it disappeared below the surface of the sand (duration). Once the animal had completely reburied it was assumed to be safe from any immediate threat of predation.

Statistical analyses of both the reburial duration and lag were undertaken for those *Ensis arcuatus* above the MLS using the video records. This analysis was limited to razor clams above the MLS because it was difficult to accurately resolve the activity of the smaller clams from the video record. Nested analysis of variance (ANOVA) was performed according to Sokal and Rolf (1995) for unbalanced data sets, with the random factor ‘days’ (Da) nested within the fixed factor ‘sand type’ (Sa).

3. Results

3.1. Dredge contents

The contents of each dredge haul were used to estimate the total catch as a proportion of the total dredge contents. The marketable catch (*E. siliqua* and *E. arcuatus* combined) represented a variable proportion of the dredge contents on each occasion. On average, the hydraulic dredge fished 67.6 ± 56.3 g *E. siliqua* m^{-2} and 97.58 ± 116.0 g *E. arcuatus* m^{-2} and generated 529.0 ± 295.7 g total discard m^{-2}. The size of the catch in any tow depended on a number of separate factors, including differences in the composition of the infaunal species from month to month as well as small-scale heterogeneity in the distribution of clams across the seabed at Hunterston Sands.

Six species, which represented the discard and which included undersized and severely damaged razor clams, dominated the dredge hauls (Fig. 1). The burrowing heart urchin *Echinocardium cordatum* was the dominant species, representing approximately 60% (by wet weight) of the total discard. In spite of the thin test of this species, on each occasion between 60 and 70% of the urchins collected were found to be intact. After the heart urchin, the next most common species were severely damaged, viz. *Ensis siliqua*, *Ensis arcuatus* and otter shells *Lutraria lutraria*, whilst the remaining two species contributed only a minor component (Fig. 1).

A total of 30 additional species from 16 different orders were also collected by the dredge whilst fishing (Table 2). Of these 30, only two species were commonly found in the catch, viz. the sand mason worm *Lanice conchilega* (Pallas, 1766) and the brittlestar *Amphiura brachiata* (Montagu, 1804). Mobile decapod species, including the shore crab *Carcinus maenas* (Linnaeus, 1758) and the hermit crab *Pagurus bernhardus* (Linnaeus, 1758), were rarely captured and only one individual sand eel *Ammodytes tobianus* Linnaeus, 1758 was ever found. Of these 24 additional species polychaete worms, brittlestars *Amphiura brachiata* (Montagu, 1804) and tube anemones *Cerianthus loydi* Gosse, 1859 were severely damaged by the dredge. The remaining species, including gastropod and venerid molluscs and the starfish *Asterias rubens* Linnaeus, 1758 and *Astropecten irregularis* (Pennant, 1777), were intact or only lightly damaged.

3.2. Dislodged animals lying in the track

In terms of wet weight, the heart urchin *Echinocardium cordatum* again dominated the megafauna dislodged by the hydraulic dredge (Fig. 2). Of the heart urchins that were dislodged and damaged by the

