MONITORING AND ASSESSMENT OF THE MARINE ENVIRONMENT

Implications of dredging induced changes in sediment particle size composition for the structure and function of marine benthic macro-faunal communities

Submitted by the United Kingdom

SUMMARY

Executive summary: The annex to this document contains a recently published article on the implications of dredging induced changes in sediment particle size composition for the structure and function of marine benthic macro-faunal communities.

Action to be taken: Paragraph 3

Related document: LC/SG 35/INF.2

Introduction

1 The annex to this document contains a recently published article entitled "Implications of dredging induced changes in sediment particle size composition for the structure and function of marine benthic macro-faunal communities". The article was published in the journal Marine Pollution Bulletin (2011) 62, 2087-2094 and authored by K.M. Cooper et al.

2 The publication is considered relevant to the Scientific Groups' assessment of the monitoring activities related to dumping operations in accordance with article 9 of the London Protocol.

Action requested of the Scientific Groups

3 The Scientific Groups are invited to take note of the information provided and comment, as they deem appropriate.

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Implications of dredging induced changes in sediment particle size composition for the structure and function of marine benthic macrofaunal communities

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ABSTRACT

A meta-analysis approach was used to assess the effect of dredging induced changes in sediment composition, under different conditions of natural physical disturbance, for the structure and function of marine benthic macrofaunal communities. Results showed the sensitivity of macrofaunal communities increased as both the proportion of gravel increased and the level of natural physical disturbance decreased. These findings may be explained by the close association of certain taxa with the gravel fraction, and the influence of natural physical disturbance which, as it increases, tends to restrict the colonisation by these species. We conclude that maintaining the gravel content of surface sediments after dredging and, where practicable, locating extraction sites in areas of higher natural disturbance will minimise the potential for long term negative impacts on the macrofauna.

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1. Introduction

Marine aggregate dredging has the potential to lead to changes in the composition of seabed sediment habitats (Sanda et al., 2000; van Dalen et al., 2000). These changes can occur in four ways. Firstly, as a result of sediment screening, whereby unwanted sediment fractions (usually sands) are returned to the seabed (Hitchcock and Drucker, 1996; Newell et al., 1998, 2004). Secondly, as a result of the 'filling' of dregge depressions and furrows with fine sediments (Dickson and Lee, 1972; Kenny et al., 1998; Boyd et al., 2002). Thirdly, as a result of 'overspill', where fine sediments, in suspension, are lost through chutes in the side of the dredger hold as the cargo is loaded (Newell et al., 1998). Fourthly, as a result of the exposure of underlying sediments which are different in nature to the original substrata (Kenny and Rees, 1996; Cooper et al., 2007). Material rejected by screening and overspill may also accumulate outside the boundaries of the extraction site, depending on local hydrodynamic conditions (Poirier and Kennedy, 1984; Hitchcock and Drucker, 1996; Newell et al., 2004; Cooper et al., 2006).

Changes in sediment composition can have implications for resident and recolonising fauna, resulting in the establishment of a faunal community that differs from the assemblage present before the dredging (Despere, 2000; Boyd et al., 2002, 2005; Barrio Froján et al., 2011). Recognising the potential for such changes, Government policy (ODPM, 2002) requires developers to leave the seabed in a similar physical condition to that present prior to dredging. This measure is designed to enhance the possibility of, and rate at which, the seabed recovers physically and biologically to its pre-dredged condition. Whilst this policy has a clear scientific justification and is consistent with the principle of sustainable development, two important questions arise. Firstly, how can we decide what does, and does not, constitute an acceptable 'similar' physical condition? Secondly, how important is the preservation of sediment granulometry for faunal recovery in different localities? This question arises given the results from Kenny et al. (1991) and Rees et al. (1999), working at dredge sites off the east coast of the UK. They identified a combination of totally induced sediment mobility and the abrasive effects of sand in suspension as important factors influencing benthic communities, and not simply sediment granulometry. The importance of sediment stability in controlling community structure is also highlighted in Newell et al. (1998). In addition, Seidler and Newell (1998), Newell et al. (2001) and Cooper et al. (2007) all reported the lack of a close correspondence between the distribution of different sediment types and benthic communities observed in the vicinity of marine aggregate dredging sites in areas of high natural disturbance. For this reason, Seidler and Newell (1999) suggest that a return of sediment composition may not always be a pre-requisite for faunal recovery.

