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# Recovery of the seabed following marine aggregate dredging on the Hastings Shingle Bank off the southeast coast of England

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## Abstract

The aim of this study was to investigate the effect of dredging intensity on the physical and biological recovery times of the seabed following marine aggregate dredging. Two areas of seabed, previously subject to, respectively, relatively high and lower levels of dredging intensity, were identified on the Hastings Shingle Bank. Two reference areas were also selected for comparative purposes. All four sites were monitored annually over the period 2001–2004, using a combination of acoustic, video and grab sampling techniques. Since the site was last dredged in 1996, this was intended to provide a sequence of data 5–8 years after cessation of dredging. However, an unexpected resumption of dredging within the high intensity site, during 2002 and 2003, allowed an additional assessment of the immediate effects and aftermath of renewed dredging at the seabed. The early stages of recovery could then be assessed after dredging ceased in 2003. Results from both dredged sites provide a useful insight into the early and latter stages of physical and biological recovery. A comparison of recent and historic dredge track features provided evidence of track erosion. However, tracks were still visible 8 years after the cessation of dredging. Within the high dredging intensity site, recolonisation was relatively rapid after the cessation of dredging in 2003. Rather than indicating a full recovery, we suggest that this initial ‘colonization community’ may enter a transition phase before eventually reaching equilibrium. This hypothesis is supported by results from the low intensity site, where biological recovery was judged to have taken 7 years. Further monitoring is needed in order to test this. An alternative explanation is that the rapid recovery may be explained by the settlement of large numbers of *Sabellaria spinulosa*. As the resumption of dredging within the high intensity site limited our assessment of longer-term recovery it is not yet possible to assume that a 7-year biological recovery period will be applicable to other, more intensively dredged areas at this or more distant locations.

*Keywords:* Hastings Shingle Bank; recovery; benthos; aggregate; dredging; seabed; environmental impact

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## 1. Introduction

Currently, around 21% of the supply of sand and gravel in England and Wales comes from the marine environment. In 2005 this demand amounted to 21.09 million tonnes of aggregate (Crown Estate records, unpublished). This material, primarily used in construction and coastal defence, is sourced from licenced extraction areas around the coast of the United Kingdom, using either anchor or trailer suction hopper dredging vessels.

As would be expected, ongoing dredging operations lead to reductions in the numbers of species and individuals in the immediate vicinity within licenced areas (e.g. Shelton and Rolfe, 1972; Kenny et al., 1998; van Dalfsen et al., 2000; Sardá et al., 2000; van Dalfsen and Essink, 2001; Boyd et al., 2003, 2005).

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In addition, physical changes such as the creation of dredge furrows or pits, depending on the method of dredging employed, and alterations to the composition of seabed sediments may also result (Dickson and Lee, 1972; Millner et al., 1977; Kenny et al., 1998; Desprez, 2000; Limpenny et al., 2002; Boyd et al., 2003, 2004). Whilst the severity and persistence of such effects depend on local environmental conditions (e.g. hydrography, geology, and type of benthic community), it is generally assumed that they will disappear, typically on timescales of 1–10 years. In order to promote recovery, licence conditions normally dictate that the seabed be left in a 'similar' condition to that which existed prior to the onset of dredging. As the acceptability of dredging activities is likely to depend on the persistence of any impacts after the event of cessation, as well as their severity and spatial extent while extraction is taking place, it is important that those responsible for the management of such activities have information on recovery-times.

A number of authors have investigated the capacity for the physical and biological recovery of the seabed at Hastings Shingle Bank following dredging (Dickson and Lee, 1972; Shelton and Rolfe, 1972; Rees, 1987; Kenny, 1998). Whilst these studies have made predictions about likely physical and biological recovery-times, none have provided definitive times. As a result, recovery time predictions are often based on available studies from elsewhere. For example, Kenny et al. (1998), working off North Norfolk, suggest that this process could be expected to take around 2–3 years. However, their study followed recovery after a 'one-off' experimental dredging event, rather than the more sustained dredging more commonly associated with commercial sites. In recent years, the availability of empirical data on recovery-times at commercial sites has increased (e.g. Boyd et al., 2003, 2004, 2005) and, in general, suggests that recovery-times may typically be longer than 2–3 years. The variability in the findings from different locations, and in response to different dredging regimes (Boyd et al., 2004), indicates that there is still a need to increase the number of such case studies in order to build a more complete picture of recovery rates around the coast of the UK. The present study was designed to test earlier predictions regarding recovery-times at the Hastings Shingle Bank (Dickson and Lee, 1972; Rees, 1987; Kenny, 1998) with special reference to the effects of dredging intensity.

## 2. Materials and methods

### 2.1. Study site

The study site is located approximately 6 nautical miles south of Hastings off the south coast of England (Fig. 1). Water depths vary from 14 to 40 m below chart datum, and the tidal ellipse is aligned in an NE–SW direction. The maximum spring tidal current velocity is 2.6 knots (Admiralty Chart 536). On the flood tide the flow is in a north-east direction, whilst water flows south-west on the ebb. Current meter studies in the area (Rees et al., 2000) and observations of seabed transport features from this study indicate that the net sediment transport is in a north-easterly direction.

Hastings Shingle Bank was first licenced for aggregate dredging in September 1988. Since this time there have been a number of changes to the boundaries of the extraction licence. In 2001, sub-areas X and Y (see Fig. 1) were both relinquished and replaced by a new licence. Whilst this new licence encompasses part of the old sub-area X, some previously dredged areas fall outside, making them suitable for an investigation of recovery. In addition, it was considered unlikely that the northern extreme of the new licence (the area which overlaps with Area X) would be dredged during the period of this study, and so this area was also considered suitable for investigation. However, in 2002 dredging resumed within this area and continued into 2003. Therefore results from the high intensity site in these two years represent conditions within a current aggregate extraction area.

### 2.2. Sampling design

Since 1993, every vessel dredging on a Crown Estate licence in the UK has been fitted with an Electronic Monitoring System (EMS). This consists of a computer linked to a Global Positioning System (GPS) and one or more dredging status indicators. Every 30 s the computer automatically records the date, time and position of all dredging activity. EMS information was interrogated in order to locate areas of the seabed within Area X which had been subjected to different levels of dredging intensity.

Areas of high and lower levels of dredging intensity were identified from the 1996 EMS data (see Fig. 2), the last year that the study site had been dredged prior to sampling in 2001. The area of high dredging intensity represented >4.99 h of dredging whereas the area of lower dredging intensity is equivalent to <1 h of dredging, within each 100 m by 100 m block. Treatment boxes, measuring 300 m by 200 m, were assigned to these two areas of seabed (see Fig. 1).

