2003-01-01

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http://hdl.handle.net/10026.1/1356

10.1016/s1054-3139(03)00015-8
Ices Journal of Marine Science
Oxford University Press (OUP)

ICES Journal of Marine Science, 60: 381–392. 2003
doi:10.1016/S1054–3139(03)00015-8

An experimental study of the ecological impacts of hydraulic bivalve dredging on maerl

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Hauton, C., Hall-Spencer, J. M., and Moore, P. G. 2003. An experimental study of the ecological impacts of hydraulic bivalve dredging on maerl. – ICES Journal of Marine Science, 60: 381–392.

A short-term experiment to assess the ecological impact of a hydraulic blade dredge on a maerl community was carried out during November 2001 in the Clyde Sea area on the west coast of Scotland. A fluorescent sediment tracer was used to label dead maerl, which was then spread out on the surface of sediment to act as a proxy for living maerl. The fauna collected by the dredge was dominated by the bivalves *Dosinia exoleta* and *Tapes rhomboides*, which were found to be intact. The target razor clams *Ensis* spp. were caught in low numbers, which reflected the low abundance of this genus within the maerl habitat. The hydraulic dredge removed, dispersed and buried the fluorescent maerl at a rate of 5.2 kg m^{-2} and suspended a large cloud of sediment into the water column, which settled out and blanketed the seabed to a distance of at least 8 m either side of the dredge track. The likely ecological consequences of hydraulic dredging on maerl grounds are discussed, and a case is made for protecting all maerl grounds from hydraulic dredging and establishing them as reservoirs to allow for the recruitment of commercial bivalve populations at adjacent fished sites.

Keywords: hydraulic dredge, maerl, *Ensis* spp., *Dosinia exoleta*.

Received 27 May 2002; accepted 25 January 2003.

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Introduction

The use of suction dredges and related mobile fishing gear is now widespread in countries such as USA (Meyer *et al.*, 1981; Ismail, 1985), Italy (Pravanovi and Giovanardi, 1994) and Portugal (Gaspar *et al.*, 1994; Chícharo *et al.*, 2002). Hydraulic dredging is not so well established in Scotland, although it has been used on a small scale to exploit shallow-burrowing bivalves, such as the cockle *Cerastoderma edule* (Chapman *et al.*, 1994), and deep-burrowing species, such as razor clams *Ensis* spp. (Tuck *et al.*, 2000).

Early research into the use of this type of gear in Scotland demonstrated that the immediate physical impact of the gear on the sea bed was dramatic, but of limited duration in exposed or high-energy sites (Hall *et al.*, 1990). However, concerns were expressed with regard to the potential long-term impact of this type of gear when fished repeatedly in sheltered bays and inlets. As a result of these concerns, the use of suction and hydraulic dredges was restricted throughout a large part of Scotland under an amendment to the Inshore Fishing (Scotland) Act 1984 (Inshore Fishing (Prohibition of Fishing and Fishing Methods) (Scotland) Order 1989). This Order defines suction dredging as "the raising from the sea bottom of material, fish and shell fish with gear involving the use of a solids pump or air lift, or water jets to dig into the sea bottom;" and therefore includes suction and hydraulic dredges.

Hydraulic dredges (also termed water-jet dredges) operate differently from suction dredges as they do not bring vast quantities of sea-bed material to the surface. But recent investigations into the impacts of hydraulic dredges (Tuck *et al.*, 2000) have demonstrated that the physical effects on the sea bed were very similar to those created by suction dredging. Given these similarities, Tuck *et al.* (2000) recommended that hydraulic dredges continue to be regulated under the above Order, but that limited hydraulic dredge fishing could be allowed in certain areas if pursued through the establishment of a Regulating Order (Clarke, 2001).

Although a small, hand-collected, fishery for razor clams (*Ensis* spp.) has existed in Scotland for a number of years, improvements in handling, depuration (Younger, 2000) and transportation, combined with increased demand in southern Europe, have led to an expansion of the fishery. The value of the UK fishery rose from ca. £60 000 in 1994 to £343 252 in 1998 (MAFF, 1999), with an average price of £2547 paid per tonne and a maximum value of £4000 per tonne (Fishing News, 1998). Presently, the fishery is exploited by divers using SCUBA, although commercial interest in hydraulic dredging for razor clams and other deep-burrowing bivalves is predicted to increase in Scotland (McKay, 1992; Hall-Spencer *et al.*, 2003). This is partly due to current efforts to reduce fishing pressure on fin-fish species within the North Atlantic and North Sea, and partly due to recent difficulties experienced by scallop fishers because of extensive closures caused by shellfish biotoxins including amnesic shellfish poisoning (ASP) throughout Scotland (Fishing News, 2000).

Maerl beds are constructed by unattached calcareous rhodophytes (nongeniculate Corallinaceae) forming complex sediments that typically support a highly diverse flora and fauna (Grall and Glémarec, 1998; Hall-Spencer, 1998). They occur worldwide (Foster, 2001) in areas where currents prevent smothering with silt, and they slowly accumulate to form calcareous deposits. Northern European maerl beds typically occur in shallow (<32 m) waters where there are high rates of water exchange. This encourages the growth of an abundance epifaunal and infaunal bivalves, including scallops (*Aequipecten* spp., *Pecten* spp.), razor clams (*Ensis* spp.) and clams (*Dosinia* spp., *Tapes* spp.) making maerl habitats attractive to fishers (Hall-Spencer, 1998; Hall-Spencer *et al.*, 2003). However, maerl deposits take hundreds to thousands of years to accumulate since even optimal growth rates are extremely slow (Potin *et al.*, 1990; Foster, 2001). For this reason, two of the main maerl-forming species in Europe, *Lithothamnion corallioides* and *Phymatolithon calcareum*, are protected under the EC Directive on the Conservation of Natural Habitats and Wild Fauna and Flora (1992).

Concerns have been expressed on the sensitivity of maerl beds to mollusc dredge fisheries (MacDonald *et al.*, 1996; Hall-Spencer, 1998) and, as a result, the current work sought to quantify the major immediate impacts of hydraulic dredging on maerl grounds. This research proved timely as the collected data allowed predictions to be made regarding the impacts that would occur if in future hydraulic dredging for razor clams or other bivalve species was prosecuted on such ecologically diverse habitats. Rather than sacrifice a pristine area of living maerl habitat, the present study was carried out on a scallop-dredged site where live maerl cover was very low (ca 2%). A small-scale hydraulic dredging experiment was designed to determine: (a) the immediate physical impacts on the granulometry of the maerl habitat; and (b) effects on major habitat-structuring organisms within the maerl system. Dead maerl was marked with a non-toxic fluorescent dye to act as a proxy for live maerl during the dredging experiment.