Improving our understanding of the relationship between sediment granulometry and the structure and function of macrofaunal communities is important for the management of marine

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aggregate dredging. For example, it will help identify those locations where it is more and less important to try to preserve sediment particle size composition, and hence where sediment screening should and perhaps should not be permitted. It will also help to determine whether there is a rational scientific justification for the active restoration of sediment particle size composition at sites of former marine aggregate dredging (e.g. Cooper et al., 2011a). The aim of this study was to determine to what extent changes in sediment composition, as a resulting of marine aggregate dredging, matter for the structure and function of benthic communities.

2. Methods

2.1. Data

A dataset comprising 368 samples of macrofauna and sediment particle size, from 12 individual surveys (11 sites) conducted between 2000 and 2008, was compiled for the purposes of this study. Each constituent dataset was originally collected to investigate the local impacts of marine aggregate dredging on macrofauna and sediments. All surveys included replicate samples taken from both a Reference site and one or more Treatment sites (Table 1). Reference sites were selected, typically using acoustic data, to be representative of the likely pre-dredge condition. All samples were acquired during the same survey using a 0.1 m² Hamon grab. Sub-samples were acquired for sediment particle size, with the remaining material processed for macrofauna over a 1 mm mesh sieve. Fauna were identified to the lowest level possible, usually species.

The extraction sites used in this study included actively dredged sites (Areas 106, 408, 430, 447, 351, 12273), and areas where dredging had ceased (Areas 305, 222, X, Y, Owers). For the operational sites, only samples taken from Treatment sites outside the active dredge zones were included in the analyses. Samples taken within active dredge zones were not included in subsequent analyses as dredging was likely to be the overriding influence on assemblage composition. All extraction sites included in this study have been subject to commercial dredging, typically over many years, although the intensity of dredging, tonnages extracted and dredging techniques employed vary between sites. It should be noted that two datasets from Area 222 are included in the study. Both datasets, one from 2004 and the other from 2007, relate to different stages in a process of physical and biological recovery at this site.

To account for differences in the reporting of sediment particle size, these data were reduced to percentage fractions for gravel, coarse sand, medium sand, fine sand and mud. In addition, the species list was subjected to a process of rationalisation to account for different levels of taxonomic resolution between surveys. Biomass data were available for all surveys, with the exception of Area 305.

2.2. Site classification

In a Geographic Information System, maps of surface sediment distribution and natural physical disturbance were overlaid in order to produce maps showing the distribution and disturbance class of sand and gravel dominated sediments (Fig. 1). Both input layers were taken from Flegler et al. (2011). Although, for the purposes of the current study, the disturbance map was simplified into high, medium and low disturbance. The original seven disturbance categories were derived from a cluster analysis of georeferenced data, based on the following variables: mean annual chlorophyll concentration, mean annual suspended particulate matter, frequency of sediment reworking and sediment composition. The frequency of reworking is the number of days per year that the bed is disturbed as a result of shear stress induced by waves and tidal currents.

As the aggregates industry does not target muds these sediments were not considered further. The output maps identified six sediment classes. These included high, medium and low disturbance sands, and high, medium and low disturbance gravels.

Each of the 11 sites selected for this study were then overlaid on the output maps, allowing each site to be classified according to the dominant sediment type and the level of natural physical disturbance (Fig. 2). Where site specific sediment data (see Table 1) contradicted the broadband information, then the site data were used in the classification. Area 408 was classified as 'Gravel, low disturbance', despite the sediment samples suggesting a dominance by sand, due to evidence of a gravel armouring reported in Cooper et al. (2005).

