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Impact and recovery associated with the deposition of capital dredgings at UK disposal sites: Lessons for future licensing and monitoring

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ABSTRACT

The majority of studies relating to impacts and recovery at dredgings disposal sites have concentrated on areas subject to regular and frequent disposals of maintenance dredgings over relatively long time periods. In comparison less is known regarding the significance of impacts and the recovery processes associated with the disposal of capital dredgings that commonly involves the infrequent deposition of heterogenous material over relatively restricted time periods. Impacts and recovery processes are likely to be different to those associated with the disposal of maintenance dredgings. For example, findings suggest that capital dredgings deposited at both the Roughs Tower and Barrow-in-Furness result in the occurrence of persistent changes to seafloor substrata within the license area and this subsequently effects the composition of associated faunal communities present. Moreover, whilst the two disposal sites are geographically distinct similar species are identified as being particularly sensitive to capital disposal activities in both areas.

1. Introduction

The disposal of dredged materials around the coast of England and Wales is regulated under part 2 of the Food and Environment Protection Act 1985 (FEPA) that control all marine deposits below mean high water springs. In licensing the disposal of dredged material at sea, numerous conditions associated with the relevant national and international conventions and directives (e.g., the London Convention of 1972 (LC72), the OSPAR convention, the Environmental Impact Assessment Directive (97/11/EEC), the Habitats and Species Directive (92/43/EEC), the Wild Birds Directive (79/409/EEC) and the Strategic Environmental Assessment Directive (85/337/EEC) must be considered to determine whether likely impacts arising from the disposal are acceptable (MEMG, 2003). Additionally, the recently adopted Water Framework Directive (WFD, 2000/60/EC)), which requires that good chemical and ecological status is achieved in inland and coastal waters by 2015, and the EU Marine Strategy Framework Directive (2008/56/EC), which requires that good environmental status is achieved in EU marine waters by 2021, will influence future decisions surrounding the licensing of dredged material disposal in UK waters. Criteria considered under the various conventions and directives include the presence and levels of contaminants in the materials to be disposed of, along with perceived impacts on any sites of conservation value in the vicinity of disposal. Additionally, any potential use of the material must be considered prior to a disposal consent being issued (MEMG, 2003).

Dredging activities can largely be categorised as either maintenance or capital dredging. Maintenance dredging typically involves the periodic removal of fine material deposited as a result of natural processes (i.e. tidal currents, wave action, river flow etc.) in order to allow safe navigation into ports and harbours. Capital dredging is typically associated with the initial deepening of a channel, harbour or berthing facility or is involved with a variety of construction activities such as excavation of underwater trenches for tunnels, cables or pipelines in addition to other civil engineering works (MEMG, 2003).

The majority of studies relating to impacts and recovery associated with dredged material disposal have tended to focus on maintenance disposal operations at either coastal sites (Birchenhough et al., 2006; Bolam et al., 2006; Essink, 1999; Fredette and French, 2004; OSPAR, 2008; Rees et al., 1992; Smith and Rule, 2001; Whomersley et al., 2008), or intertidal placement sites as part of the beneficial use of dredged material (Bolam and Whomersley, 2003, 2005; Ray, 2000; Ray et al., 1994). Such studies have provided valuable insights into the impacts on the seabed (i.e., nutrient inputs, increased turbidity, enhanced sedimentation, etc.) and associated faunal communities (i.e., smothering, abrasion etc.), along with recovery rates resulting from different disposal regimes in a variety of environmental conditions. The resulting improvement in our understanding of such processes has proved essential to inform decisions relating to disposal, and in the formulation of licence conditions that may be imposed to limit any adverse consequences.

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In comparison, far less is known regarding the significance of impacts and the recovery processes associated with the marine disposal of capital dredgings. Compared with maintenance disposals, such disposal operations are generally far larger (at any one time), occur far less frequently and have low or zero levels of contamination associated with them. Therefore, in relation to the disposal of capital material, physical impacts are most likely to be dominant due to the physical nature of the material often being far less similar to that of the sediments in the receiving environment. As such, it may be inappropriate to use the information gained and conclusions reached from studies pertaining to maintenance deposition to those pertaining to capital disposal; the impacts and recovery processes are likely to be very different. Consequently, when faced with dealing with or advising on new applications for capital licences, regulatory authorities are able to draw upon a far more limited literature body or scientific understanding relative to maintenance applications. This situation is a particular concern at present in view of the pressure on ports to deepen their approach channels and berthing areas to accommodate increasing vessel draughts.

There is, therefore, an urgent need for more studies to be undertaken focusing explicitly on the impacts and recovery rates and mechanisms of capital disposal events, both within and outside the UK. In this study, we investigate the impacts associated with, and recovery of, two large and contrasting capital disposal operations along the English coast, Roughs Tower and Barrow-in-Furness. At both sites, we study the temporal changes in macrofaunal communities and sediments associated with their largest capital disposal event, and, as neither site has since been subject to deposits of comparable size, we study the consequent recovery processes.

2. Methods

2.1. Site descriptions

2.1.1. Roughs Tower

Roughs Tower disposal site is situated off the SE coast of England, in the outer Thames Estuary, at a relatively shallow depth of 10–20 m (Fig. 1). The site is characterised by moderately strong tidal currents and occasional exposure to the effects of wave action at the seabed (Rees et al., 2002). The residual drift of sediments in the vicinity of the disposal site is locally complex and largely affected by a combination of seafloor topography and the effects of wind energy though a net southward residual drift has been observed in the outer Thames region (Rees et al., 2002; Talbot et al., 1982).

The complex of licensed areas that comprise the Roughs Tower disposal site has historically received a mixture of materials arising from regular maintenance dredging of neighbouring navigational channels along with sporadic capital dredgings (Rees et al., 2002) (Fig. 2a). Additionally, sewage sludge was disposed of at Roughs Tower until 1996. Previous studies have shown that the site is highly dispersive and suspended load disperses with the dominant SW/NE tidal directions and bedload appears to move in a predominantly northerly direction (HR Wallingford, 1997). Whilst fine materials arising from the disposal of maintenance dredging are shown to disperse relatively quickly from the site, coarser gravely materials and stiff clay arising from capital disposals were shown to persist for years following placement (HR Wallingford, 1997).

A comparatively large (i.e., 24 MT) disposal of capital material comprising mainly of stiff clay with smaller amounts of gravel, sand and mud was licensed for disposal during 1998–99 (Rees et al., 2002). Since it was predicted that such a large placement would almost exceed the sites disposal capacity, it was effectively closed from all further disposal operations in 2000.

A number of conditions were attached to the capital disposal license, primarily to ensure containment of the material within the licensed site boundaries following deposition. This involved the construction of a clay and rock bund along the northern and western boundaries of the licensed site followed by gradual infilling of central regions with softer mixed sediments. Finally, a gravel layer was deposited over the western area of the license in an attempt to promote colonisation by commercially important shellfish species (Rees et al., 2002).