Materials and methods

Study site

Stravanan Bay, in the Clyde Sea area has one of the most thoroughly surveyed maerl grounds in the world (Hall-Spencer and Moore, 2000) The maerl is situated on a shoal ~0.5 km off the SW coast of the Isle of Bute and covers an area of 6.75 ha from −6 to −15 m Chart Datum (CD). This site has been dredged commercially for scallops for the past four decades, with dredgers seen working the site each year during 1994–2001. The environmental characteristics, scallop-dredging history and macrobenthic ecology of these grounds have been described by Hall-Spencer (1998), Hall-Spencer and Atkinson (1999) and Hall-Spencer and Moore (2000).

Experimental fishing protocol

On 12 November 2001, two buoys were laid 20 m apart at −10 m CD to delimit the width of an area to be fished, centred on 55°45.14′N, 05°04.18′W. Divers then made a series of preliminary measurements and records as detailed in subsequent paragraphs. On 13 November 2001, "RV Aora" (15 m, 224 kW) was used to tow a hydraulic blade dredge from east to west between the two buoys, then the divers recorded a series of post-dredge measurements, as subsequently described.

The blade dredge employed consisted of a 0.39-m wide hollow tooth, which penetrated the sea bed to a depth of 0.34 m (Figure 1). Sea water was delivered to the dredge from 24.2 kW Godwin ET 150/TS2 pump set at a rate of approximately 320 $m^3\,min^{-1}$ and a pressure of approximately 2×10^5 Pa, by 30 m of 0.1 m diameter layflat hose. A steel box (0.17 m × 0.77 m × 0.53 m) of 4 cm × 1.5 cm diamond-pattern mesh extended behind the dredge mouth to retain the catch. Similar hydraulic blade dredges have recently been used around the Western Isles (Tuck *et al.*, 2000) and may be widely adopted if the industry expands within Scotland. The dredge was towed once over the test plot for 8 min resulting in a fished area of 128.3 m^2.

After fishing, the dredge was hauled and emptied on deck. A visual estimate was made of the percent maerl, rock and shell debris within the catch prior to sorting. The megafauna were identified, counted and inspected for external signs of damage (cracked shells, missing limbs etc.). Live and dyed maerl were picked out as the catch was sorted into categories (Cnidaria, Nemertea, Annelida, Crustacea, target species of Mollusca, non-target species of Mollusca, Bryozoa, Echinodermata, Chordata, Rhodophycota, Chromophycota, Chlorophycota). The ash free dry weight (g AFDW) of each taxon was then determined.

Assessments of maerl removal and granulometry

Dead maerl was dredged from the periphery of the Stravanan Bay ground using a naturalist's dredge (Eleftheriou and

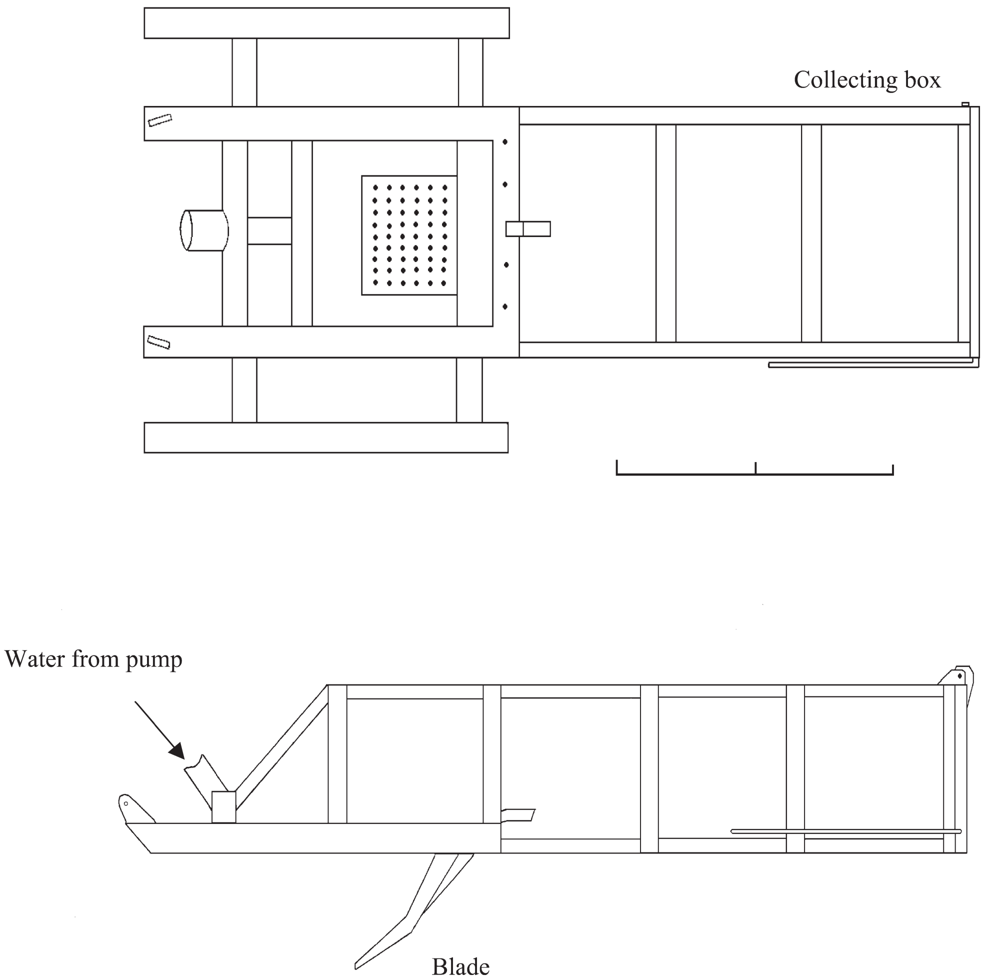

Figure 1. Scale drawing of the UMBSM hydraulic blade dredge in plan view (top) and side elevation (bottom). Scale bar represents 1 m. Note, the mesh (diamond-pattern, 4 cm × 1.5 cm) covering the surfaces of the collecting box has been omitted for clarity.