2.3. Assessment of benthic structure and function

The structure of macrofaunal communities was assessed using the species abundance data. The function of macrofaunal communities was assessed using four approaches: Somatic Production (Sp), Biological Traits Analysis (BTA), Infaunal Trophic Index (III), and the Rao coefficient (see Cooper et al., 2008 for detailed methodologies, and descriptions of the behaviour of each metric in response to marine aggregate dredging). Each of these techniques resulted in the formation of a separate multivariate dataset which was subjected to the same analyses as the species abundance data.

2.4. Data analysis

A total of six multivariate matrices were produced. These included one each for sediment composition and faunal structure, and four for faunal function (Table 2).

2.4.1. Univariate

The total number of species (S), abundance (N) and somatic production (Sp) were calculated for all samples. Differences in the mean value of each measure were compared between the different sediment disturbance classes using graphical techniques.

2.4.2. Multivariate

Multivariate analyses were performed using PRIMER 6" (Clarke and Warwick, 1994). ANOSIM tests were used in order to determine the extent of any difference between each Treatment/Reference site pairing identified in Table 1, based on the six multivariate datasets listed in Table 2. A mean of the four functional ANOSIM R values was produced to represent faunal function in subsequent analyses. The R statistic from this test provides a measure of the similarity between two or more groups of samples. An R value of 0 indicates no difference between the groups, whilst an R value of 1 indicates a complete difference.

Based on each Treatment/Reference comparison, we then assessed the apparent sensitivity of faunal assemblages to changes in sediment particle size composition, using a weighted sensitivity index (wSI). Values of the index were calculated for both structural and functional sensitivity using the equations below.

\[
wSI = \frac{R(\text{structure})^2}{R(\text{psa})} \quad \text{and} \quad wSI = \frac{R(\text{function})^2}{R(\text{psa})}
\]

The index is simply the ratio of the squared ANOSIM R value for faunal structure or faunal function, to the ANOSIM R value for sediment particle size data. Squaring the faunal R value increases the
<table>
<thead>
<tr>
<th>Survey</th>
<th>Site</th>
<th>Year (study reference)</th>
<th>Years since last dredged</th>
<th>No. of samples</th>
<th>Sediment: Disturbance</th>
<th>Treatment(s)</th>
<th>Reference sample particle size composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humber</td>
<td>Area 408</td>
<td>2004 (Cooper et al., 2005)</td>
<td>5</td>
<td>30</td>
<td>Gravel - Low disturbance</td>
<td>H (10)</td>
<td>R (10)</td>
</tr>
<tr>
<td></td>
<td>Area 305</td>
<td>2003 (Neveu et al., 2004)</td>
<td>0</td>
<td>56</td>
<td>Sand - Medium disturbance</td>
<td>High Intensity North (10)</td>
<td>Control (20)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>North 100 m (4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>North 250 m (4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>North 750 m (4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>North 1250 m (4)</td>
<td></td>
</tr>
<tr>
<td>East Coast</td>
<td>Area 408</td>
<td>2003 (Neveu et al., 2004)</td>
<td>0</td>
<td>78</td>
<td>Sand - Medium disturbance</td>
<td>North East Block (12)</td>
<td>Control (20)</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>High Intensity North (10)</td>
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<td></td>
<td>North 100 m (4)</td>
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<td></td>
<td>North 4250 m (4)</td>
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<td>Thames</td>
<td>Area 305</td>
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<td>3</td>
<td>15</td>
<td>Sand - High disturbance</td>
<td>H (10)</td>
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<td></td>
<td>Area 222</td>
<td>2004 (Cooper et al., 2005)</td>
<td>7</td>
<td>30</td>
<td>Gravel - Medium disturbance</td>
<td>L (10)</td>
<td>R (10)</td>
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<tr>
<td></td>
<td>Area 222</td>
<td>2002 (van Horne et al., in press)</td>
<td>10</td>
<td>30</td>
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<td>L (10)</td>
<td>R (10)</td>
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<tr>
<td></td>
<td>Area 224</td>
<td>2008 (Ferre et al., 2011)</td>
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<td>22</td>
<td>Gravel - High disturbance</td>
<td>L (10)</td>
<td>R (10)</td>
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<tr>
<td></td>
<td>Area X</td>
<td>2004 (Cooper et al., 2005)</td>
<td>2</td>
<td>30</td>
<td>Gravel - High disturbance</td>
<td>H (10)</td>
<td>R (10)</td>
</tr>
<tr>
<td></td>
<td>Area Y</td>
<td>2004 (Cooper et al., 2005)</td>
<td>1</td>
<td>30</td>
<td>Gravel - High disturbance</td>
<td>L (10)</td>
<td>R (10)</td>
</tr>
<tr>
<td></td>
<td>Area 351</td>
<td>2000 (Bolten and Rees, 2001)</td>
<td>0</td>
<td>16</td>
<td>Gravel - Low disturbance</td>
<td>H (10)</td>
<td>R (10)</td>
</tr>
<tr>
<td></td>
<td>Area 12</td>
<td>2003 (Bolten and Rees, 2001)</td>
<td>0</td>
<td>16</td>
<td>Gravel - Low disturbance</td>
<td>H (10)</td>
<td>R (10)</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* As the time of survey.
Fig. 1. Schematic diagram illustrating how input maps of (i) surface sediment distribution and (ii) natural physical disturbance were combined, in a GIS, to produce maps showing the distribution and disturbance class of sand and gravel dominated sediments. Both input maps were adapted from Iglesiet al. (2013).