Two reference sites were also selected, using side-scan sonar and video images of the seabed. Note that these sites were not considered representative of 'baseline' conditions, as there was insufficient information on which to determine what actually constitutes the likely pre-dredging status of the area. However, they were considered to be representative of the wider environment surrounding the extraction licence and outside of the influence of potential dredging effects. The area of each reference box was half that of the treatment boxes.

Within each treatment box, 10 randomly positioned sampling stations were identified (stratified random design). In order to achieve the same sampling density, only five random stations were identified within each reference site. All station positions were re-randomised each year and details of the locations sampled are presented in Table 1.

### 2.3. Sample collection

One 0.1 $m^2$ Hamon grab sample was collected from each randomly positioned sampling station within the high and

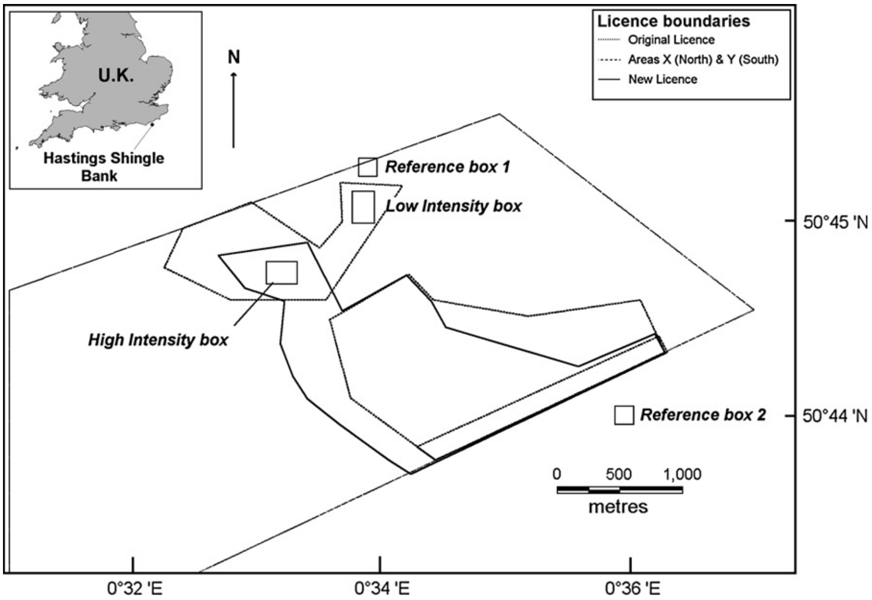


Fig. 1. Treatment boxes in relation to positions of historic (original, Area X and Area Y) and current (new licence area) aggregate extraction licence on the Hastings Shingle Bank.

low intensity sites and the reference sites in each year of the study (2001–2004). Samples were collected in July aboard the RV Cirolana (2001 and 2002) and RV Cefas Endeavour (2003 and 2004). Following estimation of sample volume, a 500 ml sub-sample was removed for laboratory particle size analysis. The residual sediment was then washed over a 1 mm square mesh sieve to extract the macrofauna, which was then back-washed into a watertight container and fixed in 4–6% buffered formaldehyde solution (diluted in seawater).

### 2.4. Acoustic and video surveys

A side-scan sonar survey was undertaken using a Datasonics™ SIS 1500 digital chirp system in July of each year

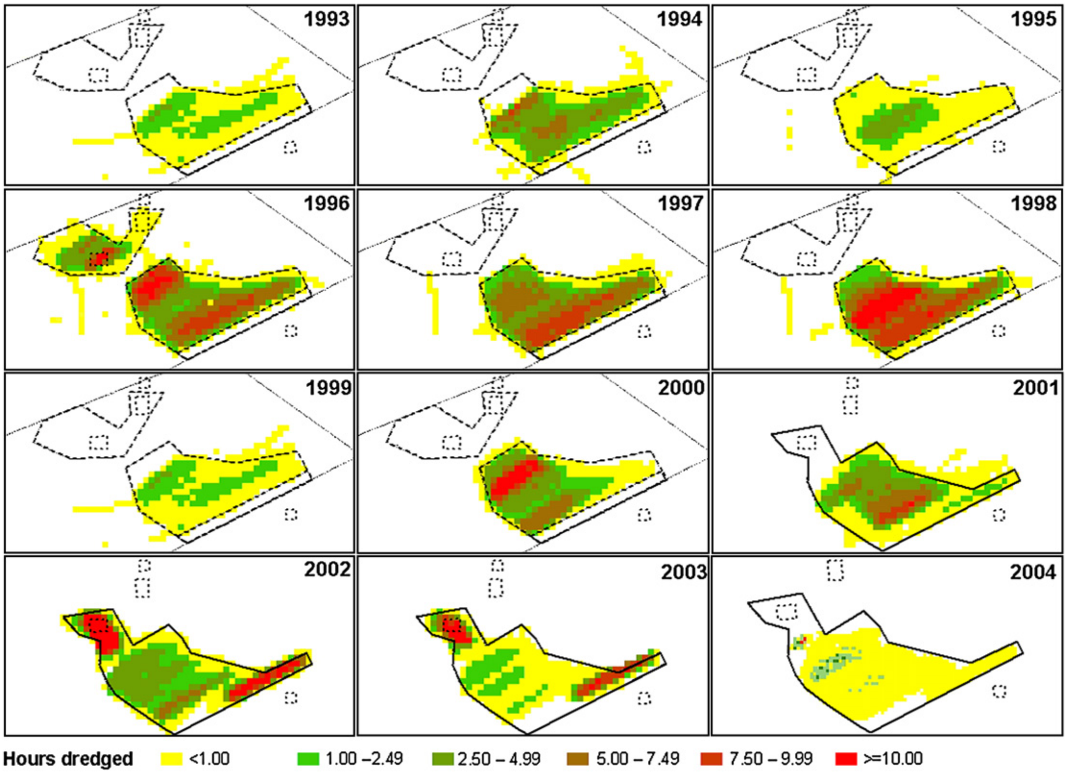


Fig. 2. Location and intensity of dredging (hours) over each 100 m × 100 m block at Hastings Area X in relation to the positions of the high and low sampling sites in years 1993–2003 (source Electronic Monitoring System data provided by the Crown Estate).