Holme, 1984). This maerl was washed with fresh water, dried and then dyed with an orange fluorescent sediment tracer called Emutrace™ (Emu Ltd, Hampshire). On the day of dredging, with the dredge positioned on the sea bed and with the water pump switched off, divers distributed a total of 42 kg of the dyed maerl over an area of 5.2 m^2 immediately in front of the dredge. This produced a 2-cm deep layer of dyed proxy, which was representative of typical European maerl beds that have a live maerl layer ranging from 0 to 8 cm deep (Hall-Spencer and Moore, 2000; Grall and Hily, 2002). Five replicate core samples (0.1 m diameter) were then taken by the divers to record the vertical distribution of the dyed maerl immediately prior to dredging. These cores were kept vertical throughout the sampling process. Once the cores had been recovered, the water pump was switched on and the dredge was towed through the dyed maerl. Immediately after dredging, divers recovered five more core samples from the dredge track at the location of the dyed maerl.

For analysis, the cores were divided into 3 cm horizons. Dyed maerl was removed with forceps and the numbers of dyed thalli were counted for each depth horizon. The dyed maerl was dried (70°C) to constant weight along with the remaining components of each depth horizon in order to determine the densities of dyed maerl before and after dredging. After drying, each of the depth horizons were dry-sieved and weighed to determine a particle-size distribution using a standard series of mesh sizes from 4 to 0.063 mm according to Buchanan (1984).

Assessment of suspended sediment

On the 12 November 2001, divers placed 10 labelled plastic buckets (each 18.5 cm diameter and 14 cm deep) at 0, 1, 2, 4, and 8 m on transects running perpendicular to the towed corridor, i.e. north of the north buoy and south of the south buoy (Hall-Spencer and Moore, 2000). These were left for

1 h to collect background levels of settling sediment, and were then sealed with watertight lids and recovered. On the following day, and at approximately the same tidal state, divers arranged a further 10 sediment traps in the same configuration and removed the lids immediately before dredging. After fishing, the proximity of the "0 m" sediment traps to the dredge track was measured and, after 1 h, the traps were again sealed and retrieved. This ensured that the sedimentation rates calculated for each day were based on observations made at the same tidal state. The sediment in each trap was allowed to settle, excess water was siphoned-off and the sediment was washed twice in distilled water to remove salt. After resettlement, the supernatant was again siphoned-off, and then the remaining sediment was dried at room temperature and weighed.

Dredge track observations

Immediately after dredging, divers recorded the dimensions of the track created by the gear. The overall length of the track was measured, and five replicate measurements of the breadth of the track, to the nearest 0.5 cm, were recorded. These measurements were repeated 1 month after the dredge track had been created, in order to quantify the persistence of the track features.

The behaviour and distribution of biota were recorded during 30 min dives immediately before and after dredging. A Sony PC-110 digital video camera held in a Sea and Sea VXPC110 underwater housing was used in conjunction with a tape measure laid out for scale. A 100 m $\times$ 10 m strip of the sea bed was recorded before fishing and this was repeated along the dredge track 1 h after the gear had passed through. The digital camera was also used to take photoquadrats along two perpendicular transects over the patch of dyed maerl. One transect ran E–W along the dredge track, the other ran N–S across the dyed maerl to record its distribution after the passage of the hydraulic gear.

Results

Study site

Video and diver observations prior to hydraulic dredging provided an overview of the complex surface sediment structure within the experimental plot. The sediment was clearly megarippled at -10 m CD, with coarse maerl-gravel lying in parallel ridges, about 0.10 m high with a wavelength of about 1.2 m. The clean gravel ripples had fewer fauna than the intervening silty sediment strips where squat lobsters (*Galathea intermedia*) and juvenile flatfish were aggregated. Superimposed upon this coarse level of habitat structure were smaller features, such as burrows, feeding pits and faecal mounds that formed a complex mosaic over the seabed. Pebbles and dead mollusc shells were common, particularly along the troughs of the sediment megaripples, and they provided hard substrata for the attachment of a variety of seaweeds and sessile animals. The most numerous megafauna present on the experimental plot were starfish (*Asterias rubens* and *Marthasterias glacialis*) that were seen feeding on infaunal bivalve molluscs. The maerl habitat was modified by occasional large phaeophytes (*Laminaria saccharina* and *Desmarestia aculeata*), which each could attain 2 m length. These phaeophytes bound maerl and provided shelter for motile epifauna, such as swimming crabs (*Necora puber*) and juvenile cod (*Gadus morhua*). Close examination of the maerl-gravel revealed an array of less conspicuous organisms that further modified the structural properties of the habitat, such as the tube-dwelling anemone *Cerianthus lloydii* and the large, burrowing thalassinidean shrimp *Upogebia deltaura*.

Catch analysis

The hydraulic dredge was towed between the marker buoys for 8 min at a speed of about 16 m min^{-1}. The dredge came up a third full (366 kg) and was estimated to contain 65% maerl, 20% stones and 15% shells. The maerl was predominantly dead (characteristic of the site), with small amounts (<1%) of live maerl and the fluorescent-dyed proxy. The shell debris mainly consisted of intact *Dosinia exoleta* and *Tapes rhomboides* shells. The stones were mostly pebbles, with cobbles <0.1 m in diameter. A striking feature of the catch composition was the high abundance of large live bivalves such as *D. exoleta*.

The 0.34 m^3 of dredged material contained a highly diverse catch. Table 1 summarises records of biomass (AFDW) for each of the phyla caught within the hydraulic dredge. Macroalgae only comprised 1% of the AFDW, but were represented by 28 species, showing that the dredge scraped up surface material as it passed through the sediment. Torn kelp (*L. saccharina*) comprised the bulk of the macroalgae collected. As would be expected, encrusting (e.g. *Cruoria pellita*) and shell-boring algae (e.g. *Osteobium quickettii*) showed low levels of mechanical

Table 1. Biomass (g AFDW) of each of the phyla caught in a 127 m hydraulic dredge run on 13 November 2001 at -10 m CD on Stravanan Bay maerl ground, Bute.

Phylum	AFDW (g)	%
Cnidaria	0.94	0.2
Nemertea	0.13	0.0
Annelida	4.94	1.2
Crustacea	7.59	1.9
Mollusca	375.36	94.1
Bryozoa	0.01	0.0
Echinodermata	5.68	1.4
Chordata	0.01	0.0
Rhodophycota	0.74	0.2
Chromophycota	3.32	0.8
Chlorophycota	0.05	0.0
Total	398.77	100

damage within the catch. In contrast, thin foliose forms (e.g. *Nitophyllum punctatum*) and filamentous algae (e.g. *Polysiphonia fucoids*) were usually torn from the substratum and damaged. Likely causes for this damage are: (a) impact with the gear frame; (b) the hydraulic force of the water jet as the sediment was fluidised; and (c) abrasion with debris within the dredge basket. The haul included ca. 960 live *P. calcareum* thalli, many of which were broken, together with ca. 2800 of the dyed maerl fragments. The captured macrofauna comprised a total 60 species and 99% of the biomass (AFDW) present (Table 1).