Fig. 2. Location and classification (sediment/disturbance) of study sites, based on the output maps in Fig. 1.

Table 2

<table>
<thead>
<tr>
<th>Data type</th>
<th>Dataset</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment</td>
<td>1.</td>
<td>Particle size, N Major sediment classes</td>
</tr>
<tr>
<td>Faunal structure</td>
<td>2.</td>
<td>Species, Abundance values (species by station matrix)</td>
</tr>
<tr>
<td></td>
<td>3.</td>
<td>HIA, Value of trait expression (trait by station matrix)</td>
</tr>
<tr>
<td>Faunal function</td>
<td>4.</td>
<td>III, Value of expression (Trophic group by station matrix)</td>
</tr>
<tr>
<td></td>
<td>5.</td>
<td>Somatic production, Production values (family by station matrix)</td>
</tr>
<tr>
<td></td>
<td>6.</td>
<td>Rao, Rao coefficient values (trait by station matrix)</td>
</tr>
</tbody>
</table>

value of the index for larger faunal differences. This was considered important as there is likely to be greater concern over larger faunal differences.

For each sediment group, Values of wIS were plotted for each sediment/disturbance class, with groups arranged in order of increasing natural physical disturbance. The statistical significance of the resulting trend was then assessed using the non-parametric Mann–Kendall statistic (Mann, 1945; Kendall, 1975). We used the statistical programming environment R (R Development Core Team, 2010) to carry out the analyses. The Mann–Kendall statistic works by looking at each wIS value and counting the number of data points in higher groups that are greater than it (assigned +1) and also the number that are less than it (assigned –1). These values are summed over all wIS values to create a statistic, M.

The null distribution of M (i.e., assuming no trend) was calculated by Monte-Carlo simulation as follows. The observations were re-ordered at random so that they were potentially assigned to
different groups and the value of M calculated. This was repeated 10,000 times. These values of M under the null hypothesis were compared against the observed value of M to estimate the p-value (Manly, 2001).

Given that ANOSIM R values do not indicate the direction of change – they merely identify the magnitude of any difference between samples from the Treatment and Reference sites – it is important to gain further insight into the nature of differences between Treatment and Reference sites. This was achieved by examining the percentage difference between sites in terms of the number of species, abundance, somatic production and the different sediment fractions. The average sediment composition of each site was determined using SIMPER analysis.