Table 1
Co-ordinates of treatment boxes

| Treatment | Code | Box co-ordinates |  | Area ($m^2$) | Number of samples collected |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  | Latitude | Longitude |  | 2001 | 2002 | 2003 | 2004 |
| High intensity site | HIGH ’01–’04 | 50° 44.784′N<br>50° 44.670′N | 00° 33.090′E<br>00° 33.336′E | ~60,000 | 10 | 10 | 10 | 10 |
| Low intensity site | LOW ’01–’04 | 50° 45.144′N<br>50° 44.982′N | 00° 33.780′E<br>00° 33.960′E | ~60,000 | 10 | 10 | 10 | 10 |
| Reference site 1 | REF ’01–’04 | 50° 45.314′N<br>50° 45.221′N | 00° 33.833′E<br>00° 33.980′E | ~30,000 | 5 | 5 | 5 | 5 |
| Reference site 2 | REF ’01–’04 | 50° 44.046′N<br>50° 43.954′N | 00° 35.898′E<br>00° 36.047′E | ~30,000 | 5 | 5 | 5 | 5 |

(2001–2004). The purpose of these surveys was to identify the spatial distribution of superficial sediment types and bed-forms across the current and relinquished zones of the Hastings Shingle Bank extraction area and also across the wider region. Thirteen survey lines (approximately 5 km long) were surveyed in a north–south orientation using a 400 m line spacing in order to achieve 100% coverage of the survey area. The digital data were acquired and post-processed using the Triton Isis™ and Delphwin™ software packages, producing a geo-referenced, on-screen mosaiced image of the survey lines.

Multi-beam surveys were carried out using a dual-head, hull-mounted, Kongsberg Simrad EM 3000D high-resolution multi-beam sonar. The purpose of these surveys was to provide detailed bathymetric data in order to monitor the dimensions of dredge tracks over the period. The data were corrected in real time for vessel movements using a Kongsberg Seatex Motion Reference Unit (MRU 5). Soundings were acquired using TEI Inc, Triton Isis™ software and the data were tidally corrected and gridded using the TEI Inc, Bathypro™ processing package. The data were presented using IVS3D Fledermaus™ software. Given the depths of water encountered, multi-beam swathe widths were typically half of the side-scan sonar swath widths.

Where conditions allowed, photographic surveys using underwater video and stills techniques were conducted using a Simrad™ video camera and a Benthos DSC™ 4000 digital stills camera mounted within a robust metal frame. These surveys were used to obtain additional ground-truth information on the physical and biological status of the seabed. The camera frame was lowered close to the seabed as the vessel drifted with the tide. Video images were recorded automatically onto high-resolution digital tape. Deployments of approximately 10 min duration were carried out over the high and low intensity sites, and also the reference sites.

## 2.5. Sample processing

### 2.5.1. Macrofauna

In a fume cupboard, the formaldehyde solution was removed by draining the sample over a 1 mm mesh sieve. The sample was then subjected to a series of washes with fresh water, which served to remove any remaining formaldehyde and also to remove any lighter animals. Small aliquots of the remaining sediment were then transferred to a white plastic tray and examined under an illuminated magnifier in order to remove any remaining animals. Specimens were placed into a labeled Petri-dish, containing a preservative of 70% Industrial Methylated Spirits. The animals were then identified to the lowest possible level, usually species, and enumerated. Finally, the blotted wet weight (in milligrams) for each species, from replicate samples, was recorded.

### 2.5.2. Sediment particle size

The sediment sub-samples from each grab were analysed for their particle size distributions. Samples were first wet-sieved on a 500 μm stainless steel test sieve using a sieve shaker. The <500 μm sediment fraction passing through the sieve was allowed to settle from suspension in a container for 48 h. The supernatant was then removed using a vacuum pump and the remaining <500 μm sediment fraction was washed into a Petri-dish, frozen for 12 h and freeze-dried. The total weight of the freeze-dried fraction was recorded. A sub-sample of the <500 μm fraction was then analysed using a laser sizer. The >500 μm fraction was washed from the test sieve into a foil tray and oven dried at ~90 °C for 24 h. It was then dry-sieved on a range of stainless steel test sieves, corresponding to 0.5 phi intervals, down to 1 phi (500 μm). The sediment on each sieve was weighed to 0.01 g and the values were recorded. The results from these analyses were combined to give a full particle size distribution for each sample.

## 2.6. Data analysis

Analyses techniques were chosen to determine:

(1) whether there were statistically significant differences between the dredged and reference locations, and, if so;
(2) whether there was any evidence of a trend towards increasing similarity over time.

### 2.6.1. Sediment variables

Particle size data are summarized as annual means taken from the high and low intensity sites and also the reference sites. In addition, multivariate techniques (Principle Component Analysis and ANOSIM) were used in order to identify differences between the sediment particle size composition of samples from high and low dredging intensity and reference sites.

#### 2.6.2. Macrofaunal assemblage structure

Ash Free Dry Weights (AFDW) were calculated using standard conversion factors (Ricciardi and Bourget, 1998). The univariate measures of total abundance ($N$), numbers of macrofaunal species ($S$) and biomass (AFDW) were calculated and plotted over time. This allowed a visualisation of any trends (e.g. increasing or decreasing abundance at different sampling locations and over time). The significance of differences between sites was tested using one-way ANOVA.

All multivariate analyses were performed using the software package PRIMER v. 6.1.5 (Clarke and Gorley, 2001).

## 3. Results

### 3.1. Sediment characteristics

Differences, in terms of mean particle size composition, between the high and lower dredging intensity and the reference sites in each year of the study are shown in Fig. 3a and within each site over the course of the investigation in Fig. 3b. In 2001, all sites showed a high degree of similarity, especially between the site of lower dredging intensity and reference sites. This observation was confirmed by the results of an ANOSIM test. However, a number of predominately sandy samples, not encountered at the reference sites, were found within both dredged areas. During 2002 and 2003 dredging resumed within the high intensity site and sediments became coarser in comparison to the lower intensity and reference sites, which remained similar to one another. By 2004 (after the cessation of dredging) the high dredging intensity site had become sandier and in general, more similar to the lower intensity and reference sites.