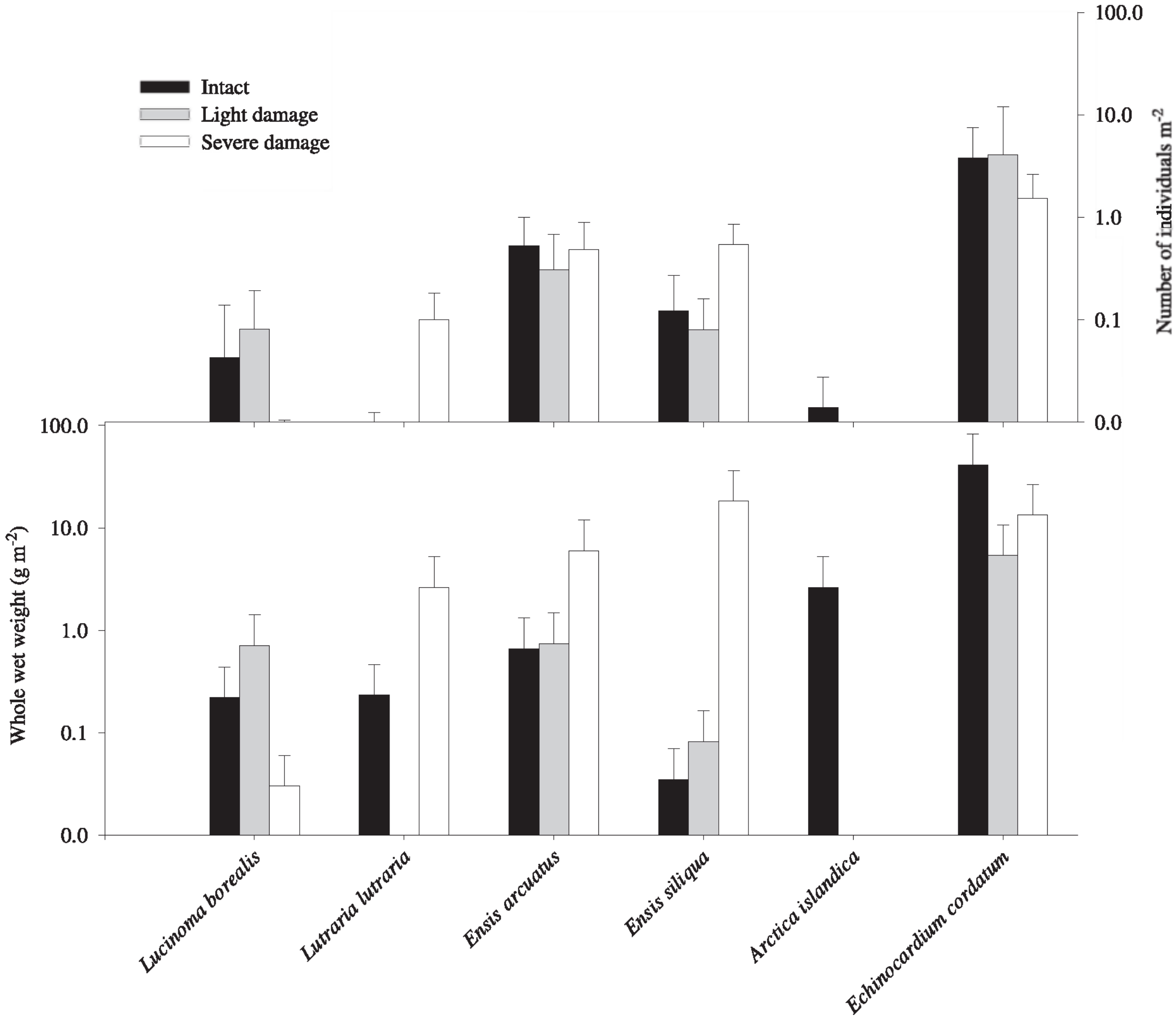

Fig. 1. Analysis of the damage caused to the discard generated from dredge hauls at Hunterston Sands. (mean + SD, n = 10) expressed in terms of the number of individuals (top) and whole wet weight (bottom) for each species and damage category. Note logarithmic scale used for y axis.

dredge, approximately 10% by weight were found to have patches of missing spines on their tests and were classified as lightly damaged. It was impossible to confirm from this study whether or not these heart urchins lost their spines as a result of abrasion by the dredge or whether they had been lost naturally whilst burrowing through the sand. The remaining 20–30% of *E. cordatum* suffered severe damage, many being completely smashed by the dredge. For every 100 m^2 of seabed dredged, approximately 130 individual *E. cordatum* weighing 8200 g (whole wet weight) were dislodged, of which ca. 90 individuals (5800 g) were intact and ca. 20 individuals (1070 g) were severely damaged.