Flatfish and squat lobsters were recorded on the pre-dredge survey of the experimental plot, but were absent from the catch, reflecting the slow towing speed of the gear. However, some motile fauna were caught such as swimming crabs (*Liocarcinus* spp.), which perhaps hid, rather than fled, from the approaching gear. Sessile epifauna (e.g. hydroids, serpulids, barnacles, bryozoans) and slow-moving epifauna (e.g. gastropods, starfish, clingfish) were caught in low numbers, confirming that surface sediment had become entrained into the dredge. Most of the catch, however, was of infauna. The anemone *C. lloydii*, nemertines and various polychaetes were found in the catch, but only the smallest or most robust forms were found alive. For example, polychaetes with strong tubes or tough bodies appeared undamaged (e.g. *Owenia fusiformis*, *Glycera* spp.), whereas most fragile species were torn and fractured (e.g. *Alentia gelatinosa*, *Chaetopterus variopedatus*, *Polygordius lacteus*).

Large infaunal bivalves made up the majority of the catch (94% of the AFDW biomass), the smaller animals having been washed through the dredge mesh. Fourteen bivalve species were present (Table 2), of which the semelid *Abra alba* and the tellin *Arcopella balaustina* are new records for the site (Hall-Spencer, 1998). The population of *Ensis arcuatus*, a main target species, would appear to be below commercially exploitable densities on the Stravanan Bay maerl ground as only 10 individuals were caught during the 127 m tow. It ranked as the sixth most common bivalve caught. This species contributed 3% of the total bivalve biomass caught and ranged from 7.9 to 16.9 mm in breadth, three of which (30%) had smashed shells.

Table 2. Numbers of bivalves caught in a 127 m hydraulic dredge run on 13 November 2001 at −10 m CD on Stravanan Bay maerl ground, Bute.

Species	Number caught
Nucula nucleus	1
Parvicardium scabrum	5
Lutraria angustior	6
Ensis arcuatus	10
Arcopella balaustina	1
Moerella donacina	1
Gari tellinella	14
Abra alba	2
Clausinella fasciata	33
Timoclea ovata	5
Tapes rhomboids	39
Dosinia exoleta	261
Mya truncata	1
Thracia villosiuscula	24

The most numerous bivalve caught was the venerid *D. exoleta*. This bivalve has a much thicker shell than *Ensis* spp. and none of the 261 individuals caught had damaged shells. The captured *D. exoleta* were up to 59.5 mm in length, the maximum length yet recorded for this species (previous record = 57.7 mm; Tunberg, 1984). They dominated the catch, yielding 84% of the bivalve biomass and 79% of the total biomass caught in the hydraulic dredge. Another edible venerid, *T. rhomboides*, was the second most numerous bivalve caught, and contributed 9% of the total biomass caught in the dredge. This species also has a thick shell and only one of the 39 individuals was damaged.

The catch composition indicates that the dredge probably did not fish efficiently beyond a sediment depth of about 0.3 m. Pre-dredging surveys showed that burrows of *Upogebia deltaura* were common along the fished corridor, but none of these deep-burrowing thalassinidian shrimps was caught. *U. deltaura* constructs burrows to depths of 0.68 m in Stravanan Bay maerl (Hall-Spencer and Atkinson, 1999). Similarly, the deepest-burrowing bivalves within the maerl habitat at Stravanan Bay were *Lutraria angustior* and *Mya truncata*, adults of which can be found at sediment depths of 0.40 and 0.52 m, respectively (Hall-Spencer and Atkinson, 1999). Their long siphons cannot be fully retracted within their shells, which explains the presence of torn-off siphons in the dredge. It seems unlikely that these bivalves would survive such an injury since their siphons may contribute about 25% of the body mass.

Assessment of maerl removal and granulometry

The number and total dry weight of dyed maerl were both significantly lower in the cores collected after dredging (comparing number of thalli $t = 2.813$, comparing weight of thalli $t = 3.109$; $p < 0.05$ for both comparisons). The mean number of dyed thalli was reduced by 72%, from 2563 ± 1270 ($\pm$SD, $n = 5$) per core to 729 ± 715 ($n = 5$). Mean dry weight of dyed maerl was reduced from 71.8 ± 31.7 to 19.9 ± 19.8 g per core. A single pass of the hydraulic dredge removed dyed maerl at a rate of approximately 5.2 kg maerl m^{-2}, corresponding to ca. 183 000 thalli m^{-2}. Only a small proportion of the dyed maerl was dredged up (corresponding to 128.1 g m^{-2}) as most of it was dragged across the sea bed and buried. This observation was confirmed by a visual assessment of the distribution of dyed proxy after dredging, as discussed subsequently.

Particle-size analyses (PSA) of the different depth horizons (0–3, 3–6 and 6–9 cm) in each core are summarised

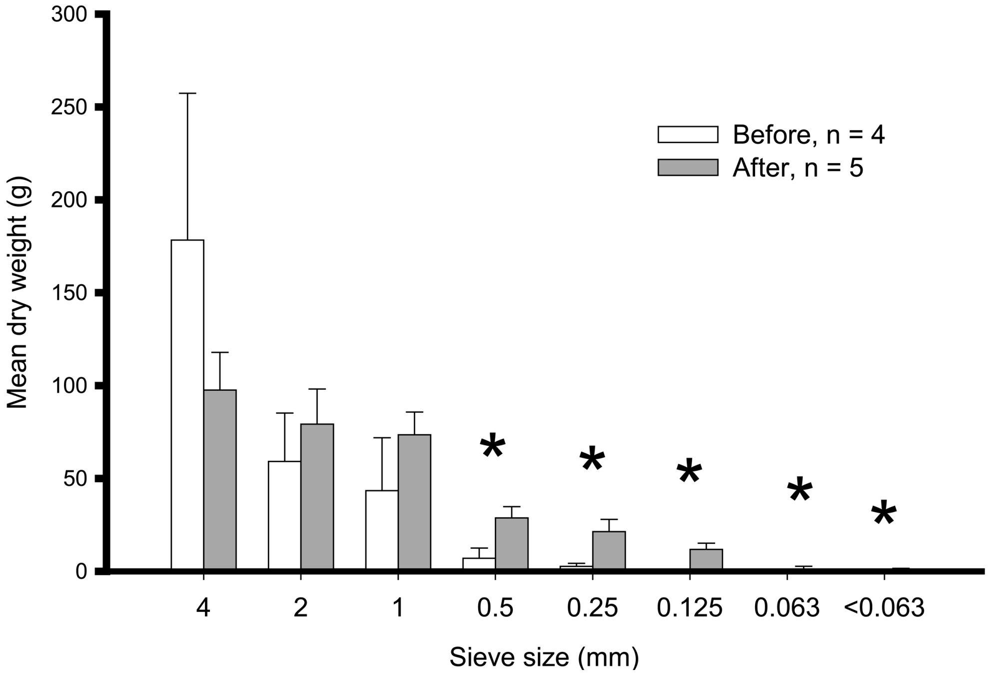

Figure 2. Mean dry weights of sediment size classes in the 0–3 cm horizon of cores taken before and 1 h after fishing. Significant differences between before and after dredging for each size fraction ($p < 0.05$, ANOVA and *a posteriori* Tukey–Kramer multiple comparisons, $\log_{10}$-transformed data) are indicated with an asterisk, error bars = +1 SD.