### 3.2. Acoustic and video surveys

#### 3.2.1. Broad scale spatial survey

Fig. 4 shows a mosaic of side-scan sonar data from 2002 upon which is superimposed the boundaries of the current and historic licenced extraction areas. Also shown are the high and low intensity and reference sites (see Fig. 1). Within the current licence, gravely sediments are intensively furrowed by tracks formed by suction hopper trailer dredgers. Surrounding the licenced zones are a number of relatively undisturbed areas of stable sandy gravel, indicated by darker uniform patches on the side-scan mosaic. The two reference sites from the present study are sited within two such areas, to the north and south-west of the current licence. Similar areas are present immediately to the north-east of the extraction licence and in the extreme south-west of the survey area. In contrast, areas of sand, as indicated by the lighter patches on the side-scan mosaic, are found to the north-east and extreme north-west of the licence. In the extreme north-east of the survey area the sandy substratum is formed into large sand waves. Other areas surrounding the current licence are characterised by thin discontinuous veneers of sand overlying coarser deposits. These observations are consistent with other studies in the area (Brown et al., 2004).

#### 3.2.2. Temporal investigation of study sites

Fig. 5(a–d) shows side-scan sonar images collected from the high and lower dredging intensity sites and reference site 1, in 2001 and 2002. In 2001, weathered dredge tracks, orientated inan NE–SW direction, were clearly visible within the high intensity site (Fig. 5a). The features were in-filled with sand and it appeared that they may have formed from the agglomeration of individual tracks. In 2002, recent dredging activity (characterised by a generally N/S track orientation) had begun to mask these historic dredging-related features (Fig. 5b) and in 2003 they had all but disappeared. Video images revealed that the recent tracks were characterised by steep ridges of clean gravel on either side of the track, the bases of which were in-filled with sand (see Fig. 6a). The dimensions of a characteristic track from this area, determined using multi-beam bathymetric data were estimated to be $4\ \text{m} \times 0.24\ \text{m}$.

Weathered dredge tracks are apparent from the side-scan sonar image within the lower intensity site in all four years, but to a far lesser degree than in the high dredging intensity site (Fig. 5c). Video images collected in the lower intensity site in 2003 were similar to those collected in 2001, with a smooth, flat sediment profile comprising of flat sandy gravel occasionally masked by sand veneers (Fig. 6b). In contrast to the recent dredge tracks found in the high intensity site, the historic tracks found within the low intensity site were wider and shallower ($6.5\ \text{m} \times 0.10\ \text{m}$). These tracks are estimated to be at least 7 years old, according to the EMS data.

Side-scan sonar images of the reference sites show that the surrounding sediments are generally similar between 2001 and 2004. The seabed consists of flat generally featureless sandy gravels, with occasional sand veneers (Fig. 6c). In 2002, the side-scan sonar image provides some evidence that demersal fishing activity, indicated by paired tracks, has occurred in this area (Fig. 5d).

### 3.3. Macrofaunal assemblage structure

Overall, a total of 457 taxa were found at Area X from the 120 samples collected between 2001 and 2004. The numbers encountered annually were 268, 328, 268 and 306.

#### 3.3.1. Univariate analyses

Fig. 7 shows a comparison of various univariate measures at each sampling site in 2001–2004. In 2001, 5 years post cessation, significantly lower ($p > 0.05$) numbers of species were found at the high intensity site in comparison with the reference sites. In addition, although abundance values were not significantly different between these two sites, this could be attributed to elevations of the barnacle *Balanus crenatus* from within the site of high dredging intensity. This had the effect of masking reductions in the abundance of many other species at this site. *B. crenatus* appears to fulfill a role as an opportunistic colonizer of gravel substrata exposed during the dredging process. Following dredging within the high intensity site in 2002 and 2003, the numbers of species, individuals and biomass remained significantly lower in comparison with the