The bivalves *Ensis arcuatus*, *E. siliqua* and *Lutraria lutraria* dominated the remaining biomass of the dislodged megafauna. These species did not survive the passage of the dredge as well as the heart urchins, with between 20 and 100% suffering severe damage in any one track. Both species of razor clam suffered severe damage from the dredge, either having their pedal muscles ripped off or being broken in half, probably caused by the slicing action of the leading edge of the dredge blade. *Ensis siliqua*

Table 2
Taxa and relative abundance of additional megafauna and macrofauna found in the UMBSM dredge hauls at Hunterston Sands (C = common, O = occasional, R = rare)

Class	Order	Family	Taxon	Authority	Qualitative abundance
Hexacorallia	Ceriantharia	Cerianthidae	*Cerianthus lloydi*	Gosse, 1859	O
Polychaeta	Phyllodocidae	Aphroditidae	*Aphrodita aculeata*	Linnaeus, 1758	R
		Phyllodocinae	*Anaitides lineata*	(Claparede, 1870)	R
		Glyceridae	*Glycera gigantea*	Quatrefages, 1866	R
		Nereididae	*Nereis longissima*	Johnston, 1840	O
	Eunicida	Eunicidae	Eunicidae sp.		R
	Spionida	Chaetopteridae	*Chaetopterus variopedatus*	(Renier, 1804)	R
	Capitellida	Arenicolidae	*Arenicola marina*	(Linnaeus, 1758)	O
	Oweniida	Oweniidae	*Owenia fusiformis*	Chiaje, 1842	R
	Terebellida	Pectinariidae	*Lagis koreni*	Malmgren, 1866	R
		Terebellidae	*Lanice conchilega*	(Pallas, 1766)	C
	Sabellida	Sabellidae	*Sabella pavonina*	Savigny, 1820	R
Eumalacostraca	Decapoda	Paguridae	*Pagurus bernhardus*	(Linnaeus, 1758)	R
		Portunidae	*Liocarcinus depurator*	(Linnaeus, 1758)	R
			Carcinus maenas	(Linnaeus, 1758)	R
Gastropoda	Neogastropoda		*Neptunea antiqua*	(Linnaeus, 1758)	R
Pelecypoda	Veneroida	Tellinidae	*Fabulina fabula*	(Gmelin, 1791)	O
			Moerella pygmaea	(Loven, 1846)	R
		Veneridae	*Chamelea striatula*	(da Costa, 1778)	O
			Clausinella fasciata	(da Costa, 1778)	R
			Venerupis senegalensis	(Gmelin, 1791)	R
			Dosinia exoleta	(Linnaeus, 1758)	O
	Myoida	Myidae	*Mya truncata*	Linnaeus, 1758	R
Asteroidea		Astropectinidae	*Astropecten irregularis*	(Pennant, 1777)	O
	Forcipulatida	Asteriidae	*Asterias rubens*	Linnaeus, 1758	O
Ophiuroidea	Ophiurida	Amphiuridae	*Amphiura brachiata*	(Montagu, 1804)	C
Holothuroidea	Apodida	Synaptidae	*Labidoplax* sp.		R
Osteichthyes	Perciformes	Ammodytidae	*Ammodytes tobianus*	Linnaeus, 1758	R

were dislodged by the dredge at a rate of approximately 35 g m^{-2} (0.2 individuals m^{-2}), of which only 52% by weight were intact. By contrast, 18 g m^{-2} (1.7 individuals m^{-2}) of *E. arcuatus* were dislodged by the dredge, of which almost 60% were severely damaged.

The remaining dislodged megafauna consisted of relatively small and robust bivalve molluscs, including the venerid clams *Dosinia exoleta* (Linnaeus, 1758) and *Chamelea striatula* (da Costa, 1778) and the hatchet shell *Lucinoma borealis* (Linnaeus, 1767). The latter species was found at a much lower density within the dredge tracks and it was usually intact or only lightly damaged (Fig. 2). The lightly damaged individuals had a chipped or abraded periostracal layer, particularly around the umbones and, as with *E. cordatum*, it was impossible to confirm whether this damage was caused by natural abrasion with the sandy seabed or whether it was a direct result of contact with the dredge.

