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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: AE 1224

2. Project title: The ecosystem consequences of sediment disturbance

3. Contractor organisation(s):
   CEFAS
   Pakefield Road
   Lowestoft
   Suffolk
   NR33 0HT

4. Total Defra project costs: £ 989,554

5. Project: start date .... 01 April 2001

   end date .... 31 March 2005

6. It is Defra's intention to publish this form.
Please confirm your agreement to do so...YES ☒ NO ☐

(a) When preparing SID 5s contractors should bear in mind that Defra intends that they be made public. They should be written in a clear and concise manner and represent a full account of the research project which someone not closely associated with the project can follow.

Defra recognises that in a small minority of cases there may be information, such as intellectual property or commercially confidential data, used in or generated by the research project, which should not be disclosed. In these cases, such information should be detailed in a separate annex (not to be published) so that the SID 5 can be placed in the public domain. Where it is impossible to complete the Final Report without including references to any sensitive or confidential data, the information should be included and section (b) completed. NB: only in exceptional circumstances will Defra expect contractors to give a "No" answer.

In all cases, reasons for withholding information must be fully in line with exemptions under the Environmental Information Regulations or the Freedom of Information Act 2000.

(b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

The seabed of the UK coastal waters and shelf is subject to a variety of pressures from human activities. These include: fishing by bottom trawlers; the dredging and disposal of dredge spoil from estuaries and harbours, to maintain navigation, which may contain contaminants; and, the extraction of sand and gravel for use in construction. Such activities may lead to the disruption of benthic communities (micro-, meio- and macro-fauna) by physical disturbance or removal of habitat; the introduction of contaminants; and changes in the cyling of carbon and nutrients within the seabed. These perturbations in turn may result in an undesirable disturbance to the overall health of the ecosystem (in terms of biodiversity, resilience and impacts on higher trophic levels).

The overall aim of the project was to establish the impact of sediment disturbance due to human activities on: the biogeochemical functioning of the seabed ecosystem (i.e. the storage and cycling of carbon and nutrients, and organic degradation); the bio-availability of sediment-bound contaminants; and, the re-distribution of toxic algae. This was placed in the context of natural disturbance due to regular tidal motions and episodic storm events. We sought to address each of these issues within the project and provide a conceptual model that could be developed as a tool for use in environmental impact assessment, and to provide a means for conveying information on the consequences of disturbance to regulators, policy makers and the general public, and to contribute to the formulation of guidance through international fora such as OSPAR (www.ospar.org). This was based on the DPSIR approach to assessing ecosystem 'health' (**D**river, **P**ressure, **S**tate, **I**mpact & **R**esponse). The project was multidisciplinary with chemists, biologists, sedimentologists, physical oceanographers and information scientists working together. A combination of field observations, laboratory experiments, modelling and GIS (Geographic Information Systems) techniques were used.

Five main scientific objectives were identified at the inception of the project, with a further two added later, and these were managed as separate 'work strands':

1. To develop a conceptual model of the consequences of sediment disturbance to support impact assessments and the development of activity-related ecological targets;
2. To assess the relative magnitude of sediment disturbance due to natural (storms and tides) and human (dredging, fishing and construction) activities, at both local and regional scales;
3. To assess the effect of sediment disturbance on the biogeochemical functioning of coastal marine sediments;
4. To assess the effect of sediment disturbance on contaminant (PAHs, TBT, Cu and other metals) bio-availability and toxicity;
5. To assess the effect of sediment disturbance on the occurrence and distribution of toxic algal

cysts and the conditions under which the toxic algae would thrive.

6. To support a project funded under the EU 6th Framework programme: COBO - towards a Coastal Ocean Benthic Observatory. This commenced in March 2004, consisting of a consortium of 12 partners from 6 countries (www.cobo.org.uk).
7. To undertake a review of existing information and conduct additional research into environmental conditions on and around the Souter Point disposal ground off the NE coast of England.

The results of the project have been reported in a number of contract reports, peer-reviewed publications, conference presentations and other outputs. One of the main findings was that about 70% of the seabed in the southern North Sea is physically impacted by human activities (aggregate extraction, dredge disposal, trawling). Natural disturbance and fishing impacts are of most importance on a regional scale whilst aggregate extraction and disposal are spatially restricted (<0.1%) but intense. The spatial distribution of the trawling fleets is patchier than originally thought with significant inter- and intra- year variations in impact intensity which can be linked to management actions (i.e. closure of the Cod Box in 2001). Natural disturbance appears to mediate the sediment type and mobility, redox state and hence associated rate processes, to a significanr extent, based on a combination of field measurements and modelling techniques. The continuum from low natural disturbance (diffusional) to high natural disturbance introduces an increasing degree of natural variability against which human impacts are difficult to detect. In terms of field observations, the use of a SPI camera (Sediment Profile Imaging) proved to be a relatively cost-effective and rapid method for assessing the impact of dredge spoil disposal on the benthic fauna and general sediment characteristics. Some of the sediment process measurements are costly and time-consuming, which may impose limits on their use. The EU COBO programme will provide a range of novel in-situ technologies which will complement the more conventional methods, for future applications. The work on algal cysts illustrated the patchy distribution of particular species. The assumption that the Thames embayment would contain significant quantities was ill-founded. The experimental work allowed the conditions for excystment to be explored, generating a modelling module for inclusion in the GIS framework and providing a predictive capability of the conditions under which a toxic bloom might occur.