2.1.2. Barrow-in-Furness

The Barrow-in-Furness dredging disposal site is situated off Morecambe Bay on the NW coast of England at an approximate depth of 20 m (Fig. 1). Earlier studies have shown sediment pathways in the area to be complex but offshore transport (i.e., westerly) was dominant. Barrow-in-Furness site was commissioned during 1991 in response to the need to dispose of a large volume (8 MT in total) of mixed capital material originating from the lengthening and deepening of the access channel to Barrow docks. The material was largely comprised of silty material from the docks and dock entrances along with sand, gravel and clay from the approach channel (IMO, 2007). During subsequent years, this site has continued to receive small amounts of maintenance dredged material and occasional, small amounts of capital material (Fig. 2b).

2.2. Sample collection

2.2.1. Roughs Tower

A transect of seven stations orientated in a NE-SW direction through the disposal site (i.e., approximately along the axis of predominant tidal flow) was sampled using a 0.1 m^2 Hamon grab (Fig. 1). This sampling device has been consistently shown to be suitable for sampling sediments containing gravel and/or stiff clay (Boyd, 2002). At each station, sediments were collected for the assessment of macroinfauna and sediment particle size analysis (PSA) during years 1995, 1999, 2000–2006. Three replicates for both macrofauna and PSA were taken at each within a 100 m radius range ring around the station position. For ease of interpretation of subsequent analyses reference stations 1 and 2 (situated to the north of the disposal site) were grouped and termed NREF, stations 3, 4 and 5 (within the disposal site) were grouped and termed DISP, and reference stations 6 and 7 (south of the disposal site) were grouped and termed SREF.

2.2.2. Barrow-in-Furness

A transect of five stations was sampled at Barrow-in-Furness orientated in a westerly direction from the centre of the disposal site (Fig. 1). These stations therefore, are aligned along the principal axis of net sediment movement from the centre of the disposal site. Sediments at each station were sampled (three replicates as for Roughs Tower), using a 0.1 m^2 Day grab (most appropriate for sands and silts), for infauna during years 1991, 1993, 1996, 1999 and 2007. Samples for sediment particle size analysis (PSA) were collected only during years 1996, 1999 and 2007. During numerical analyses, stations 1 and 2 (i.e., those within the disposal site) are grouped collectively as 'DISP' and 3–5 (i.e., outside the disposal site) as 'REF.

2.3. Sample processing

Grab samples were processed according to guidelines given in Boyd (2002) and in accordance with those routinely used at a number of other dredged material disposal sites around England and Wales (Bolam et al., 2006b; Whomersley et al., 2008). A sub-sample was taken from each grab for sediment particle size analysis

Fig. 1. Map of UK showing sampling positions at Roughs Tower and Barrow-in-Furness disposal sites.

(PSA). The remaining sediments from each grab were washed over a 1 mm sieve and the >1 mm fraction retained, fixed and preserved in 4–6% buffered formaldehyde solution to help prevent dissolution of any calcereous material (i.e. mollusc shell) which may render subsequent identification of specimens more difficult.

Sediment samples for PSA were wet sieved on a 500 μm stainless steel test sieve using a sieve shaker. The >500 μm was oven dried for 12 h at 80 °C and hand sieved over a range of test sieves at 0.5 phi intervals. The sediment on each sieve was retained and weighed to the nearest 0.01 g. The <500 μm was freeze dried and weighed and a sub-sample was analysed using a Coulter LS 130 Laser-Sizer. The data from both fractions were then combined to give a full PSA breakdown for each sample. Sediments were categorised into the following size classes, gravel, coarse sand, medium sand, fine sand and silt/clay according to Folk (1954).

Macrofauna were extracted from the grab samples and preserved in 70% Industrial Methylated Spirit (IMS), a more suitable preservative for long-term storage of fixed specimens. Fauna were identified to the lowest taxonomic level possible, enumerated and weighed, after blotting, to the nearest 0.001 g. The blotted wet weights were converted to ash-free dry weight using conversion factors given in Ricciardi and Bourget (1998) and Rumohr et al. (1987). A representative reference collection was made for each set of samples collected annually.

2.4. Data analysis

2.4.1. Sediment particle analysis

Multivariate analyses of sediment particle size and macrofaunal data were carried out using version 6 of the PRIMER® software package (Plymouth Routines In Multivariate Ecological Research, Clarke and Gorley, 2006). For each disposal site a correlation based Principal Components Analysis (PCA) was applied to the sediment particle size data grouped according to the percentage of each sediment class described above. This analysis reduces the dimensionality of the multivariate space by transforming a number of potentially correlated variables into a smaller number of uncorrelated variables known as principle components. The first principal component (PC1) is the axis which maximises the variance of points projected perpendicularly onto it. The second principal component (PC2) is defined as the axis perpendicular to PC1.

2.4.2. Macrofaunal analysis

The spatial and temporal changes in macrofaunal communities were investigated using both uni- and multivariate approaches. For the former, mean species number (S – including colonials), number of individuals (N – excluding colonials), Hill's (1973) diversity and evenness indices (N1 and N2) and total ash-free dry weight (T AFDW) were calculated for each station using the raw infaunal data set. Spatial and temporal differences in mean values for each of the above variables, between stations and years, were tested for significance using a General Linear Model Analysis of Variance (ANOVA), followed by pair-wise comparisons using the Tukey–Kramer method to examine which pairs of means differed significantly. All univariate analyses were carried out using the Minitab® software package, version 15. The data were assessed for normality using the Anderson–Darling test and homogeneity of variance was checked using the Bartlett test. Any data not conforming to either of these assumptions were transformed using an appropriate transformation (Zar, 1984).

For the multivariate macrofaunal data analyses, a Bray–Curtis similarity matrix was first derived based on fourth-root transformed abundance data (colonial species excluded). Hierarchical agglomerative clustering was then performed on this similarity matrix from which non-metric multi-dimensional scaling was conducted to produce a 2-d ordination plot.