3.3. Reburial capacity

Dislodged *Ensis arcuatus* were found to be very successful at reburial, irrespective of the condition of the seabed (Table 3). Eighty-seven percent of the dislodged *E. arcuatus* had completely reburied within 3 h on undredged sand, whilst 82% had completely reburied in the fluidised sand of a fresh dredge track within the same interval. *Ensis siliqua* were also found to be very successful at reburying in both dredged and undredged sand (Table 3 and C.H. pers. obs., respectively).

Of the remaining megafaunal species tested, only the rayed artemis *Dosinia exoleta* reburied successfully within the 3-h experiment. The fact that none of

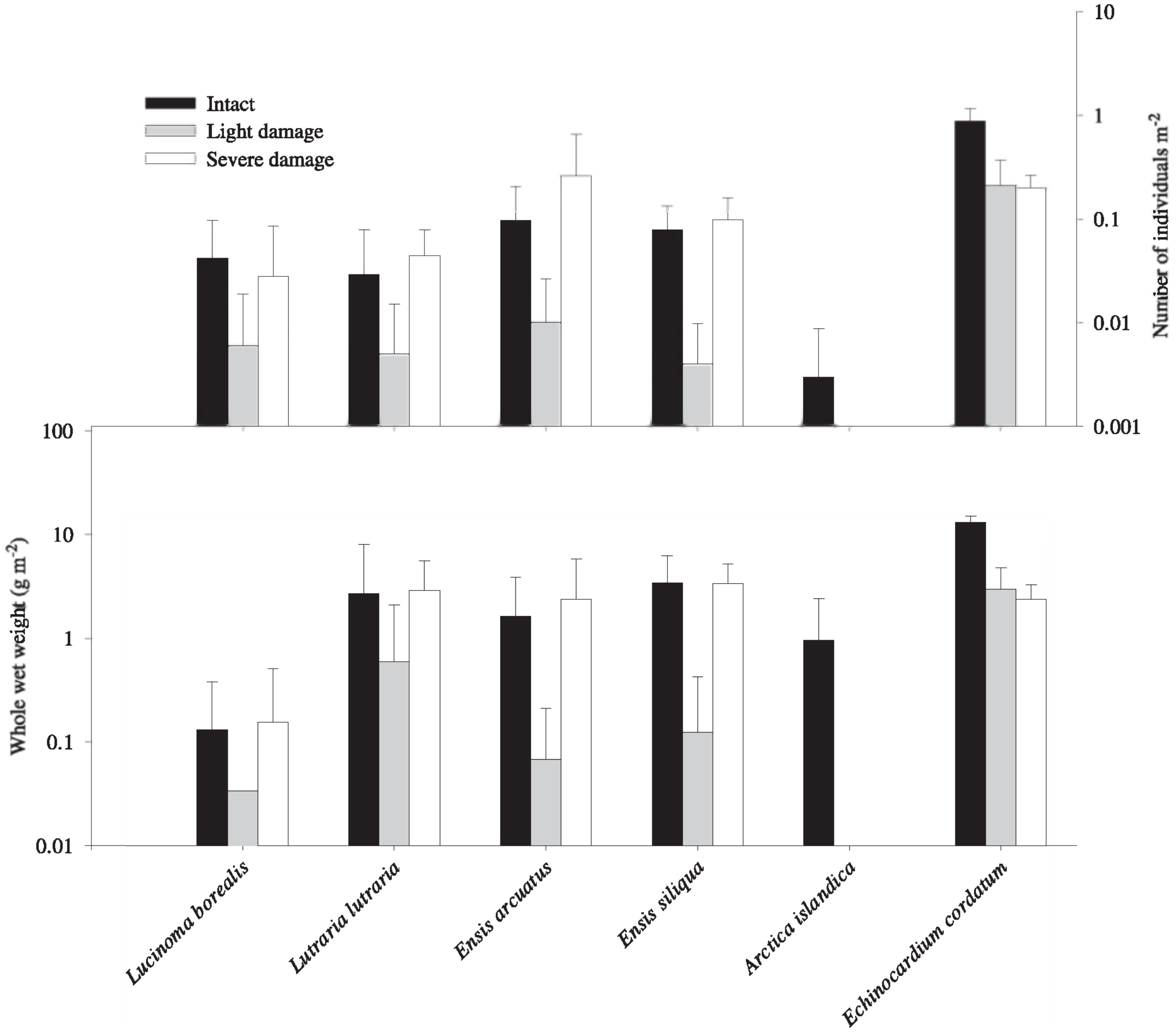

Fig. 2. Damage caused to the dislodged megafauna lying exposed in the dredge tracks created at Hunterston Sands (mean + SD, n = 10). Data presented as in Fig. 1.

the urchins was able to completely rebury within three hours contradicted independent observations made by divers following behind the gear. Their observations showed that 84.6% of heart urchins dislodged by the dredge but not brought to the surface and subjected to aerial exposure had completely reburied within 25 min. It was concluded that in the case of *E. cordatum* aerial exposure inhibited reburial activity.

There was no significant variance component in *E. arcuatus* reburial duration at the level of days with sand type, Da(Sa) (Table 4). Analysis of the pooled data revealed that the reburial duration for *E. arcuatus* was significantly ($P < 0.01$) longer on undredged sand than on the fluidised sand of a dredge track.