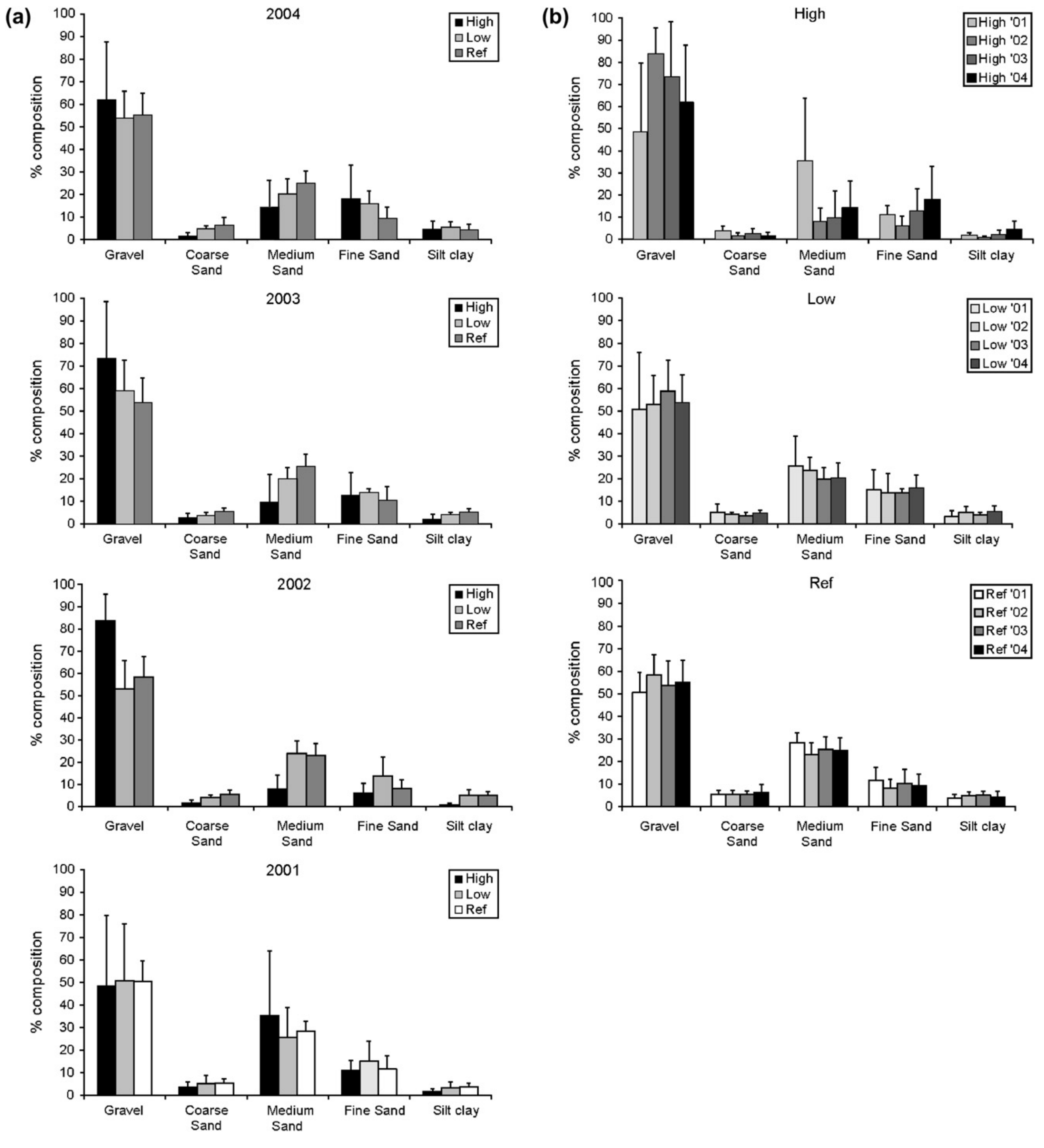


Fig. 3. (a) Annual comparisons of mean particle size composition of sediments taken from sites of high and lower dredging intensity and reference sites (2001–2004). (b) Annual records from each site are displayed together to allow inspection of the between year variation in average sediment composition (2001–2004).

reference sites. However, in 2004, values of all measures rose dramatically such that they did not differ from the reference sites. Of particular interest was the rise in mean abundance, mainly as a result of large numbers of juvenile *Sabellaria spinulosa*, a polychaete worm (Ave. 133.7 ± 278.6) within several samples. This may have been due to a shift in sediment composition to a gravelly/sandy habitat, which is known to be suitable for *S. spinulosa* colonization (Foster-Smith and Hendrick, 2003).

In 2001, numbers of species within the low dredging site were also significantly lower ($p < 0.05$) than the reference sites. In addition, high densities of *Balanus crenatus* were also found within a few of the more gravelly samples obtained from this site. Despite this local enhancement of *Balanus*, the total density of macrofauna was lower from within the area of low dredging intensity compared to elsewhere. However, by 2002, no significant differences ($p < 0.05$) were detectable between the low dredging intensity and reference sites in terms

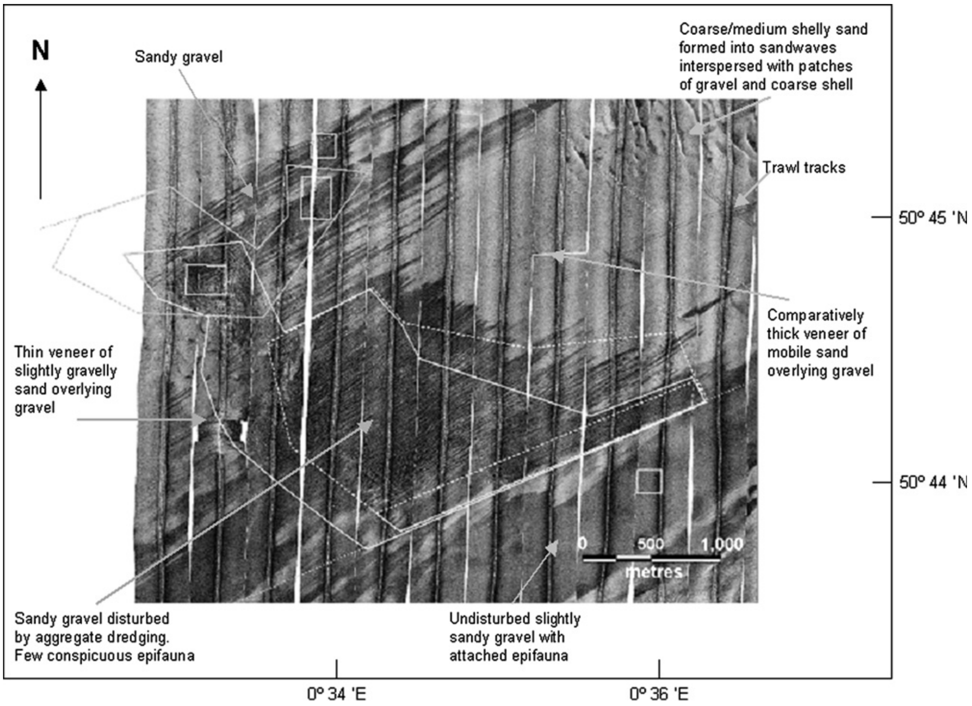


Fig. 4. Side-scan sonar mosaic showing the distribution of substrate types within and surrounding the current and relinquished extraction areas on the Hastings Shingle Bank (see Fig. 1 for licence boundaries).

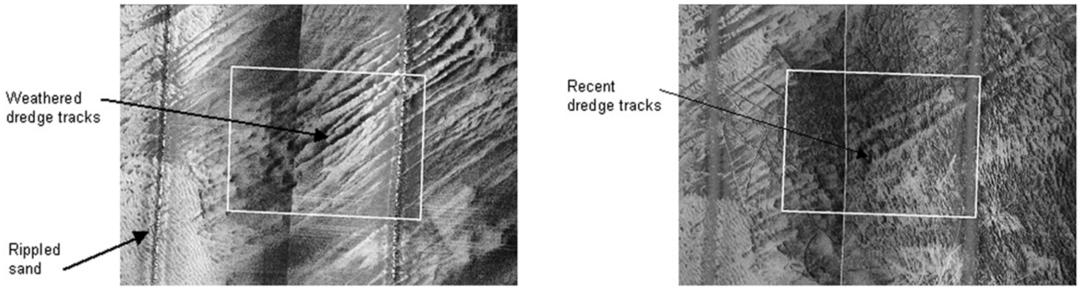
of number of species and individuals, and in 2003 biomass values were also not significantly different from reference values. This suggests that, in terms of univariate summary measures, the low dredging intensity site had recovered following 7 years after cessation of dredging.