in Figures 2–4. The hydraulic dredge tended to remove the larger fractions throughout the cores while causing an increase in the weight of the smaller fractions (Figures 2–4). In terms of percent composition, there was a significant increase in the contribution of sand fractions (2 mm → 0.125 mm) in the surface sediments after dredging. Before dredging, sand constituted 40–50% of the sediment in all three depth horizons. Immediately after dredging, there was a significant increase (between 50 and 70%) in the proportion of sand at all the three depth horizons (ANOVA and *a posteriori* SNK analysis, arcsine square-root transformed data, $p < 0.05$).

The inclusive graphic standard deviation (σ_1) was calculated for each depth horizon in each core according to the procedure described by Folk (1974). Hydraulic dredging shifted the sediment sorting classification from "very poorly sorted" to "poorly sorted" (Table 3). On the Wentworth scale (Figure 5) (Buchanan, 1984), hydraulic dredging changed the sediment from "sandy gravel" before dredging to "gravelly sand" immediately after dredging.

Suspended sediment analysis

Small amounts of sediment (ca. 1.3 $g\,m^{-2}\,h^{-1}$) were collected in traps deployed for 1 h before hydraulic dredging when the through-water visibility recorded by divers was 5 m. Immediately after fishing, however, suspended sediment had reduced visibility in the vicinity of the fished corridor to only a few centimetres. One hour later, suspended sediment had begun to disperse and settle. The dredge track had passed 5 m from the nearest sediment trap on the south transect and 13 m from the nearest trap on the north transect. Maerl around the dredged path was blanketed by newly settled silt. The mean amount of sedimentation in 10 traps placed 5–21 m from the dredge track was 28.5 $g\,m^{-2}\,h^{-1}$, i.e. more than 20 × background levels and significantly higher (Mann–Whitney Rank Sum test: $T = 55.00$, $p < 0.001$) than pre-dredge conditions. The blanketing effect of the settled sediment was still easily discernible in the trap farthest from the dredge path (21 m) where 8.6 $g\,m^{-2}$ of fine silt had settled. Based on these measurements and using the calculation established by Hall-Spencer and Moore (2000), we estimate that the hydraulic dredge caused the erosion of a minimum of 570 g of fine sediment per metre length of the hydraulic dredge track.

Dredge track observations

The dredge track was 127 m long with an average depth of 10.3 ± 3.3 cm (mean ± SD, n = 5) and an overall width of 103.6 ± 4.8 cm. The track centre was level with parallel embankments on either side, caused by the "snow-plough" effect of the stabilising runners. One month after dredging, the track had been partially eroded by wave action and, in places, the edges of the track were difficult to locate. The

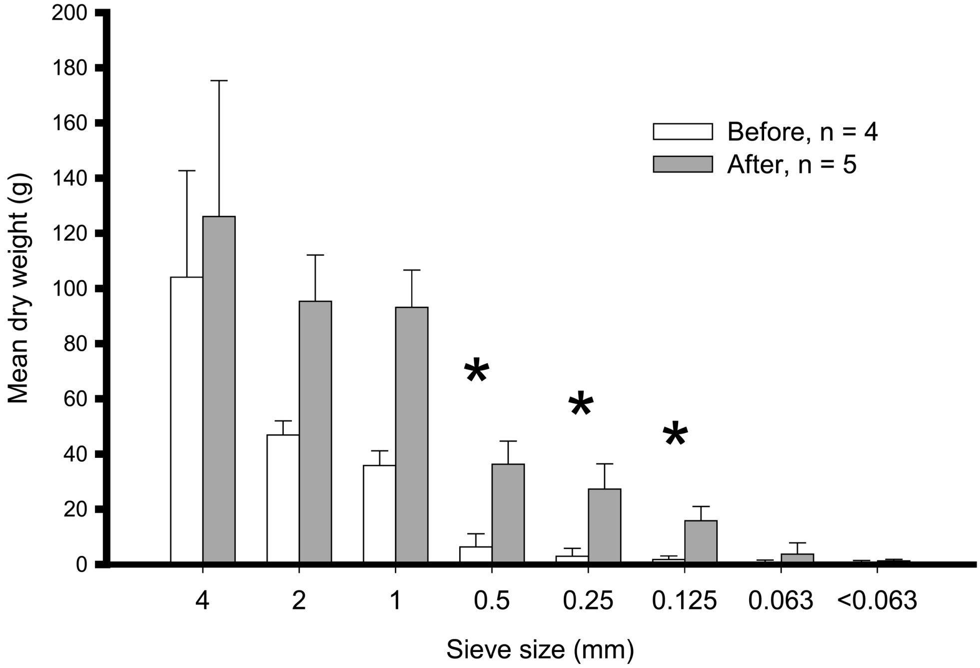

Figure 3. Mean dry weights of sediment size classes in the 3–6 cm horizon of cores taken before and 1 h after fishing. Significant differences denoted as in Figure 2.

overall depth of the track had reduced to 6.5 ± 2.7 cm, while the width had been reduced to 99.0 ± 13.9 cm.