The reburial lag data collected from the field experiments were initially $\log_{10}$ transformed to remove their positive skew (Underwood, 1981). The positive skew of the untransformed data was caused by the fact that the majority of the clams started to rebury as soon as they were laid out onto the sand by the divers whilst a small number remained torpid for a long time before any reburial activity was seen. The

Table 3
Summary of the reburial capacity of dislodged megafaunal species determined from field experiments

Sand type	Species	% completely reburied within 3 hours	Number of individuals observed in two days	Reburial duration time (range in mins)
Undredged	*Ensis arcuatus*	86.9	23	1.5–92.0
	Arctica islandica	0.0	2	–
	Mya truncata	0.0	1	–
	Echinocardium cordatum	0.0	9	–
Dredged	*Ensis arcuatus*	82.1	28	1.0–41.8
	Ensis siliqua	66.6	3	2.3–31.0
	Dosinia exoleta	100.0	1	48.4
	Mya truncata	0.0	3	–
	Echinocardium cordatum	0.0	15	–

Table 5
Nested ANOVA (Sokal and Rolf, 1995) comparing the lag in reburial of *E. arcuatus* between undredged and dredged sand

Source of variation	df	SS	MS	Weighted F statistic (F's)*	df′	$P=0.05$
Among sand type (Sa)	1	0.65	0.65	0.80	1, 2	ns
Days within sand (Da(Sa))	2	1.63	0.81	4.62[#]	n/a	s
Within subgroups (error)	41	7.22	0.18			
Total	44	9.50				

n/a = not applicable.

* An alternative weighted statistic, F's, was generated with accompanying df′ for the variation among sand to account for the unbalanced data sets (Gaylor and Hopper, 1969; Sokal and Rolf, 1995). The $MS_{Da(Sa)}$ could be tested directly without creating an alternative F's (Sokal and Rolf, 1995).

[#] $F_{0.05[2,40]} = 3.23$, therefore the variance component attributable to days within sand type was significant.

results of the nested ANOVA indicated that there was no significant difference in the reburial lag time associated with the different sand types but that there was significant variability ($P < 0.05$) from day to day during the experiment (Table 5).