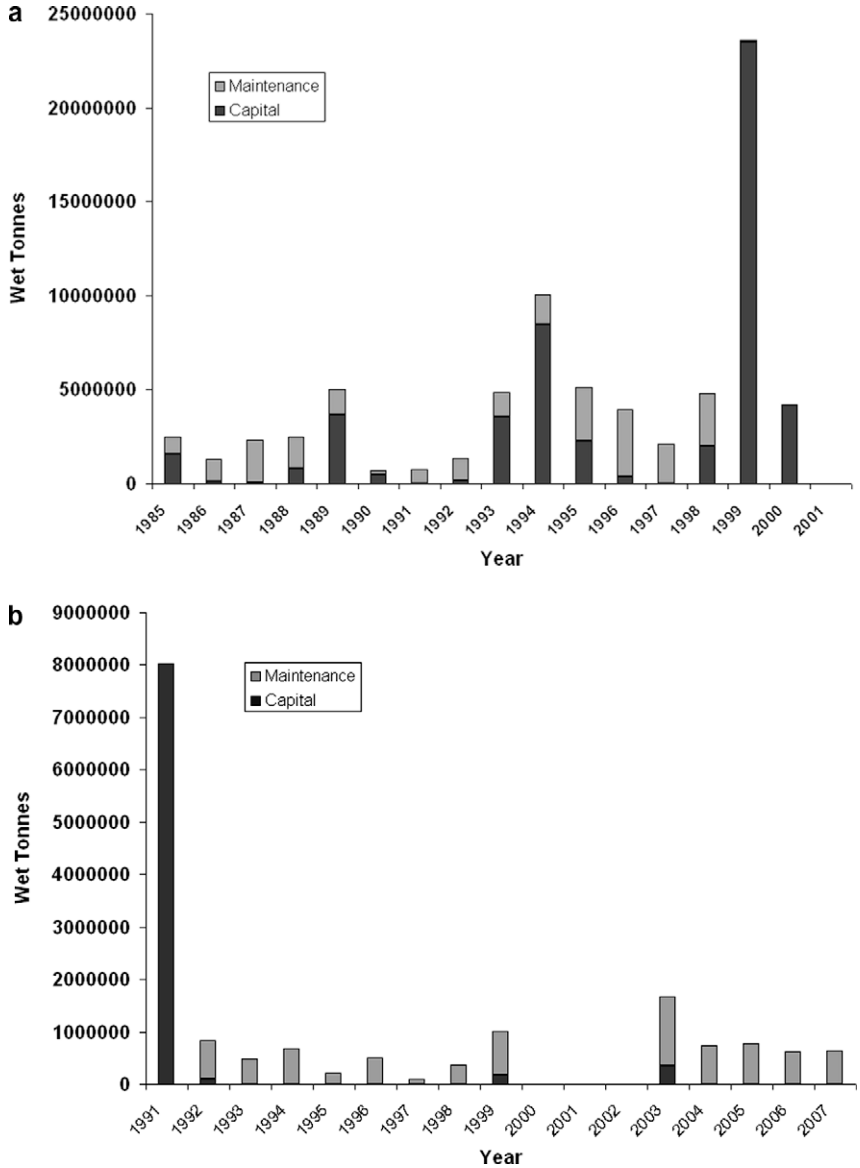

Fig. 2. Annual disposals (wet tonnes) of materials arising from capital and maintenance dredging at (a) Roughs Tower and (b) Barrow-in-Furness.

Analyses of Similarity (ANOSIM) and Index of Multivariate Seriation (IMS) were then used to explore differences in similarity of infaunal assemblages between stations and also between years at given stations. Whilst the ANOSIM was used to test between the three areas (i.e., NREF, DISP and SREF) at Roughs Tower, the IMS was employed for analyses of the data from Barrow-in-Furness as the sample design related to a gradient. Similarity Percentages (SIMPER) routine was utilised to identify which combination of species contributed most to any observed spatial or temporal patterns in macrofaunal communities.

3. Results

3.1. Roughs Tower

3.1.1. Particle size analysis

Analyses of sediment particle size composition present in samples obtained at Roughs Tower were confined to gravel, sand and silt/clay size classes, as these were the only variables consistently recorded on the more historic samples. Principal Component Analysis (PCA) indicated that, whilst the sediments in the disposal site and the surrounding areas were relatively heterogeneous there were some general spatial patterns in sediment composition (Fig. 3). Samples collected at reference stations situated to the north of the disposal site (NREF) were characterised by relatively higher sand percentages whilst samples collected from stations within the disposal site (DISP) and reference stations situated south of the disposal site (SREF) were characterised by relatively higher percentages of gravel (Fig. 3). Additionally, examination of the PSA data indicated that a sub-set of samples collected within the disposal site were characterised by relatively high percentages of silt and clay. Examination of historical timings and volumes of disposals at Roughs Tower suggest that such observations may be attributed to the relatively large volumes of capital dredgings, comprising relatively high percentages of stiff clay, deposited in the disposal site during 1994 and 1999.

3.1.2. Faunal communities

Spatial and temporal patterns relating to the univariate measures were investigated using ANOVA. Whilst the global tests indicated some significant differences were present in relation to all metrics tested (Table 1), pair-wise comparisons showed significant

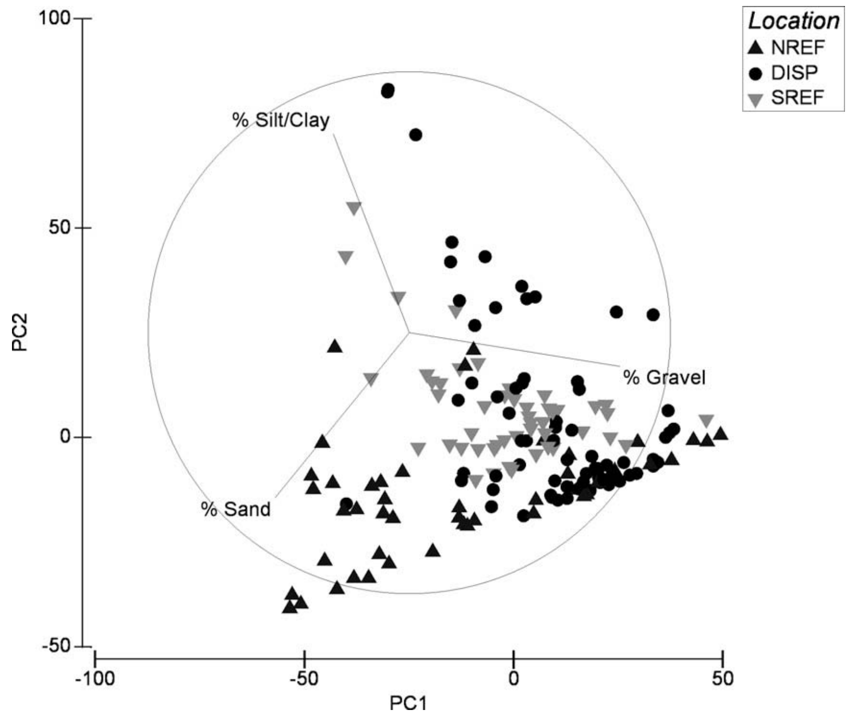

Fig. 3. Principal Component Analysis (PCA) of sediment composition data obtained from Roughs Tower. The superimposed circle illustrates the vectors of the variables relative to PC1 and PC2. The vector length reflects the importance of that variable's contribution to the two PC axes.

Table 1
Results from ANOVA comparing species number (S), number of individuals (N), diversity (N1), evenness (N2) and ash-free dry weight (AFDW) between the different areas (NREF, SREF and DISP) over time at Roughs Tower.

Metric	Factor
S	Area: $F = 14.57$, DF = 2, $P < 0.001$ Year: $F = 4.90$, DF = 8, $P < 0.001$
N	Area: $F = 12.71$, DF = 2, $P < 0.001$ Year: $F = 9.22$, DF = 8, $P < 0.001$
N1	Area: $F = 18.35$, DF = 2, $P < 0.001$ Year: $F = 7.35$, DF = 8, $P < 0.001$
N2	Area: $F = 11.26$, DF = 2, $P < 0.001$ Year: $F = 8.54$, DF = 8, $P < 0.001$
AFDW	Area: $F = 10.87$, DF = 2, $P < 0.001$ Year: $F = 1.55$, DF = 8, $P = 0.143$

differences between areas (NREF, SREFand DISP) during a given year were only present for number of species (S), number of individuals (N) and diversity (N1). Numbers of species (S) were significantly higher at the south reference area (SREF) relative to all other areas during 2001 and within the disposal site (DISP) relative to the NREF during 2004 (Fig. 4a). Examination of the underlying data indicated that the higher values of S at SREF could be attributed to greater numbers of polychaetes species during 2001. Higher numbers of species within the disposal during 2004 could be attributed to increased numbers of attached species (i.e. Actiniaria and Ascidiacea) and this may have resulted from the presence of coarse disposal materials providing suitable attachment sites.