### 3.3.2. Multivariate analyses

The MDS ordination (Fig. 8) indicates a large degree of overlap of samples from the areas of low dredging intensity and the reference sites. Comparison of ANOSIM *R*-values (Table 2) shows that by 2003 no significant difference

(a) Weathered dredge tracks infilled with sand within site of high dredging intensity in 2001

(b) Recent dredge tracks within site of high dredging intensity in 2002



(c) Weathered dredge tracks within site of low dredging intensity in 2002

(d) Undisturbed sandy gravels at reference site 1 in 2002

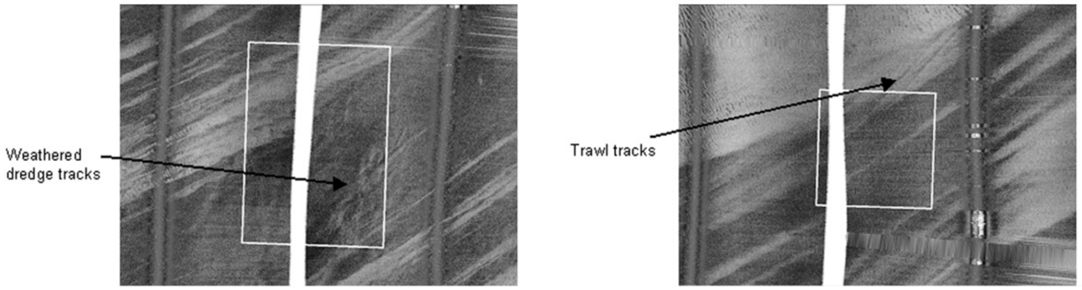


Fig. 5. (a–d) Examples of side-scan sonar records from high and low dredging intensity sites and reference site 1.

Dredge track within the high dredging intensity site

Sandy gravel sediments within the low dredging intensity site

Sandy gravel sediments with abundant epifauna within reference site 1

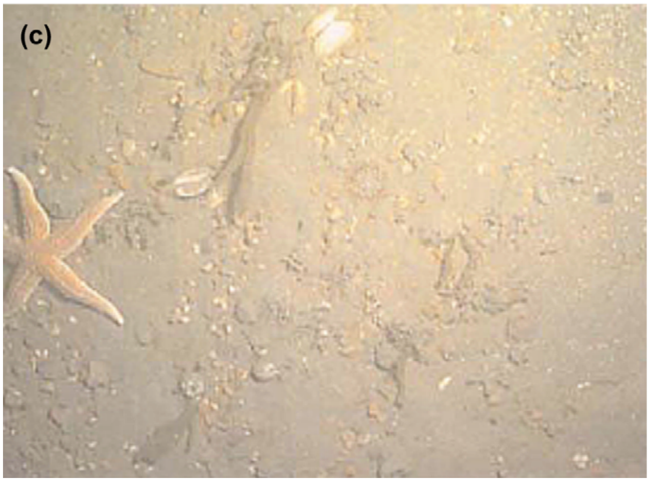


Fig. 6. (a–c) Underwater photographic images taken from sites of high and lower dredging intensity and reference site 1 in 2003. Each image represents an area of seabed of approximately 1.4 m by 1.0 m.

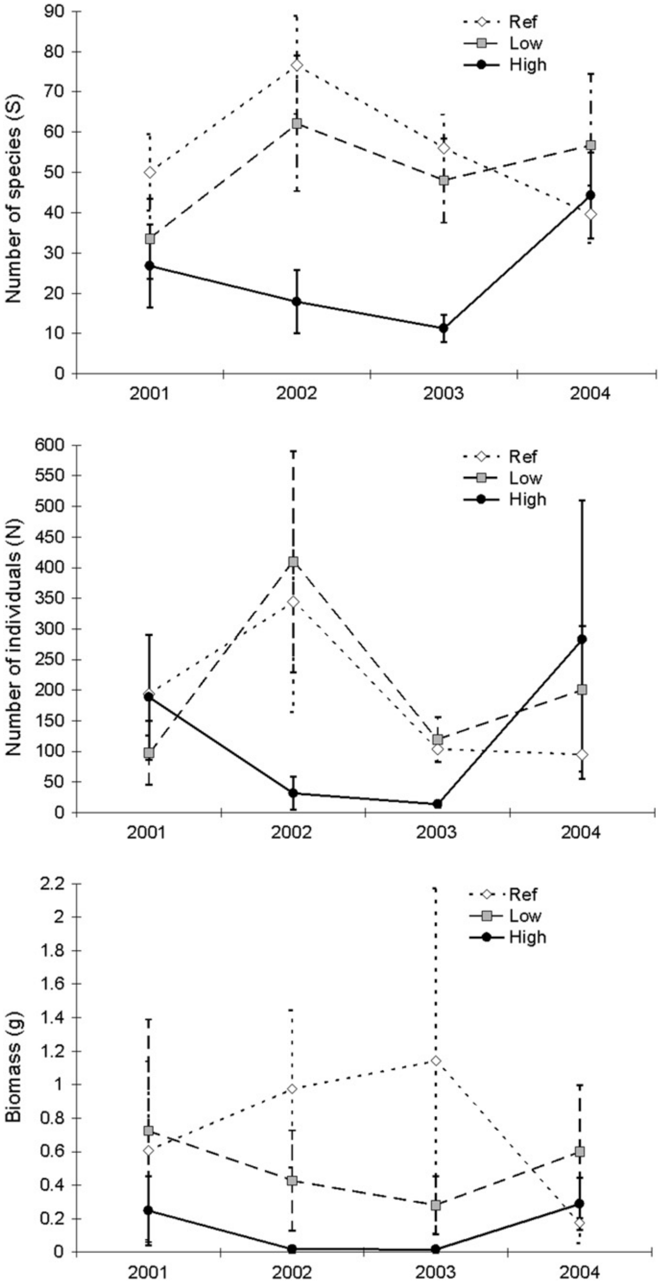


Fig. 7. Summary of means and 95% confidence intervals for numbers of species ($S$), number of individuals ($N$) and biomass (AFDW(g)) from sites of high and lower levels of dredging intensity and two nearby reference sites between 2001 and 2004.

($p > 0.05$) could be detected between the low dredging intensity and the reference sites. This suggests that restoration of the fauna was achieved in those parts of Hastings Area X exposed to lower levels of dredging intensity after a period of approximately 7 years since the cessation of dredging.

In 2001, 5 years after cessation of dredging, over half of the samples from the high dredging intensity site were present in the main cluster of the MDS. Samples are more diffusely separated on the MDS in 2002 and 2003, whilst dredging took place. This suggests that they are biologically dissimilar to samples collected elsewhere and reflect the substantially

Fig. 8. MDS of Bray–Curtis similarities from fourth root transformed species abundance data (colonial species excluded) at the high and lower dredging intensity sites and at the reference sites (data from 2001–2004).

reduced densities of organisms present. By 2004, less than 12 months after the last dredging episode, only one high intensity site sample is found outside the main cluster. Despite this, ANOSIM values indicate a persistent difference between the high intensity and reference sites. This value, however, may be exaggerated by an apparent shift in the reference sites, as shown on the MDS ordination. For this reason a comparison with the low intensity site may be more meaningful and this indicates only a small difference between high and low intensity sites.