3.4. Modelling the impact of hydraulic dredging

The data collected during this study were combined and used to model the fate of the 6 dominant megafaunal species disturbed in order to collect 10 kg of marketable razor clams with the hydraulic dredge at Hunterston Sands (Fig. 3). Approximately 29 kg of *Echinocardium cordatum* would be disturbed; 23.5 kg of which would be brought to the surface in the dredge collecting box only to be returned to the seabed as discard. None of the discarded *E. cordatum* would successfully rebury, as would also be the case with the severely damaged razor clams and otter shells that would also be discarded. The fishing process would dislodge over five kg of *E. cordatum* at the seabed although nearly 90% of these individuals would successfully rebury within 30 min. Reburial of intact or lightly damaged razor clams would also approach 85–90% and, for the majority of razor clams, would take

Table 4
Nested ANOVA (Sokal and Rolf, 1995) comparing the reburial duration of *E. arcuatus* between undredged and dredged sand

Source of variation	Degrees of freedom (df)	Sum of squares (SS)	Mean square (MS)	Estimated F statistic (Fs)*	$P=0.05$
Sand type (Sa)	1	5068.17	5068.17	31.58	s[†]
Days within sand (Da(Sa))	2	321.01	160.50	0.490[#]	ns
Within subgroups (error)	39	12,786.48	327.86		
Total	42	18,175.66			

[†] s = significant, ns = not significant.

* F statistic could only be estimated because of the complication of unbalanced data sets. An alternative statistic, Fs, could not be generated in this case, as the conditions of the Satterthwaite approximation did not hold (Gaylor and Hopper, 1969; Sokal and Rolf, 1995).

[#] Pooling this term (Underwood, 1997) and retesting the MS_{Sa} over $((SS_{Sa(Da)} + SS_{within})/41)$ generated a new Fs of 15.85 with 1 and 41 df which was significant ($P < 0.01$).