Significantly higher numbers of individuals were identified within the disposal during 2001, relative to the NREF (Fig. 4b), and this could be attributed to peaks in the abundance of the tube-dwelling polychaete *Lanice conchilega* and the boring bivalve *Barnea parva,* a species which was found to be solely associated with the stiff clay deposits (Pers. Obs) that originated from the capital disposals. However, significantly higher numbers of individuals identified in the disposal site during 2004 resulted from increased abundances of the amphipod *Dypopedos manacanthus* and the mussel *Mytilus edulis*.

Significantly higher values of diversity (N1) were only identified at the south reference area (SREF) during 2000 and 2002 (Fig. 4c).

Multivariate analyses were performed to examine community differences between reference stations situated to the north of the disposal site (NREF), reference stations situated to the south of the disposal site (SREF) and stations inside the disposal site (DISP), and to determine whether any spatial patterns in community characteristics of faunal communities persist over time. Results indicated that no significant differences in macrofaunal communities were apparent between stations located in the disposal site and those situated in the reference areas during 1995 (ANOSIM test statistic $R = 0.102$, $P = 0.117$). However, significant differences in macrofaunal communities were detected between stations situated in the disposal site, relative to those situated in both the north and south reference areas during 1999 (Table 2) (Fig. 5). This coincided with the timing of largest annual volume of capital disposal experienced at this disposal site during the period it was licensed (Fig. 2a). SIMPER results indicated that this was primarily because of decreased abundances of the bivalves *Abra alba* and *Nucula nucleus* within the disposal site relative to both reference areas (Table 3). During 2000–2005 faunal communities in all three locations differed significantly from each other. In 2006, the ANOSIM test indicated that macrofaunal communities sampled in the disposal site were no longer significantly different from those sampled in the southern reference stations (Table 3) (Fig. 5). This observation resulted from the fact that the faunal communities of both areas had characteristically high abundances of a number of epifaunal taxa associated with coarse substrates (e.g., Actinaria and Ascidiacaea) and relatively high abundances of the bivalve *A. alba* and the amphipod *Dypoedos monacanthus* (Table 3). Significant differences did, however, persist between stations situated in the disposal site and those located to the north of the disposal site (Table 2, Fig. 5).

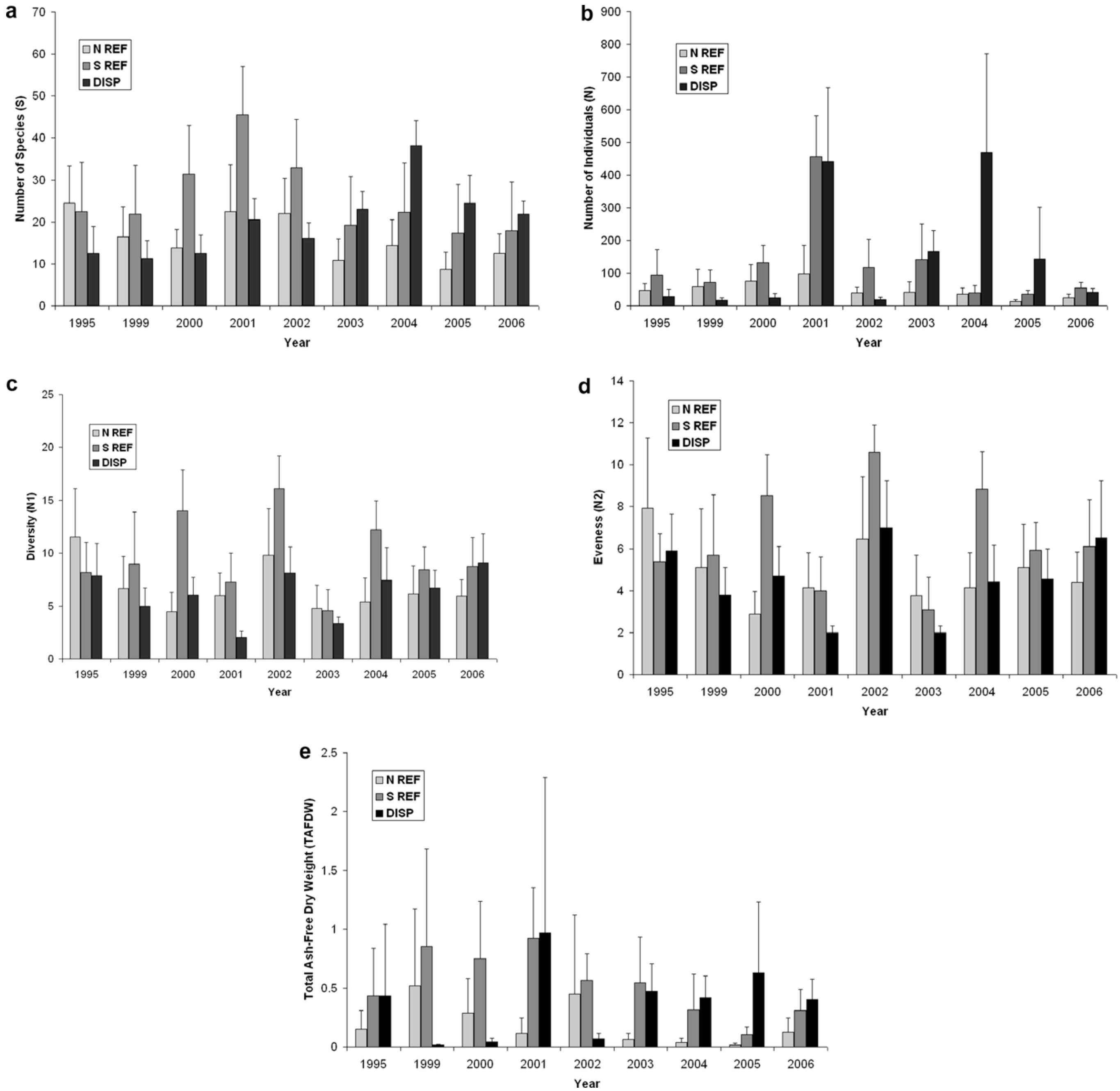

Fig. 4. Mean numbers of species (a), numbers of individuals (b) and diversity (c), evenness (d) and ash-free dry weight (e) in samples collected within and outside the Roughs Tower disposal site.

The observed dissimilarity in patterns of change over time between the disposal and the two reference locations (Fig. 5) further supports the likelihood that temporal shifts in community composition within the disposal site are most probably in response to the disposal activity as opposed to any natural variations in community composition.

3.2. Barrow-in-Furness

3.2.1. Particle size analysis

At Barrow-in-Furness, PSA data was only available for the final three surveys, i.e., during 1996, 1999 and 2007. Sediment particle size class data (i.e. % gravel, % coarse sand, % medium sand, % fine sand and % silt/clay) indicated that spatial patterns were apparent (Fig. 6). The majority (88.7%) of this variation could be explained by PC1 and PC2 (Fig. 6). The variability of the sediments collected from stations within the disposal site were generally greater than those collected from the reference stations (Fig. 6). Samples collected from stations within the disposal site were characterised by relatively high percentages of medium and coarse sand and gravel whilst those collected from reference sites were less heterogeneous and were largely comprised of fine sand.