As with the coring investigation previously outlined, dyed maerl was used to find out how hydraulic dredging would affect live maerl cover. Photoquadrats taken prior to dredging showed that a roughly rectangular 5.2 m^2 area of the experimental plot had been thinly covered with the dyed proxy. The fluorescent material lay up to 2 cm thick but had

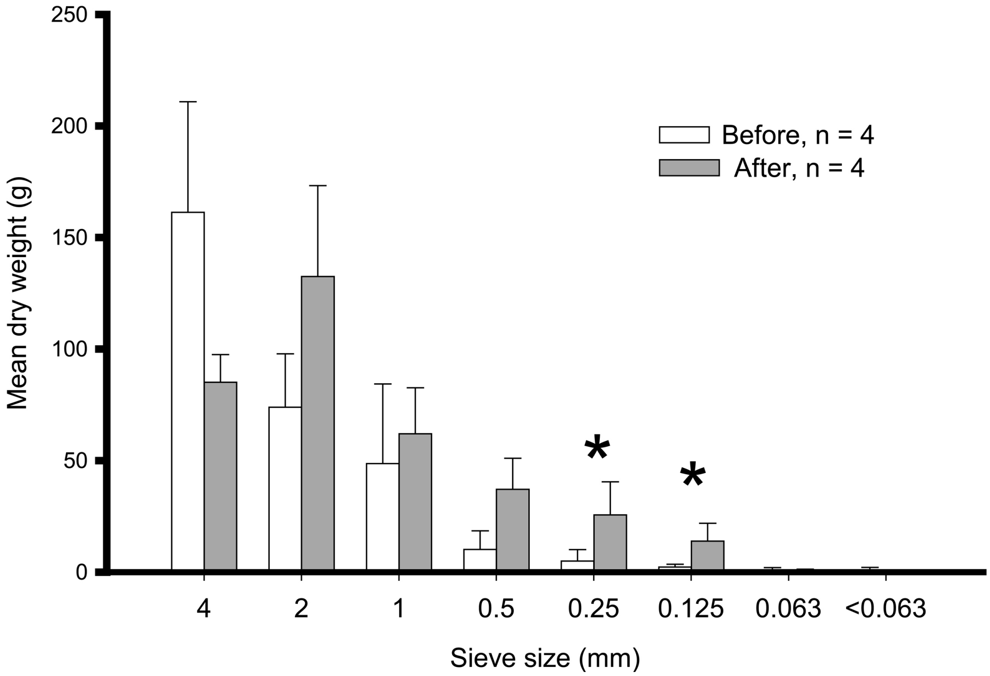

Figure 4. Mean dry weights of sediment size classes in the 6–9 cm horizon of cores taken before and 1 h after fishing. Notation as before.

Table 3. Summary of the inclusive graphic standard deviations (σ_1) calculated according to Folk (1974).

	Horizon (cm)	Mean σ_1	SD	n	Classification
Before	0–3	2.07Φ	0.37Φ	4	Very poorly sorted
	3–6	2.15Φ	0.13Φ	4	Very poorly sorted
	6–9	2.46Φ	0.33Φ	3	Very poorly sorted
After	0–3	1.83Φ	0.14Φ	5	Poorly sorted
	3–6	1.78Φ	0.11Φ	5	Poorly sorted
	6–9	1.59Φ	0.07Φ	4	Poorly sorted

<100% cover due to the presence of protruding pebbles (Plate 1A). After fishing, the dredge had reduced dyed maerl cover from 83 to 16% through the centre of the experimental plot. Dyed maerl remained clearly visible at its pre-dredge density showing that major sediment redistribution was restricted to the direct path of the hydraulic gear (Plate 1B). Photoquadrats taken along the dredge track revealed low numbers (<1% cover) of small and broken fragments of dyed material along the 100 m length surveyed, indicating where maerl had passed through the metal mesh of the dredge.

Video and diver observations taken after hydraulic dredging provided a stark contrast to pre-dredging conditions. Through-water visibility was much reduced as the gear had created a cloud of fine suspended sediment. Newly settled mud coated kelp (*L. saccharina*) up to 20 m from the dredge track. Gross habitat structure remained similar to pre-dredging conditions on either side of the track, although maerl and sessile filter-feeding sponges were covered in about 1 mm of silt. The track itself was flattened. The complex benthos-sediment structural features recorded prior to dredging had been removed. Pebbles and shells that had previously been arranged along troughs of the sediment megaripples were spread out and buried along with the attached biota of seaweeds and sessile fauna. Nesting gobies (*Pomatoschistus minutus*) and cryptic crustaceans (e.g. *G. intermedia*) were absent and may have dispersed as the gear approached. Large epibiota, such as kelp and starfish, had been removed and were noted as by-catch (above). Small, thick-shelled animals remained on

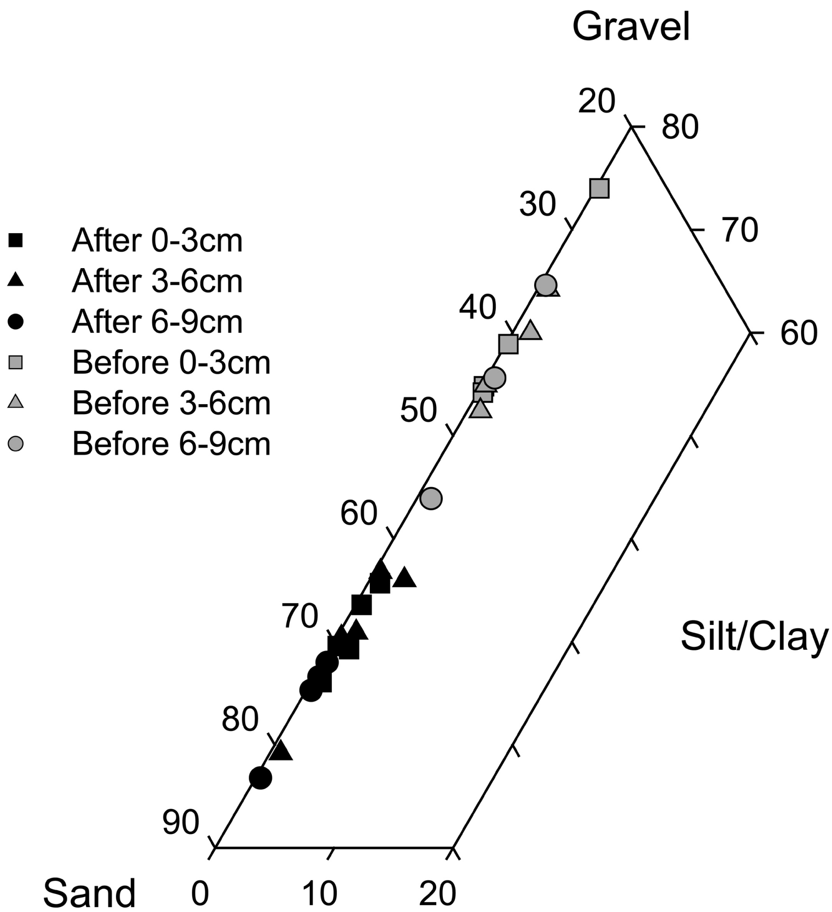

Figure 5. Modified ternary plot showing the change in classification of maerl ground, according to the Wentworth Scale, associated with a single pass of the UMBSM hydraulic dredge.