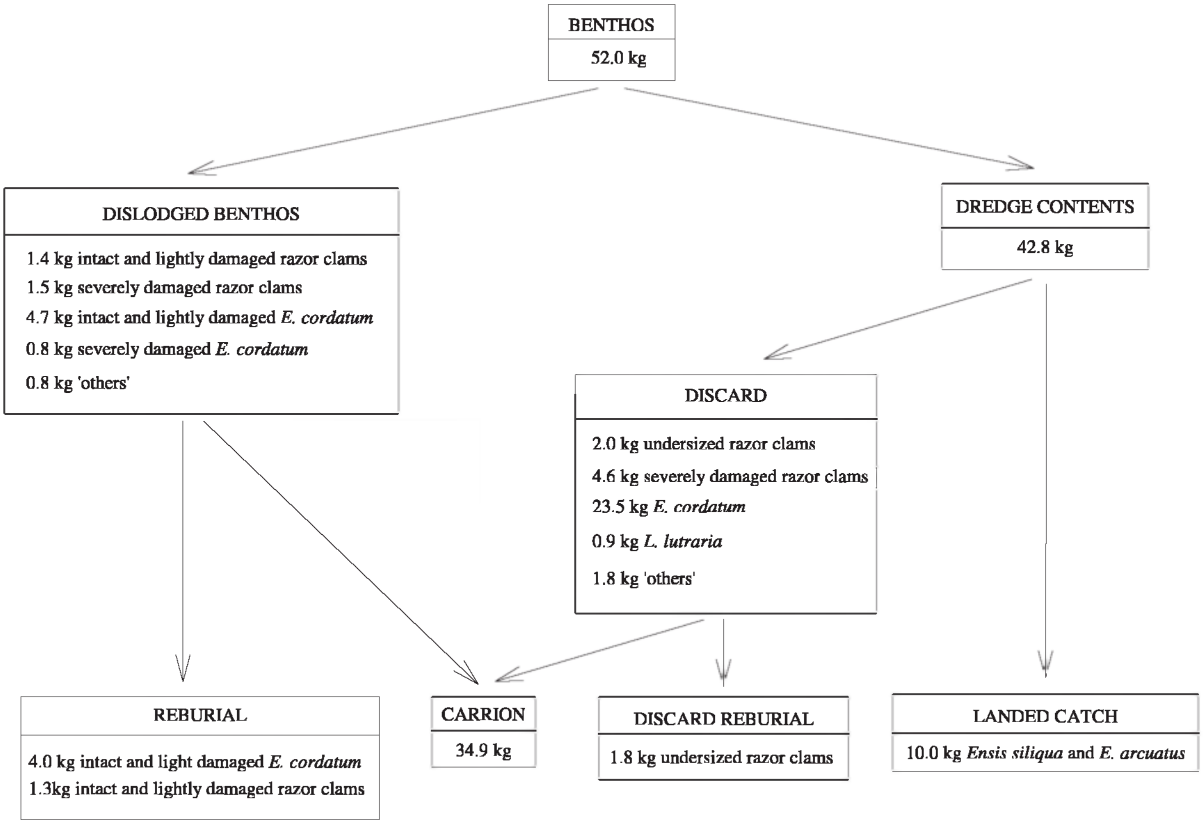

Fig. 3. The fate of the benthic megafauna dislodged and dredged at Hunterston Sands in order to land 10 kg of razor clams (*Ensis arcuatus* and *Ensis siliqua*). The model was produced by combining estimates of the damage to the discard as well as fauna lying exposed in the dredge tracks with estimates of reburial capacity.

place within a few minutes, potentially before the arrival of any scavengers on the dredge track (Fonds et al., 1998; Chícharo et al., 2002; C.H. pers. obs.).

4. Discussion

The target species only ever formed a minor component (< 30%) of the dredge contents. As a result, the site used for this study was perhaps not representative of a commercially viable population of clams which would support a hydraulic fishery. However, the methods used in this study could be applied to monitor the commercial and environmental sustainability of fisheries based on larger razor-clam beds located at other sites. Previous work (Tuck et al., 2000) has shown that elsewhere in Scotland the landed catch can represent a much larger proportion (≥ 70%) of the dredge contents.

The proportion of razor clams that were severely damaged during fishing also affected the quantity of catch landed, as the markets require a whole and relatively undamaged product. Any severely damaged and undersized individuals would be returned to the seabed as discards. Some clams, which could be sold, suffered chips or minor cracks in their shell. This light damage often occurred to the posterior shell margin near the clams' siphons and was caused by impacts inside the dredge collecting-cage as the water jets washed the animals around. Severe damage was probably caused when the blade hit and sliced through individuals that were still restrained distally by unfluidised sand.

The high survival rate of *E. cordatum* was considered to be a function of the slow towing speed of the dredge in combination with the large volumes of water used to fluidise the sand, which would have pushed many of the urchins away from the blade of the dredge. In addition, the fact that the heart urchin does not have structures analogous to the vulnerable muscular foot of bivalves meant that this species could be displaced more readily without sustaining damage. The slow towing speed used in this study also contributed to very low abundance of mobile species within the dredge hauls. In particular, decapod crustaceans and fish were seen to move away from the path of the dredge long before they were washed into the collecting box.

The high rate of attrition suffered by *Ensis* spp. and *Lutraria lutraria* was attributable to their morphology (elongate bivalves with relatively thin shells) and the depth at which they were found within the sand. To successfully extract these species intact from the seabed required a much slower towing speed than was possible in the current work (<3 m min^{-1}, pers. obs.) in order to give sufficient time for the water to adequately fluidise the sediment in front of the dredge and around the bivalves (Kauwling and Bakus, 1979; Lambert and Goudreau, 1996).

The reburial capacity of *Ensis* spp. and other megafaunal bivalves has previously been reported (Henderson and Richardson, 1994; Coffen-Smout and Rees, 1999; Chícharo et al., 2002) although this study has been the first to demonstrate that even razor clams which have been brought to the surface in the dredge collecting box retain an ability to rebury rapidly. Reburial capability was not impeded by the fluidised sand of a fresh dredge track, which indicated that the bivalves were still able to use their pedal muscles to create an effective anchor in the sediment. Indeed, the fact that the reburial duration of *Ensis arcuatus* was significantly shorter on a fresh dredge track indicated that the fluidised sand offered less physical resistance to penetration by both the pedal muscle and the shell of the razor clams.