3.2.2. Faunal communities

Patterns relating to the univariate measures of macrofaunal community structure were investigated using ANOVA. Significantly higher values of number of species (S) and number of individuals (N) were consistently present at stations located in the

Table 2
R values derived from ANOSIM tests for differences in macrofaunal assemblages at northern reference stations (NREF), southern reference stations (SREF) and within the Roughs Tower disposal site (DISP) during years 1995, 1999, 2000–2006.

Year	DISP vs. N REF	DISP vs. S REF	N REF vs. S REF
1995	0.135	−0.017	0.278*
1999	0.318*	0.459**	0.151
2000	0.414**	0.735**	0.709**
2001	0.336**	0.284*	0.469**
2002	0.363**	0.587**	0.506**
2003	0.723**	0.367*	0.433**
2004	0.749**	0.641*	0.676**
2005	0.863**	0.391**	0.757**
2006	0.564**	0.168	0.188*

* Denotes significant differences at $P < 0.05$.
** Denotes significant differences at $P < 0.01$.

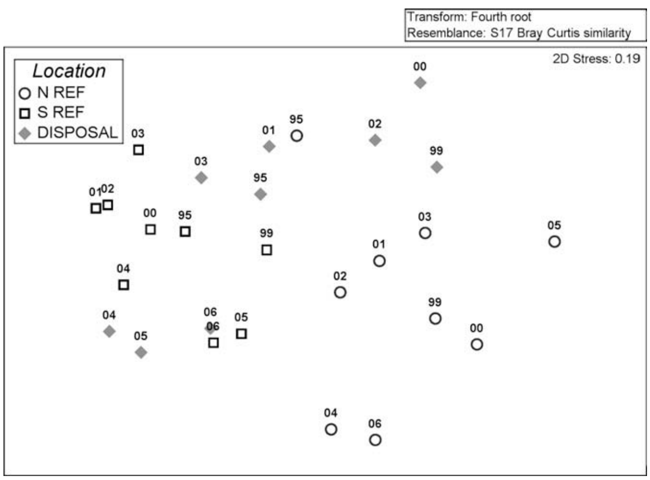

Fig. 5. MDS ordination of Bray–Curtis similarities from 4th root transformed Roughs Tower macrofauna data, with replicates averaged across year for each area. Numbers indicate the year of sampling and symbols refer to the location in relation to the disposal site (N REF = North Reference, S REF = South Reference, DISPOSAL = Disposal Site).

reference area relative to those inside the disposal during all sampling occasions (Table 4, Fig. 7a and b). Significantly higher values of diversity (N1) and evenness (N2) were identified at stations within the disposal during years 1999 and 2007 only (Table 4, Fig. 7c and d). Significantly higher values of ash-free dry weight (AFDW) were present at reference sites during all years excluding 1991 (Table 4, Fig. 7e).

As the transect at Barrow-in-Furness represents a gradient of increasing distance away from the disposal site (i.e., increasing distance from the potential disturbance), the serial pattern of community structure was examined using the Primer routine Index of Multivariate Seriation (IMS). This test result indicated that a significant gradient occurred along the transect during all years sampled with strongest gradients identified during 1991, 1999 and 2007 (Table 5). Such findings could be attributed to the relative abundances of a sub-set of species along the transect. For example, the taxa characterising the communities inside the disposal site were exclusively polychaetes (except during 1996 and 2007 when variations in successful recruitment of *Mytilus edulus* were also responsible for community differences) while a number of bivalve species (i.e. *A. alba*, *Nucula nitidosa*, *Thracia* sp. and *Mysella bidentata*) were also responsible for characterising the communities outside of the disposal area (Table 6).

Temporal patterns in macrofaunal communities at individual stations were also examined; the resulting Multi-dimensional Scaling (MDS) ordination indicated that temporal patterns were different at stations located in the disposal site relative to those situated outside the disposal site (Fig. 8). Whilst temporal changes in community structure follow similar trends at stations located outside the disposal site (i.e. 3, 4 and 5) progressing to the right of the plot over time, those stations situated within the disposal site were less consistent. Additionally, the magnitude of temporal change exhibited by the disposal site communities was greater. Finally, community changes between 1999 and 2007 were consistent in all stations, resulting in a significant move towards the bottom of the plot perhaps indicating that the communities at all stations were responding to a common influence during this time period.

4. Discussion

4.1. Impacts of the disposal of capital material on infaunal communities

Whilst considerations governing the disposal of maintenance and capital materials have some similarities (i.e. volume of material deposited, timescale of disposal, etc.), generalities or conclusions reached regarding the impacts of maintenance dredged material disposal may not be applied unequivocally to those for capital events. Changes in macrofaunal community composition resulting from the former may be attributable to changes in sediment particle size composition (Somerfield et al., 1995), reduced food intake of filter feeding organisms due to increased concentrations of suspended particle matter (Essink, 1999; Essink and Bos, 1985; Widdows et al., 1979), smothering (Essink, 1999; Bolam and Whomersley, 2005) or increases in the concentration of contaminants (Somerfield et al., 1995). However, an assessment of the ecological consequences of the disposal of dredged material (including capital and maintenance) at sites around the coastline of England and Wales carried out by Bolam et al. (2006b) showed that whilst the communities within the disposal sites were generally faunistically impoverished, the degree of impact was largely site-specific. A number of factors were found to contribute to the site-specific nature of impacts and these included variability between disposal sites in terms of their environmental conditions (hydrodynamic regimes, habitat type in the receiving environment), natural variability of associated faunal communities along with variability in the nature of the disposal activity (material type, frequency, volume, timing). Thus, when comparing the impacts associated with the disposal of capital and maintenance dredgings, differences in the nature of the receiving site and the materials disposed of are likely to result in differences with respect to both the severity and longevity of impacts.

It may be expected that initial impacts associated with the disposal of both maintenance and capital dredgings present themselves in a similar way, in that the immediate effects on the receiving substrate, and its associated fauna, are likely to be a result of smothering. Subsequently, this is likely to result in a general reduction in species number, density of individuals and overall biomass within the disposal site. Such an effect was true for both sites included in this study in that species number, number of individuals and total ash-free dry weight were observed to be lower within the disposal sites and differences in these measures between the disposal and reference areas were most pronounced during or shortly after disposal. Furthermore, multivariate techniques identified that similar taxa were the main contributors to observed community differences between disposal and reference areas at both disposal sites. Most notably, these included the bivalve species *Nucula* sp. and *A. alba*. Reductions in numbers of these bivalve species following capital disposal events may be attributed to their preference for substrates characterised by fine sediments (Degraer

Table 3
Results from SIMPER analysis of Roughs Tower macrofauna data. Cumulative percentage (Cum. %) of characterising species is shown.