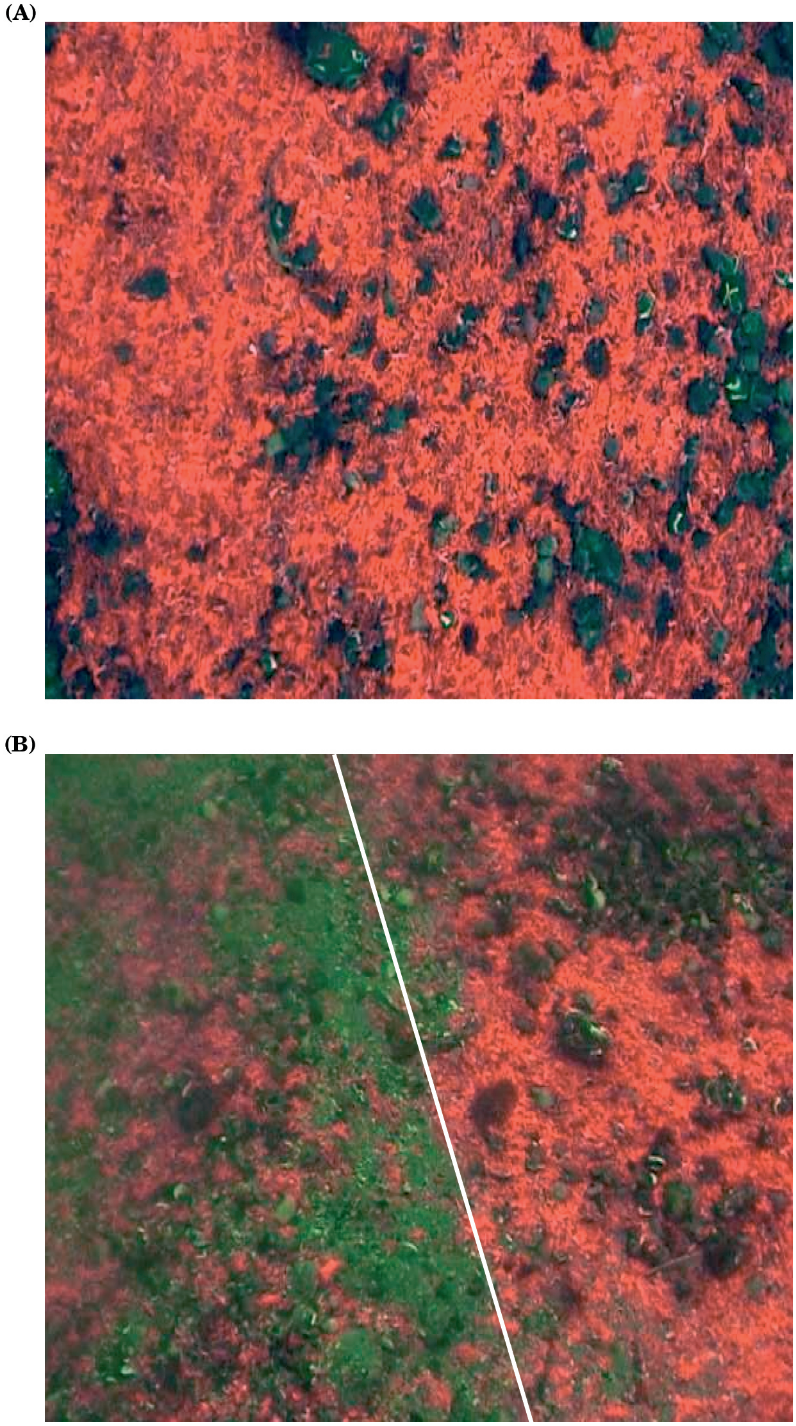

Plate 1. Photoquadrats of experimental plot on maerl with pebbles in Stravanan Bay, November 2001. (A) Before fishing, showing an 83% cover of orange-coloured maerl. (B) After fishing, showing hydraulic dredge track (left of the white solid line) where dyed maerl is reduced to 16%, on the right dyed maerl cover has remained unaffected by the passage of the gear. Photo width = 1.25 m.

Table 4. Damaged megafauna and scavenging organisms recorded on video 1.5–2 h after hydraulic dredging of maerl bed at Stravanan Bay, November 2001. Before dredging there was no damaged fauna or scavengers feeding in the experimental area.

Damaged fauna	Number visible	Scavengers	Number feeding
Chaetopterus variopedatus	1	*Liocarinus depurator*	2
Cancer pagurus	1	*Necora puber*	12
Lutraria angustior	9	*Pagurus bernhardus*	2
Ensis arcuatus	5	*Buccinum undatum*	2
Tapes rhomboides	1	*Pleuronectes platessa*	1
Mya truncata	1	*Gadus morhua*	10
Astropecten irregularis	1		
Asterias rubens	2		
Echinocardium pennatifidum	5		
Neopentadactyla mixta	8		
Ascidiella aspersa	2		

the track intact (e.g. *Clausinella fasciata*) whereas more fragile organisms were damaged (e.g. *Cerianthus loydi*). Table 4 shows the range of macrofauna found dead or dying in the vicinity of the 127 m dredge track; an underestimate as small organisms were not seen clearly on the video images. Damage included a smashed edible crab (*Cancer pagurus*) and several broken irregular urchins (*Echinocardium pennatifidum*) that lay partially buried on the track surface. Torn *Lutraria angustior* and *Mya truncata* siphons were found along the track, indicating damaged individuals below while other organisms had crawled out of the disturbed sediment and lay exposed at the side of the track.

Benthic feeding behaviour was strongly affected by the hydraulic fishing activity. Prior to fishing, the experimental plot had two starfish (*Asterias rubens* and *Marthasterias glacialis*) feeding on buried bivalves. Two hours after fishing, crabs, whelks and fish had aggregated within the track and begun to feed on the exposed carrion. Those that were large enough to be seen on the post-dredging video are enumerated in Table 4. Some scavengers attacked animals that were apparently undamaged, for example *Liocarcinus depurator* attacked *E. arcuatus* as they attempted to re-burrow in sediment adjacent to the dredge track.

Discussion

This paper has summarised the results of a short-term hydraulic dredge impact study conducted on a maerl habitat in Stravanan Bay, Bute, within the Clyde Sea area. This maerl bed was chosen as it was a previously impacted habitat and represented a more responsible choice than the hydraulic dredging of a pristine maerl bed. Dead maerl was collected and dyed with a fluorescent marker to simulate living maerl at the surface and, as such, this work represents a novel application of a non-toxic sediment tracer in the marine environment. Importantly, the majority of the impacts described in this study are the result of the large volumes of water used to fluidise the sea bed, which is a characteristic of all hydraulic shellfish dredges regardless of their design. Consequently, these data and conclusions can be considered relevant to the management of all hydraulic dredge fisheries world-wide.