In order to explore differences in the nature of faunal communities from each sediment/disturbance class, a Principle Components Analysis (PCA) ordination, based on untransformed sediment particle size data (percentage contribution of gravel, coarse sand, medium sand, fine sand, mud) was produced. As variables were all in the same format it was not necessary to normalise the data. A SIMPER analysis, based on square-root transformed species abundance data, was used to identify the characterising species from both gravel and sand dominated samples. Bubble plots, overlaid on the PCA plot, were used to explore relationships between the abundance of individual species and sediment composition.

3. Results

3.1. Univariate

Despite the high variability, there was evidence for a general decline in the mean numbers of species, abundance and total somatic production as the level of natural physical disturbance increased (Fig. 3). In addition, within a disturbance class, mean values of all univariate measures were higher in gravel dominated samples compared with those dominated by sands, with the exception of total somatic production in areas of medium natural disturbance.

3.2. Multivariate

For both structural and functional WSI, there was evidence of a negative trend with increasing natural physical disturbance (M (structure) = 279; p-value = 0.001; M (function) = 205; p-value = 0.01) (Fig. 4). Having established differences between groups, we make the following observations. Firstly, that within a broad sediment group (gravel, sand or gravel), the sensitivity of faunal communities to changes in sediment particle size composition decreases as the level of natural physical disturbance increases. Secondly, that within disturbance groups (medium or low), assemblages found on gravel are more sensitive to changes in sediment composition than those on sand. Lastly, the converging of structural and functional WSI values suggests that assemblages may become less resistant to functional change as the level of natural physical disturbance increases.

On the whole, changes were considered to be detrimental. Of the thirty-seven Treatment/Reference comparisons, 76% resulted in a reduction in the number of species, 68% in a reduction in the number of individuals, and 65% in a loss of production (Fig. 5). Generally, faunal changes were associated with an increase in the proportion of sand and a decrease in the proportion of gravel (Fig. 5).

In addition, the relationship between the sediment particle size data of individual samples, and relative disturbance classes (see Fig. 1) was examined by PCA (Fig. 6a). Samples from low disturbance areas were dominated by gravel sediments, whilst samples from medium and high disturbance areas were quite evenly distributed across the sediment spectrum. Gravel sediments were generally associated with higher numbers of species, individuals and greater total somatic production (Fig. 6b-d).

The abundance of individual characterising species, identified using the SIMPER routine, was overlaid on the same PCA plot (Fig. 7a). This suggests that many of the characteristic species in gravel dominated sediments (e.g. Pomatochara lamarcki, Balanus crenatus, Cassidulina alata) favour coarse sediments (Fig. 7a). In contrast, many of the characteristic species found in sand dominated sediments (e.g. Ophelio borealis, Glycera alba, Nephtys caeca) can also be found in the sand component of gravel dominated sediments (Fig. 7b). For certain species common to both sand and
Fig. 4. Weighted sensitivity index (wSI) values for different sediment/disturbance classes, arranged in order of increasing natural physical disturbance. The structural wSI is shown by solid symbols, the functional wSI by open symbols. Mean values are shown by large symbols and joined by solid black line (structure) and dashed black line (function).

Fig. 5. Percentage change for (a) the number of species (S), abundance (N) and total somatic production (P); (b) The major sediment classes (g - gravel, s - sand, m - mud) at the Treatment site, relative to the Reference site (see Table 1 for sediment particle size composition of Reference site samples). Median values are shown by horizontal bars.

Gravel dominated sediments (e.g. *Lumbrineris gracilla*, *Aonides paucibranchiata*, *Sabellaria spinulosa*), the presence of gravel appears to be associated with an enhancement in their abundance (Fig. 7c).

Fig. 6. (a) Principle Components Analysis (PCA) plot based on (a) sediment particle size data (samples coloured according to the level of natural physical disturbance), and superimposed bubble plots for (b) numbers of species (per 0.1 m²); (c) abundance (per 0.1 m²) and (d) total somatic production (kJ m⁻² yr⁻¹).