Year	N REF		S REF		DISP	
	Species	Cum. %	Species	Cum. %	Species	Cum. %
1995	*Lanice conchilega*	30.6	*Abra alba*	27.1	*Lanice conchilega*	27.6
	Glycera lapidum	40.2	*Lanice conchilega*	40.8	*Spiophanes bombyx*	44.8
	Nymphon brevirostris	47.2	*Notomastus*	51.5	*Notomastus*	56.9
	Mytilus edulis	53.4				
1999	*Spiophanes bombyx*	18.9	*Abra alba*	25.1	*Bathyporeia elegans*	38.6
	Scoloplos armiger	30.6	*Actiniaria*	36.9	*Lanice conchilega*	56.6
	Abra alba	42.2	*Lumbrineris gracilis*	46.4		
	Ophelia borealis	53.2	*Aphelochaeta marioni*	54.6		
2000	*Abra alba*	19.2	*Abra alba*	10.8	*Scalibragma inflatum*	45.2
	Goodallia triangularis	32.7	*Actiniaria*	20.9	*Bathyporeia elegans*	53.6
	Nucula nucleus	45.5	*Scalibragma inflatum*	30.2		
	Goniada maculata	53.1	*Lanice conchilega*	38.3		
			Lumbrineris gracilis	45.3		
			Nemertea	52.3		
2001	*Lanice conchilega*	23.7	*Lanice conchilega*	15.8	*Lanice conchilega*	37.4
	Goniada maculate	35.9	*Sabellaria spinulosa*	25.6	*Dypopedos monacanthus*	50.1
	Abra alba	45.6	*Abra alba*	35.3		
	Scoloplos armiger	54.0	*Dyopedos monacanthus*	42.3		
			Lumbrineris gracilis	49.0		
			Harmothoe impar	54.7		
2002	*Scoloplos armiger*	21.1	*Actiniaria*	10.1	*Notomastus*	24.8
	Abra alba	36.7	*Lumbrineris gracilis*	19.5	*Scoloplos armiger*	44.0
	Bathyporeia elegans	49.6	*Scoloplos armiger*	27.9	*Abra alba*	57.9
	Nucula nucleus	57.6	*Nemertea*	36.2		
			Mysella bidentata	43.0		
			Abra alba	48.7		
			Nereis longissima	53.1		
2003	*Scoloplos armiger*	34.6	*Lanice conchilga*	19.2	*Lanice conchilega*	31.4
	Lagis koreni	56.4	*Lumbrineris gracilis*	35.5	*Actiniaria*	45.2
			Lagis koreni	44.6	*Spiophanes bombyx*	54.4
			Sabellaria spinulosa	52.7		
2004	*Abra alba*	36.8	*Nemertea*	18.6	*Dyopedos monacanthus*	13.7
	Notomastus	51.3	*Glcera alba*	29.7	*Actiniaria*	26.5
			Notomastus	39.9	*Mytilus edulis*	36.5
			Aphelochaeta sp.	46.7	*Abra alba*	44.3
			Dyopedos monacanthus	53.2	*Notomastus*	51.1
2005	*Ophelia borealis*	38.9	*Nemertea*	18.8	*Actiniaria*	24.5
	Scoloplos armiger	70.6	*Lumbrineris gracilis*	35.4	*Abra alba*	38.7
			Dyopedos manacanthus	47.5	*Dyopedos monacanthus*	51.1
			Abra alba	59.6		
2006	*Abra alba*	33.2	*Abra alba*	25.0	*Actiniaria*	23.3
	Nucula nucleus	54.6	*Nucula nucleus*	33.0	*Dyopedos monacanthus*	39.5
			Sabellaria spinulosa	40.4	*Nemertea*	48.9
			Notomastus	47.2	*Ampelisca spinipes*	58.4
			Actiniaria	53.7		

et al., 2006; Hayward and Ryland, 1990) along with their sensitivity to smothering and increased concentrations of suspended particle matter (Essink, 1999).

4.2. Recovery of infaunal communities following disposal of capital dredgings

Whilst the results of this study support the findings that initial impacts of dredgings disposal generally result in an associated impoverished faunal community it is perhaps during the recovery phase that variability in the receiving environment and disposal regime have the greatest influence in terms of recovery potential and rate of recovery (Bolam and Rees, 2003).

The temporal dataset acquired at Roughs Tower allowed a longer period of potential recovery (2000–2006) to be examined during which no disposal activities occurred following closure of the site in 1999. Patterns of recovery at the Roughs Tower disposal site are slightly complicated by the licence condition that required containment of materials through construction of a bund along the northern and western edges of the disposal site along with a gravel seeding treatment to be applied to the south-west region of the licensed area following its relinquishment. At Barrow-in-Furness, any assessment of recovery processes following the capital deposit in 1991 must appreciate any potential impacts associated with the continued deposits of small volumes of maintenance dredged material during subsequent years.

Evidence of recovery of infaunal communities was more pronounced within the Roughs Tower disposal site than within that of Barrow-in-Furness. For example, values of species number, number of individuals and ash-free dry weight were generally higher within the Roughs Tower disposal site, relative to the reference areas, from 2003 onwards. Moreover, during 2001, peak abundances of annelids were observed in samples collected within the disposal site. This was relatively soon after the largest capital disposal this area had ever received and was shown to be attributable to relatively high numbers of individuals belonging to the tube-dwelling polychaete species *L. conchilega*. This observation was also reported by Rees et al. (2002) whose study suggested that

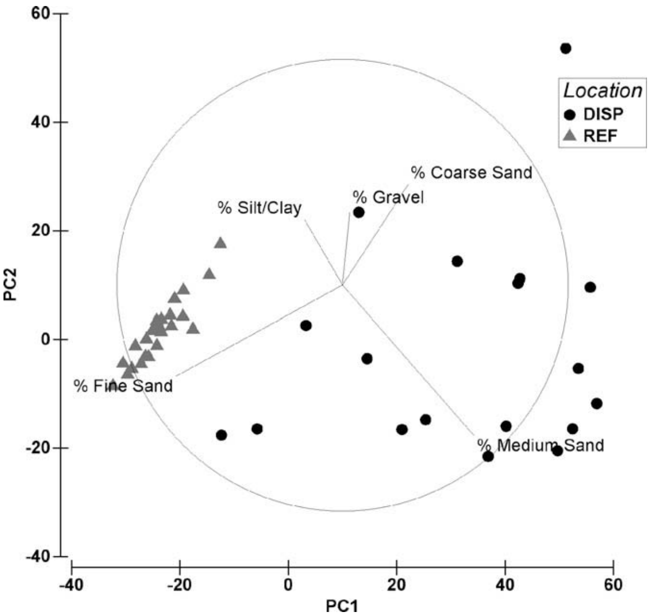

Fig. 6. Principal Component Analysis (PCA) of sediment composition data of samples collected at Barrow-in-Furness. The superimposed circle illustrates the vectors of the variables relative to PC1 and PC2. The vector length reflects the importance of that variable's contribution to the two PC axes.

Table 4
Results from ANOVA comparing species number (S), number of individuals (N), diversity (N1), evenness (N2) and ash-free dry weight (AFDW) between stations inside and outside the Barrow-in-Furness disposal during different years.