Community groupings were further explored using the similarity percentages Programme SIMPER. Table 3 shows the characterising species of the study sites in 2004. Generally, the fauna at all sites was characteristic of sandy gravel sediments. The lower dredging intensity and reference sites showed similar community structures across all years, although the importance of the characterising species for each site was variable over time. The high dredging intensity site exhibited a decrease in the abundance of the opportunistic colonizing species *Balanus crenatus* during 2002 and 2003 following the resumption of dredging within this area. In 2004, 12 months after dredging had ceased, *B. crenatus* had again become established within the high dredging intensity site along with the tube-dwelling polychaete, *Sabellaria spinulosa*.

## 4. Discussion

By sampling areas previously subject to high and lower levels of dredging intensity, the survey was designed to allow investigation of the effects of dredging intensity, both in terms of the severity of impact and subsequent recovery-times.

Table 2
*R*-values derived from the ANOSIM test for macrofaunal assemblages from locations of high and lower dredging intensity and from the reference sites at Area X in 2001–2004. * Denotes significant difference at $p < 0.01$; ** denotes significant difference at $p < 0.05$

| Year | HIGH/REF | LOW/REF | HIGH/LOW |
|---|---|---|---|
| 2001 | 0.178** | 0.120** | 0.091* |
| 2002 | 0.637** | 0.158** | 0.459** |
| 2003 | 0.602** | 0.056 | 0.568** |
| 2004 | 0.572** | 0.222** | 0.250** |

At the outset of this work in 2001 it was anticipated that, following cessation of dredging in 1996, the study would provide information on the status of the seabed, within both dredged sites, 5–8 years after cessation. Whilst this was the case for the low intensity site, dredging resumed, during 2002 and 2003, within the high intensity site. Although not foreseen, this resumption allowed an assessment of the immediate effects of ongoing dredging on the seabed, and its aftermath 1 year after cessation. Together, the results from both sites provide a useful insight into the processes leading to recovery of the seabed following marine aggregate dredging at this site.

### 4.1. Physical effects and recovery

The effects of ongoing dredging activity were visible at the high intensity site in 2002 and 2003, where the seabed appeared extremely uneven as a result of north-south orientated dredge tracks. This contrasts with the flat seabed observed at the reference sites. Dredge tracks were composed of steep-sided gravel ridges separated by occasional sand-filled troughs. Despite this localised trapping of sand, particle size data revealed a coarsening of sediments during dredging, possibly as a result of the exposing of coarser deposits or the mobilisation of sand away from the site. This phenomenon was also observed by Kenny and Rees (1996) at an experimental dredged site off North Norfolk.

Older dredge tracks, seen in the high intensity site in 2001, and the low intensity site in all years (2001–2004), were different in character and provided evidence of weathering. The shape of these features suggests the furrow sides have collapsed, resulting in a widening and shallowing of the track. Individual tracks also appeared to have coalesced into larger features, and also appeared to trap sand. As a result of this weathering the seabed appeared much less uneven in comparison with the high intensity site during 2002–2004. However, the continued presence of these features, 8 years after cessation of dredging, suggest they may be long-lived, particularly given the classification of this site as one of relatively ‘low energy’ (Boyd et al., 2004). This assertion is supported by the persistence of dredge tracks at Area 107 off North Norfolk, where tracks were still visible after 7 years (Limpenny et al., 2002), and Area 222 in the Thames estuary where tracks were shown to be >10 years old (Boyd et al., 2004). Based on water depth, tidal current and wave data, Areas 222 and 107 are considered to be sites of ‘moderate’ energy (Boyd et al., 2005).

Despite the topographical changes observed above, and the occasional sandy sample encountered, particle size of sediments at both dredged sites in 2001, 5 years after cessation, was similar to the reference sites. In addition, the particle size composition of sediments within the high intensity site in 2004 was similar to reference conditions only 1 year after cessation. This accords with government requirements for the seabed to be left in a similar condition post-dredging

Table 3
Results from SIMPER analysis of macrofaunal data from Area X (all taxa excluding colonial species, fourth root transformed), listing the main characterising species from samples subject to differing levels of dredging impact in 2004. Average abundance, average similarity and the % contribution to the similarity made by each characterising species are shown. Also listed are the cumulative percentage and the overall average similarity between replicate samples from within each group

| Group | Taxon | Average abundance | Average similarity | Similarity/SD | % Contribution | Cumulative % | Overall average similarity |
|---|---|---|---|---|---|---|---|
| HIGH '04 | *Sabellaria spinulosa* | 133.70 | 2.74 | 1.61 | 7.03 | 7.03 | **39.03%** |
| | *Balanus crenatus* | 47.80 | 2.44 | 1.15 | 6.25 | 13.27 | |
| | *Poecilochaetus serpens* | 3.70 | 2.14 | 1.60 | 5.49 | 18.76 | |
| | Nemertea | 2.20 | 1.80 | 1.77 | 4.62 | 23.38 | |
| | *Galathea intermedia* | 2.70 | 1.78 | 1.79 | 4.56 | 27.94 | |
| | *Ampharete lindstroemi* | 2.50 | 1.51 | 1.17 | 3.88 | 31.82 | |
| | *Glycera tridactyla* | 1.50 | 1.36 | 1.15 | 3.48 | 35.30 | |
| | *Lumbrineris gracilis* | 3.30 | 1.33 | 1.23 | 3.42 | 38.72 | |
| | *Scalibregma inflatum* | 3.00 | 1.28 | 1.21 | 3.29 | 42.01 | |
| LOW '04 | *Lumbrineris gracilis* | 9.00 | 1.89 | 1.77 | 4.79 | 4.79 | **39.55%** |
| | *Upogebia* (juv.) | 9.00 | 1.74 | 1.88 | 4.41 | 9.20 | |
| | *Pomatoceros lamarcki* | 8.10 | 1.62 | 1.82 | 4.09 | 13.29 | |
| | *Caulleriella alata* | 3.10 | 1.50 | 1.64 | 3.80 | 17.09 | |
| | *Mysella bidentata* | 8.90 | 1.45 | 1.15 | 3.67 | 20.76 | |
| | *Echinocyamus pusillus* | 3.90 | 1.32 | 1.04 | 3.35 | 24.10 | |
| | *Poecilochaetus serpens* | 9.60 | 1.24 | 1.20 | 3.15 | 27.25 | |
| | *Scalibregma inflatum* | 6.20 | 1.23 | 1.20 | 3.10 | 30.35 | |
| | Nemertea | 3.70 | 1.19 | 1.16 | 3.02 | 33.37 | |
| | *Mediomastus fragilis* | 4.70 | 1.12 | 1.21 | 2.83 | 36.20 | |
| | *Goniada maculata* | 1.50 | 1.11 | 1.07 | 2.81 | 39.01 | |
| | *Pholoe baltica* | 2.70 | 1.11 | 1.19 | 2.80 | 41.81 | |
| REF '04 | *Echinocyamus pusillus* | 20.40 | 4.59 | 4.97 | 12.65 | 12.65 | **36.28%** |
| | *Praxillella affinis* | 3.20 | 2.69 | 5.69 | 7.41 | 20.06 | |
| | *Mysella bidentata* | 6.80 | 2.60 | 1.61 | 7.18 | 27.24 | |
| | *Lumbrineris gracilis* | 2.40 | 2.06 | 1.84 | 5.67 | 32.91 | |
| | *Notomastus* | 2.60 | 1.98 | 1.85 | 5.46 | 38.38 | |
| | Nemterea | 2.00 | 1.75 | 1.21 | 4.83 | 43.20 | |