The UMBSM hydraulic dredge fished non-selectively with respect to sedentary megafauna. Bivalves dominated the catch, constituting over 90% of the AFDW biomass, with the smallest retained being *Clausinella fasciata* (3.2 mm in length). The main bivalve caught (numerically and by weight) was *Dosinia exoleta*, which has been identified as a species with future market potential (McKay, 1992). Damage to the bivalves varied depending on shell thickness and burrowing depth. Large, relatively thin-shelled bivalves, such as *Ensis arcuatus* and *Lutraria angustior* were often broken or had their siphons ripped off, while the more compact species, such as *D. exoleta* and *C. fasciata* remained intact. Damage to other organisms also depended upon their robustness, with delicate polychaetes (e.g. *Chaetopterus variopedatus*) being killed. Most of the mobile benthos (e.g. fish, crustaceans) escaped capture because the gear was towed slowly.

The target razor clams, *Ensis* spp., were not common in our experimental haul. Most *Ensis* spp. live in sandy and silty sediments and so are unlikely to occur in commercial quantities within coarse maerl grounds. While the curved razor clam, *E. arcuatus*, does occur in coarser sediments, we now know that not all maerl beds support commercial razor clam populations. However, the fact that maerl grounds have been shown to support a wide diversity of deep-burrowing bivalve species, including some, which have been identified as commercially accessible with hydraulic dredge technology (McKay, 1992), means that the data generated from this study can be applied to future instances of hydraulic dredging on maerl, irrespective of the target species. From the viewpoint of hydraulic dredge fishery management, if populations of razor clams or other bivalves are found within maerl grounds, it would be prudent to leave these populations undredged and so provide a reservoir of adults to repopulate adjacent sandy areas that might be exploited, thereby helping to sustain a long-term fishery. Indeed this concept could be extrapolated to include the designation of protected recruitment reservoirs (Dugan and Davis, 1993) for any commercially important bivalve within the framework of fishery Regulating Orders (Clarke, 2001) or other local management schemes.

Several studies have shown that the major impact of towed demersal fisheries occurs the first time an area is fished (Jennings and Kaiser, 1998). It might be argued that previously fished maerl grounds would be of less ecological (or conservation) importance than pristine grounds, and therefore allowable as areas for commercial hydraulic dredging. However, past fishery impact studies (Jennings and Kaiser, 1998) have concentrated upon the effects on organisms that live on, or in, the surface layers of sea-bed sediment (<10 cm). Our studies are unique in that we have recorded effects on deep-burrowing fauna. None of the demersal fishing gears used previously in Scottish waters penetrate the sea bed to such an extent as a hydraulic dredge. This is a vital management consideration, because even on grounds such as Stravanan Bay, which has been heavily modified by scallop dredging over the past 40 years (Hall-Spencer and Moore, 2000), there remains a high biomass of large, long-lived, deep-burrowing organisms that would be vulnerable to hydraulic dredging. Infaunal biomass and biodiversity remain high on maerl grounds that have low live maerl cover (Hall-Spencer, 1998). Habitat heterogeneity (which drives diversity) remains high even on dead maerl deposits because the biota modifies the distribution of sand and mud fractions within the three-dimensional matrix of maerl, stones and shells.

In addition to the site-specific observations of the impacts on the biological community, this study also explored the impact on the geophysical properties of the sea bed, observations which may be regarded as being more universally applicable. The hydraulic dredge removed maerl from the surface of the sea bed at a rate of $5.2\,\mathrm{kg\,m^{-2}}$. A small proportion of the fluorescent-dyed proxy was retained in the dredge and exposed to air when the dredge was hauled. The remaining maerl was either smashed and dispersed along the dredge track or ploughed into the sea bed. Thus hydraulic dredging is detrimental to the conservation status of maerl beds; it has the potential to kill the maerl and it reduces habitat complexity and niche space for the local fauna.

Hydraulic dredging altered sediment structure to depth of at least 9 cm. A single dredge tow significantly reduced the gravel component and increased the degree of sediment sorting. On a fishery scale, repeated dredge hauls would be expected to alter the physical nature of the sediment, producing a more sorted, unconsolidated, sandier habitat. Such changes would alter the resident biological community, potentially to the detriment of future larval settlement (Butman *et al.*, 1988).

As with scallop-dredging (Hall-Spencer and Moore, 2000), we found that hydraulic dredging on maerl beds smothers surrounding habitat with suspended sediment. Previous studies of the Stravanan Bay maerl bed showed that sea-bed tidal currents did not exceed $11\,\mathrm{cm\,s^{-1}}$ and that this was insufficient to mobilise the coarse surface sediment (Hall-Spencer, 1998). The coarse-surface sediments were only naturally disturbed by bioturbation or when storm waves and wind-driven currents combined, a situation which arose approximately twice a year from 1995 to 1999 (Hall-Spencer, 1998; Hall-Spencer and Atkinson, 1999). We recorded a 20-fold increase in the amount of sediment settling around the dredge track. Again, if these data are extrapolated to a fishery situation, it is clear that hydraulic dredging could smother adjacent unfished habitats. If maerl is buried for an extended period, it ultimately dies due to lack of light. Prevailing currents would determine the size of the area affected by increased sedimentation, which should be considered when granting licences to use hydraulic gear in the vicinity of vulnerable habitats.

In summary, the impacts of hydraulic dredging on maerl are multi-faceted and both direct and indirect. Maerl beds are of sufficient conservation interest to warrant protection from the various impacts caused by hydraulic fishing gear, both as a biodiversity resource and an economic resource. Undredged maerl grounds can be of long-term benefit to fisheries, acting as reproductive reservoirs for future generations of commercially important bivalve species. As has been discussed, the habitat complexity offered by dead maerl means that protection from hydraulic dredging should be extended to cover all maerl beds, irrespective of the percent of live thalli.

Acknowledgements

This research was conducted while in receipt of funding from the European Commission under contract CFP 99/078 and from Scottish Natural Heritage under contract BAT/AA410/01/02/159. Staff at the University Marine Biological Station Millport are thanked, particularly the diving team (K. Cameron, S. Muir and R.J.A. Atkinson), crew of "RV Aora" (M. Parker, D. Frazer, W. Sloss and C. McLachlan) and C. Blance for assistance in sorting the dredge contents and processing the core samples.

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