Metric	Factor
S	Inside vs. outside: $F = 188.49$, DF = 1, $P < 0.001$ Year: $F = 4.46$, DF = 4, $P = 0.003$
N	Inside vs. outside: $F = 222.84$, DF = 1, $P < 0.001$ Year: $F = 0.52$, DF = 4, $P = 0.718$
N1	Inside vs. outside: $F = 39.93$, DF = 1, $P < 0.001$ Year: $F = 3.94$, DF = 4, $P = 0.006$
N2	Inside vs. outside: $F = 10.93$, DF = 1, $P = 0.002$ Year: $F = 6.20$, DF = 4, $P < 0.001$
AFDW	Inside vs. outside: $F = 77.21$, DF = 4, $P = 0.009$ Year: $F = 77.21$, DF = 4, $P = 0.009$

the establishment of adult populations of this species may aid recovery within the disposal site through the encouragement of colonisation by other species resulting from its ability to stabilise sediments (Callaway, 2006; Eagle, 1975). It should also be noted that relatively high numbers of *L. conchilega* were also reported during 2000 at a station situated in close proximity to Roughs Tower sampled as part of the ICES Study Group on the North Sea benthos Project 2000 (Eggleton et al., 2007). Therefore, it may be that natural population fluxes operating in the area over this time period, along with the ability of this species to re-colonise areas rapidly following disturbance (Nicolaidou, 2003; Zühlke, 2001), resulted in the observed high settlement on sediment types favoured by this species (i.e. medium grained sand with relatively high mud content) that were present within the disposal site. Rees et al. (2002) suggested that this may be a good indication that the environment of the disposal site is sufficiently benign, following cessation of disposal activities, to allow successful re-colonisation by certain species.

Investigations of community patterns within the Roughs Tower disposal site and surrounding reference areas indicated that infaunal communities within the relinquished disposal site became more similar to those present in the reference area to the south of the disposal site. This could be attributed to both areas being characterised by relatively higher numbers of individuals belonging to the groups Actiniaria and Ascidiacea along with relatively high numbers of the epibenthic amphipod species *Dyopedos monacanthus*. The increased similarity between faunal communities inhabiting the relinquished disposal site and the more gravely southern reference area is likely to have resulted from gravel seeding within the disposal site, along with enhanced retention of the coarser disposal material by the bund, rendering sediments in this area much coarser and providing suitable attachment sites for certain colonial epifauna.

Additionally, the presence of the boring bivalve *B. parva* was only recorded at stations situated within the Roughs Tower disposal site following the capital disposal event. This could be attributed to the presence of stiff clays arising from capital disposals with which this species is associated.

Impacts associated with the large capital disposal at Barrow-in-Furness resulted in a persistent reduction in numbers of species and individuals within the disposal area. This could be attributed to higher abundances of certain bivalves (i.e., *N. nitidosa*, *A. alba* and *Spisula subtruncata*) and polychaete species (i.e., *Nephtys* sp., *Spiophanes bombyx* and *Scalibregma inflatum*), naturally abundant within this area, becoming restricted to stations outside the disposal site following capital disposal. These taxa are generally associated with fine sand which naturally characterise the sea bed in this region (Degraer et al., 2006). The disposal of coarser sediments within the disposal site, and the inability of bottom currents to subsequently transport such sediments, rendered the disposal area unsuitable for colonisation by the majority of surrounding taxa. However, in 2007 certain species, including the mussel *M. edulis*, were relatively more abundant within the disposal site, possibly due to the presence of the coarser, deposited sediments providing a more favourable habitat for spat settlement. Furthermore, as mussels are generally sensitive to smothering following maintenance dredged material disposal, the prevalence of this species within the disposal site perhaps suggests that negative effects arising as a consequence of the ongoing maintenance dredgings disposal are minimal.

4.3. Implications for licensing of capital projects

This study highlights that whilst the activities of both maintenance and capital dredgings disposal have certain parallels, they also differ substantially in terms of disposal regime, associated impacts on both substrates and faunal communities and subsequent recovery patterns. Informed decisions regarding disposal site location (i.e., using information regarding sediment characteristics, local hydrodynamics, dispersive capacity, etc.) have been proven to minimise long-term impacts on the seafloor and associated faunal communities resulting from disposal of maintenance dredgings (Bolam and Rees, 2003; Roberts and Forrest, 1999; Smith and Rule, 2001; Van Dolah et al., 1984). However, results of this study suggest that the potential for dispersal (or erosion via sediment bedload transport processes) of materials arising from capital dredging operations is reduced due to the physical nature of the material (i.e. coarse gravel and stiff clay). This notion is supported by our observations at both Roughs Tower and Barrow-in-Furness by the persistently altered sediment characteristics present in the disposal sites following capital disposal. Therefore, in the case of capital dredgings disposal, the dispersive capacity of the licensed site may be less of a consideration than the potential consequences of shoaling and the similarity between sediment characteristics of the receiving environment and the disposal material. Increased similarity between the disposal material and the substrate present