4. Discussion

The purpose of this study was to investigate the significance of changes in sediment composition, as a result of marine aggregate dredging, for the structure and function of bentheic macrofaunal
communities. Data indicate that, within very broad terms, communities decline in species richness, abundance and productivity as (i) the level of natural physical disturbance increases and (ii) the proportion of gravel in samples decreases. This conclusion is in agreement with a study undertaken by Bolam et al. (2010) describing the productivity and diversity of UK shelf macrobenthic assemblages. However, faunal communities in areas of low natural physical disturbance, and with increased gravel content appear most sensitive to changes in sediment particle size composition. In contrast, faunal assemblages in areas of high natural physical disturbance, and with less gravel appear less sensitive to changes in sediment particle size composition. This observation accords with the findings of Seiler and Newell (1999), Newell et al. (2001) and Cooper et al. (2007), who reported a lack of correspondence between community composition of the benthos and static particle size distribution in unconsolidated sand and gravel deposits at Area 452 (Thames), off Folkstone (eastern English Channel) and Cross Sands (east coast), respectively. All of these areas sit within zones of high natural physical disturbance as identified by this study. The differing sensitivity of faunal communities to changes in sediment particle size composition helps explain the different physical and biological recovery times following marine aggregate dredging reported in Foden et al. (2009).

Our results suggest the presence of gravel may have an important role in explaining the negative correlation between the sensitivity of faunal communities to changes in sediment composition and the level of natural physical disturbance. Many of the species characterising gravel dominated sediments were only found in association with this sediment fraction. Therefore, a loss of gravel, the most common sediment change observed in this study, can lead to a reduction in the abundance of these species. The effect of a loss in gravel is likely to be greater in areas of low natural physical disturbance where these 'gravely fauna' are most developed, and smaller in areas of high natural physical disturbance, where the effect of sand in suspension serves to limit settlement by such species (Kenny et al., 1991; Rees et al., 1999). In contrast to these gravelly fauna, many of the characterising species from sand dominated sediments were equally likely to be found in gravel dominated sediments. As such, changes in sediment composition in these areas are likely to have a reduced impact on the overall faunal assemblage. However, although the impacts are reduced, the presence of gravel within sediments can be associated with an enhancement in abundance of a number of species commonly associated with sands and therefore some impacts are possible even in these more sand dominated habitats.

For these reasons, the policy (ODPM, 2002) which requires operators of marine aggregate extraction sites to leave sediments in a similar physical condition to those present prior to dredging appears sensible. However, this study suggests the requirement will be more or less important depending on the nature of the local environmental conditions. In addition, the approach taken in this study has shown that it may be possible to define specific limits of changes in sediment composition. This is necessary if licencing conditions regarding changes in sediment composition are to be enforceable.

Clearly some caution must be exercised in drawing firm conclusions about the differences between sediment disturbance classes due to the limited and unequal number of data points. Nevertheless, we cautiously identify a number of theoretical and practical implications resulting from our findings. Most obvious is that it may be preferable, where a choice exists, to site new aggregate dredging licences in areas of high natural disturbance. In addition, efforts should be made, so far as is practicable, to seek to maintain a similar quantity of gravel in surface sediments after dredging, particularly in areas of low natural physical disturbance (e.g. through limitations on sediment screening in areas where such material may persist). This is important given the role of gravel in providing a surface for attachment of some species, and in stabilising sands and finer sediments. Such measures will help reduce the likelihood of permanent changes in faunal community composition.
Where changes in sediment composition do arise, despite appropriate licence conditions being in place and adhered to, this raises questions of what is an appropriate management response. The currently prevailing view is to accept that a degree of impact may be inevitable, but that changes are generally acceptable when balanced against the societal benefits associated with extraction of marine aggregates. The relatively small size of impacted areas strengthens this view. However, there remains the potential for cumulative and in-combination effects. In response to this, recent work shown that it is possible to, at least in part, restore sediment composition following marine aggregate dredging (Collins and Millward, 2013). By 2011, CEFAS have reported that the present study strengthens the case for restoration, further work is required to determine whether the costs of such intervention can be justified, both scientifically and in terms of economics (Cooper et al., 2011b).

Acknowledgements

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References