thus are maximising the potential for biological recovery. These results contrast with another dredge site, Area 222, where the high dredging intensity site was observed to be sandier, possibly as a result of the screening of dredged cargoes at this site (Boyd et al., 2005). Screening is the practice of returning unwanted sediment fractions to the seabed and is not permitted on the Hastings Shingle Bank.

### 4.2. Biological effects and recovery

The effects of ongoing dredging on macrofaunal communities, evident from samples taken within the high intensity site in 2002 and 2003, included a reduction in both the numbers and variety of taxa, in agreement with other studies (Shelton and Rolfe, 1972; Kenny et al., 1998; van Dalfsen et al., 2000; Sardá et al., 2000; van Dalfsen and Essink, 2001; Boyd et al., 2003, 2005).

Results from the high dredging intensity site in 2004 provided information concerning the early stages of recovery. Less than 1 year after dredging operations had ceased, samples showed substantial increases in abundance, number of species and total biomass. Particularly interesting were the large numbers of juvenile *Sabellaria spinulosa* found within this site in this year. In addition, samples from both high intensity and reference sites are closely clustered. Whilst ANOSIM values suggest sizeable difference between the high dredging intensity and reference sites in 2004, the difference is perhaps exaggerated by a subtle shift in reference communities. This highlights a need to improve understanding of natural variability associated with macrofaunal communities found in gravel sediments. Therefore, a more useful comparison in this year can be made between high and low dredging intensity areas, which showed a much greater degree of similarity. Whilst the evidence suggests substantive biological recovery within 12 months, despite the clear topographic differences still evident within the site, it is important to consider these results in the context of those from 2001, 5 years after cessation of dredging, as they suggest conditions remained disturbed at this time.

This effect of dredging-induced disturbance was manifested in a number of ways including:

(1) A **reduced number of species** within the site of high dredging intensity during 2001;
(2) The presence of **opportunistic species** within the dredged sites. Large numbers of *Balanus crenatus* were recorded from the high dredging intensity site in 2001. Were it not for the presence of this species, total abundance values would have been significantly lower than either the low dredging intensity or reference sites. The opportunistic

nature of this species at aggregate extraction sites was also reported by Boyd and Rees (2003).

(3) **Increased variability**, in terms of particle size composition and macrofauna, within the high and low dredging intensity sites. As seen in Fig. 8, there were a number of sample outliers evident from both high and low dredging intensity sites. With one exception, these samples were all associated with predominately sandy sediments. No such samples were encountered at the reference sites and acoustic and video data suggest these samples may be associated with sand trapped within dredge tracks. Increased variability is noted as a feature of disturbance by Clarke and Warwick (1994) and has been reported by Kenny and Rees (1994), Sardá et al. (2000) and Boyd et al. (2005) in relation to aggregate extraction sites.

By 2003, multivariate analyses showed no difference between the low dredging intensity and reference sites. In common with Area 222 in the Thames estuary (Boyd et al., 2005), this suggests recovery of the macrofauna after 7 years. The similar time for recovery observed at these two sites may be linked to a number of similarities between the locations. Firstly, both sites were last dredged in 1996 and were therefore in synchronicity in terms of the recovery period. Secondly, both sites were subject to similar low levels of dredging intensity and thirdly, sediment particle size composition was similar to local reference conditions. In contrast, sediments within the site of higher dredging intensity at Area 222 were finer than those of the low intensity and reference sites (Boyd et al., 2004) and, as a result, recovery appears to be ongoing. These results contrast with a number of other case studies which together suggest that substantial progress towards recovery of the fauna could be expected within 2–4 years following cessation of marine sand and gravel extraction (Kenny et al., 1998; van Dalfsen et al., 2000; Sardá et al., 2000; ICES, 2001). However, these studies were based on experimental 'one-off' dredging events and not the sustained dredging more commonly associated with commercial extraction sites.

The apparent contradiction between the relatively rapid (<12 months) progress towards recovery seen in the high intensity site in 2004 and the 7 year period required for recovery inferred at the low intensity site in 2003 requires some further consideration. Models of succession in the marine environment following cessation of environmental disturbance (Newell et al., 1998; Boyd et al., 2005) offer an explanation which fits with the results of the current study. These models show a peak in various indices (e.g. species richness, abundance and biomass) in the early stages following a disturbance. Following this initial peak, values fall and oscillate until finally stabilising with the establishment of an equilibrium community (Newell et al., 1998). Further monitoring is required in order to validate this hypothesis at the Hastings Shingle Bank. Alternatively, rapid seabed recovery may have occurred as a result of rapid colonization by *Sabellaria spinulosa*. Side-scan sonar data together with some limited grab sampling within the high intensity site in 2005 (L.J. Seiderer, Marine Ecological Surveys, pers. comm.) suggest that the juveniles identified during this study have survived to form reef. Foster-Smith and White (2001), in a study of the Wash, noted that the most well developed *S. spinulosa* reefs seen in the area were associated with ground clearly scarred by dredging activity. They suggest this may be a result of the exposing of sediments more suitable for *S. spinulosa* colonization.

Despite the apparent differences between high and low intensity sites in 2001, the resumption of dredging within the high intensity site in 2002 limited our capability to assess the effects of dredging intensity after this time. We therefore recommend caution in assuming that the 7-year recovery figure could be applicable to other more intensively dredged areas of the Hastings Shingle Bank.

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