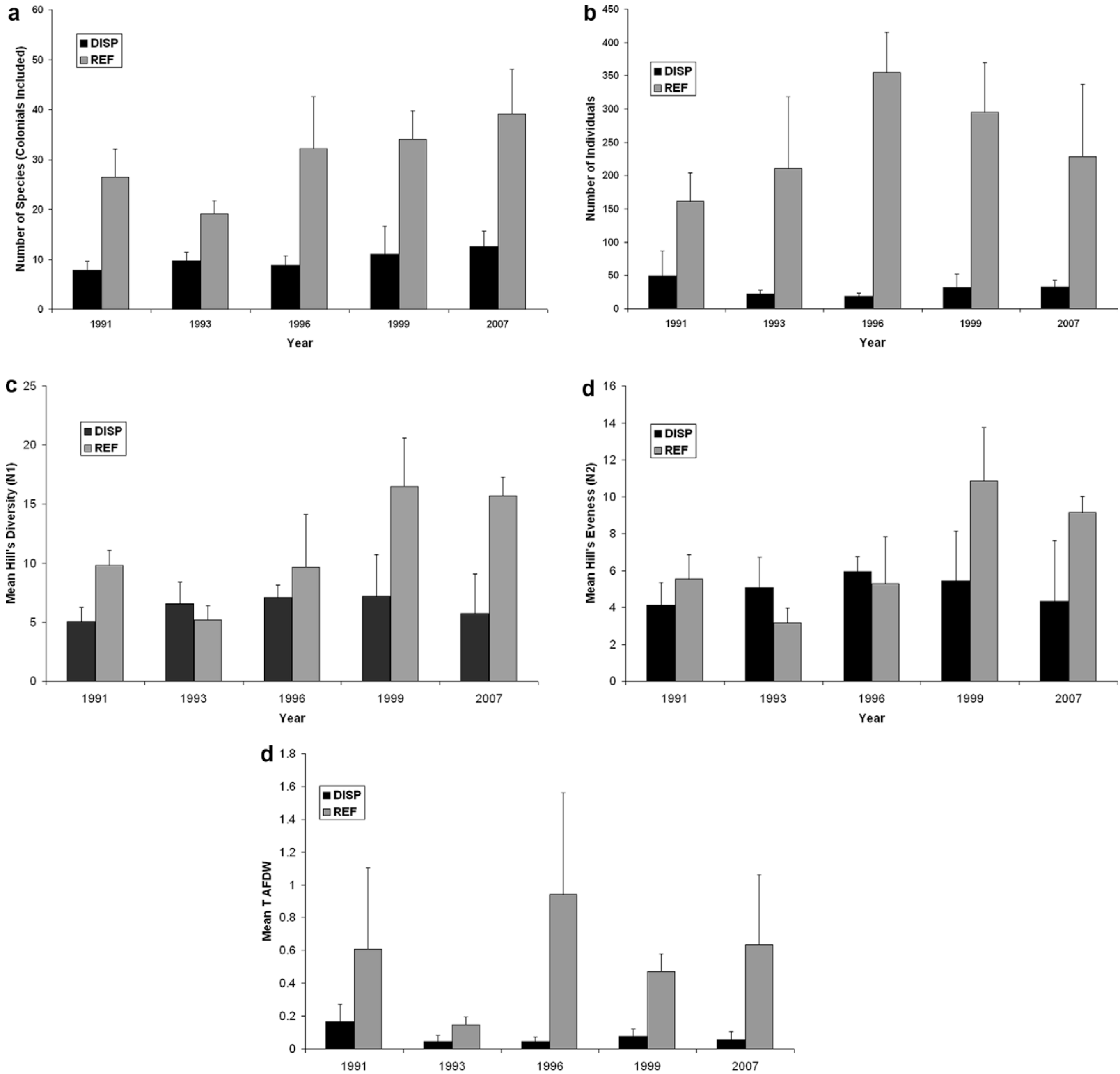

Fig. 7. Mean numbers of species (a), numbers of individuals (b), diversity (c), evenness (d) and AFDW (e) in samples collected within and outside the Barrow-in-Furness disposal site.

Table 5
Results of the Index of Multivariate Seriation (IMS) applied to macrofauna data collected at Barrow-in-Furness.

Year	Index of multivariate seriation
1991*	0.715 (0.1%)
1993	0.492 (0.1%)
1996	0.652 (0.1%)
1999*	0.772 (0.1%)
2007	0.788 (0.1%)

* Indicates years when disposal of capital dredgings occurred.

in the selected licensed site (e.g., Roughs Tower) is likely to minimise alterations to the seafloor substrate and thus allow the re-establishment of a faunal community more similar to that present prior to any disposal activity.

Whilst no inferences were made from this study regarding the effectiveness of the gravel treatment at Roughs Tower in enhancing the local shellfish fishery, as was the intention of the original licence conditions, the gravel treatment does appear to have resulted in the re-establishment of a faunal community within the disposal site that is very similar to that present in the un-impacted gravelly reference area to the south-west of the disposal site. Whilst we are unable to determine whether the re-established faunal community in the disposal site resembles that present before to disposal activities commenced (due to the absence of baseline sediment and faunal data) it may be surmised that disposal activities at this site have not resulted in any permanent detrimental

Table 6
Results from SIMPER analysis of Barrow-in-Furness macrofauna data. Cumulative percentage (Cum. %) of characterising species is shown.

Year	Inside disposal site		Outside disposal site	
	Species	Cum. %	Species	Cum. %
1991	*Magelona filiformis*	29.7	*Nucula nitidosa*	16.8
	Nucula nitidosa	55.2	*Magelona filiformis*	28.0
			Spiophanes bombyx	38.0
			Nephtys caeca	45.9
			Eteone longa	53.4
1993	*Nephtys caeca*	28.1	*Abra alba*	17.2
	Scalibregma inflatum	51.1	*Nucula nitidosa*	31.5
			Spiophanes bombyx	41.5
			Nephtys caeca	49.7
			Nephtys pente	56.9
1996	*Nephtys caeca*	33.5	*Nucula nitidosa*	13.9
	Nemertea	54.5	*Spisula subtruncata*	24.9
	Mytilus edulis	60.0	*Abra alba*	33.2
			Nephtys caecaOphiura albida	39.7
			Spiophanes bombyx	45.9
				51.9
1999	*Nephtys caeca*	32.5	*Abra alba*	9.4
	Spiophanes bombyx	61.6	*Spisula subtruncata*	18.2
			Nucula nitidosa	26.2
			Spiophanes bombyx	33.9
			Thracia phaseolina	40.9
			Ophiura albida	47.1
			Owenia fusiformis	52.7
2007	*Mytilus edulis*	38.2	*Nucula nitidosa*	9.8
	Nephtys cirrosa	58.3	*Lumrineris gracilis*	16.6
			Spiophanes bombyx	22.7
			Amphiuridae	28.7
			Phoronis	33.8
			Sthenelais limicola	38.4
			Magelona johnstoni	42.9
			Nephtys homberg	47.2
			Mysella bidentata	51.5

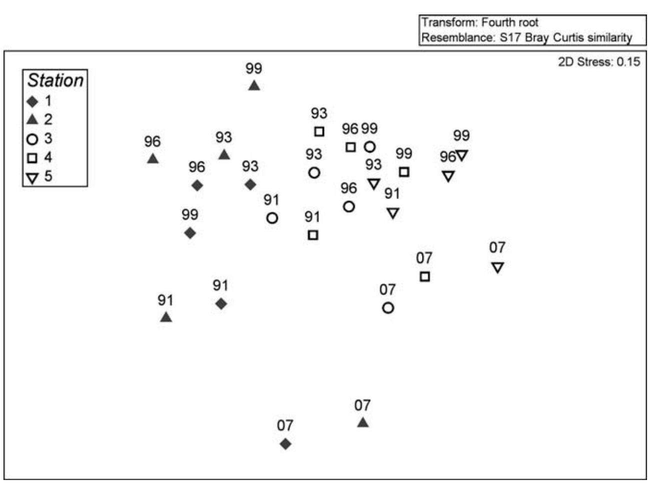

Fig. 8. MDS of Bray–Curtis similarities from 4th root transformed barrow-in-Furness macrofauna data, with replicates averaged across year for each station. Numbers indicate the year of sampling and symbols refer to the station number.

changes that have prevented re-colonisation of a community that is representative of the wider un-impacted environment. Conversely, the greater dissimilarity at Barrow-in-Furness between the materials arising from the capital dredgings disposal (i.e., rock, coarse gravel and stiff clay) and the sediments characteristic of the wider environment (i.e., fine sand) have resulted in more persistent effects of the disposal being evident at this site. However, it must be noted that post-disposal data for this site is more temporally restricted when compared with the Roughs Tower data set. Moreover, the Barrow-in-Furness disposal site remains active and thus investigations into potential recovery patterns at this site may be confounded by ongoing disposal operations.

Finally, this study has further supported the view that the disposal of dredged material does not necessarily result in barren areas of seabed that are devoid of life. As is often observed for maintenance dredged material disposal activities (Rhoads et al., 1978; Bolam et al., 2006b), impacts on benthic communities are often seen to be mere alterations to macrobenthic community structure and function, the magnitude of such alterations are often minimal where tight licence conditions have been imposed. As this study has importantly demonstrated, this applies to instances where the amount of material disposed is very significant, 24 MT for example (Roughs Tower). Of course, implicit within this is that an appreciation of the current understanding of impacts, and how these are affected by mitigation measures (or licence conditions) must be maintained in the design of such disposal projects.

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