The inability of some of the large bivalves, such as the Icelandic cyprine *Arctica islandica* and the blunt gaper *Mya truncata*, to rebury was explained by consideration of their differing morphology. Adult specimens of both of these bivalves, as well as others including *L. lutraria*, have relatively poorly developed pedal muscles. Once they have buried into the sediment as juveniles the role of this muscle becomes diminished and the growth of the foot no longer matches the growth in size of the bivalve shell. The failure of the heart urchin *Echinocardium cordatum* to rebury once exposed to the air was dramatic. Diver observations clearly indicated that dislodged urchins quickly reburied into the dredge track and it was concluded that aerial exposure inhibited reburial activity, either by causing an undefined physiological stress in the urchin or by allowing some of the coelomic fluid to drain from the test thereby compromising their thin dermal tissues or internal functioning. All of those species which were unable to rebury rapidly would provide a source of carrion for scavengers moving onto the dredge track after fishing (Fonds et al., 1998; Chícharo et al., 2002).

Ultimately the data collected during this study were collated to produce a preliminary model of the fate of the dominant megafaunal species identified in the discard in order to collect 10 kg of marketable catch (Fig. 3). It is clear from this model that the hydraulic dredge fishery could, in some circumstances and at some sites, generate a considerable quantity of discard. Using this approach it was shown that although the dredge collected approximately two kg of undersized razor clams for every 10 kg of landed catch at this site, 1.8 kg of these discarded undersized individuals would successfully rebury once returned to the seabed. This reburial would occur within a short time (between one and 30 min) and would not be impeded if the animal were to land back onto the fluidised sand of a fresh dredge track. These undersized razor clams, once successfully reburied, would be able to continue growing and so contribute toward the maintenance of *Ensis* spp. populations at this site. The total razor-clam biomass found in the dredge collecting box (16.6 kg, Fig. 3) represented 85% of the total *Ensis* biomass recovered from the dredge track (dislodged and dredged clams) and was in good agreement with an efficiency estimate of 90% independently recorded from preliminary experiments (Hauton et al., 2002). The close agreement between the model and independent estimates of dredge efficiency confirms that this method of analysing discard survival was, at least in this case, a robust approach.

Previously, the ecological cost of a number of fisheries have been empirically assessed, mainly for crustacean and fish species (Fonds, 1994; Kaiser and

Spencer 1995, Bergmann and Moore, 2001; Fonds and Groenewold, 2000; Groenewold and Fonds, 2000; Bergmann et al., 2001), or have otherwise been modelled theoretically for large-scale multiple-fleet fisheries (Mesnil, 1996). This work has adapted these ideas to consider a situation involving burrowing megafauna for which the ability to rebury is of fundamental importance. From additional observations made during this study it was assumed that between 80 and 90% of the intact or lightly damaged razor clams would successfully rebury before being attacked by predators and scavengers, whilst the remaining bivalves would be stranded on the surface of the seabed until removed by scavengers and predators. This model could be refined by incorporating a removal rate which reflected the successive arrival of different scavenging species over time (Groenewold and Fonds, 2000; Chícharo et al., 2002). None-the-less, small-scale, site-specific models have an immense potential for predicting the sustainability and ecological consequence of any fishing activity and should be considered when establishing local governance of fisheries, in accordance with the principles outlined in the recent EC Green Paper (EC Council Communication 135, 2001), which has received broad support from an independent panel of EU environmental advisers (Tasker et al., 2001).

Acknowledgements

This research was conducted whilst in receipt of funding from the European Commission under contract CFP 99/078. Staff at the University Marine Biological Station Millport are thanked, particularly the diving team and crew of RV 'Aora'. Mr C. Henderson of Portling Fisheries, Scotland, is thanked for his technical advice. Dr S.C. Jarvis and Dr G.A. Rowe are thanked for confirming all taxonomic identification. We would also like to thank three anonymous reviewers for their advice and assistance in revising the manuscript.

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