A novel approach to impact assessment has been developed which combines GIS-based disturbance information and pressure-impact models within a DPSIR framework. It can be applied on varying spatial scales and to a range of human activities, and has potential for helping to select reference areas for establishing EcoQOs (Ecosystem Quality Objectives). The impact assessment approach is quick to apply, given the availability of appropriate data and impact models (empirical or conceptual). Consequently, it can be used as a screening tool to identify limitations in scientific knowledge or help decide if a full modelling exercise is required. In this way, existing impact models can be applied within a GIS environment to give a preliminary assessment of potential effects, in terms of: sensitivity to changing disturbance distributions (management scenarios); investigations of critical model criteria (environmental conditions); or by combining information layers to provide risk assessments. In the present study the approach was applied to three case studies: the impact of trawling on sediment biogeochemistry; the potential impact of disturbance of toxic dinoflagellate cyst viability; and, the behaviour of TBT (tributyl tin, used in anti-fouling paint) at the Tyne disposal site.

The results will be fed into a number of on-going Defra projects, including the development of indicators of ecosystem health and promoting the ecosystem approach to environmental management. It will inform our input to a number of international collaborations and advice fora, including OSPAR, ICES and the EU Marbef Network of Excellence (marine biodiversiy, www.marbef.org). The work on the Tyne disposal site will be used to develop improved assessment techniques and monitoring strategies at this and other sites.

A number of areas would benefit from future research. This should include geochemical processes in coarser sediments, which were not targeted in this project but which represent the bulk of sediments on the UK shelf and may be key in addressing carbon cycling. The mediation/response links between the faunal community and biogeochemical changes proved difficult to establish but undoubtedly are of significance, as is the rate of post-impact recovery. The current models of contaminant behaviour following disturbance are insufficiently robust and rely on assumptions due to lack of site specific information. This needs to be recognised with the implied need for appropriate field and experimental data, to cover the range of sites, contaminants and biota likely to be encountered. The work on algal cysts would benefit from additional experiments on a wider range of organisms, to provide basic information on the conditions for excystment and encystment, cyst viability and probability of toxic events, from oceanographic observations combined with improved modelling descriptions. Such research would greatly strengthen the evidence base upon which management decisions depend.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
    - the scientific objectives as set out in the contract;
    - the extent to which the objectives set out in the contract have been met;
    - details of methods used and the results obtained, including statistical analysis (if appropriate);
    - a discussion of the results and their reliability;
    - the main implications of the findings;
    - possible future work; and
    - any action resulting from the research (e.g. IP, Knowledge Transfer).

Scientific Objectives

The overall aim of the project was to establish the impact of sediment disturbance due to human activities, relative to natural variability, on: the biogeochemical functioning of the seabed ecosystem; the bio-availability of sediment-bound contaminants; and, the re-distribution of toxic algae. Sediment geochemistry and its interaction with benthic organisms is relatively well described (e.g Aller, 1992; Huettal & Gust, 1992). However, the impact of various types of human disturbance (such as fishing, dredging, dredge spoil disposal, construction and aggregate extraction) on the quality and functioning of marine and estuarine ecosystems is only partly understood (e.g. Bergman and Hup, 1992; Jennings and Kaiser, 1998). Disturbance pushes ecosystems towards dominance by opportunistic species (Pearson and Rosenberg, 1978) with implications for bioturbation and the chemical regime in the sediment. Dredge spoil disposal encourages anoxia in sediments. This may promote the flow of redox-sensitive nutrients and contaminants into the water, but will also inhibit denitrification (i.e. the release of nitrogen). Trawling encourages the pulsed release of nutrients (e.g. silica, ammonium) into the water which may have implications for planktonic primary productivity. The specific impact associated with any given activity may be predicted with some confidence but the consequences for long-term and regional-scale changes are not known. Providing a robust assessment is hindered by the lack of coherent datasets at regional scales (Parker et al, 1999). Some of these activities are subject to regulation, in respect of their physical and macro-biological environmental impact, but the consequences for sediment functioning (e.g. the storage and cycling of nutrients, organic degradation, contaminant storage and transformation) are not considered. We sought to address each of these issues within the project and provide a conceptual model that could be developed as a tool for use in environmental impact assessments, and to provide a means for conveying information on the consequences of disturbance to regulators, policy makers and the general public, as well as within international fora such as OSPAR (www.ospar.org). This was based on the DPSIR approach to assessing ecosystem 'health' (**D**river, **P**ressure, **S**tate, **I**mpact & **R**esponse) which is described below (Figure 9). We envisaged that the work would support advice in relation to the Biodiversity Strategy of OSPAR, particularly looking towards the 'ecosystem approach to management', concerns in relation to Special Areas of Conservation (SAC) under the Habitats Regulations and would underpin continuous improvement in CEFAS' ability to provide integrated advice on the consequences of disturbance of the marine environment.

Five main scientific objectives were identified at the inception of the project, and these were managed as separate 'work strands':

8. To develop a conceptual model of the consequences of sediment disturbance to support impact assessments and the development of activity-related ecological targets;
9. To assess the relative magnitude of sediment disturbance due to natural (storms and tides) and human (dredging, fishing and construction) activities, at both local and regional scales;
10. To assess the effect of sediment disturbance on the biogeochemical functioning of coastal marine sediments;
11. To assess the effect of sediment disturbance on contaminant (PAHs, TBT, Cu and other metals) bio-availability and toxicity;
12. To assess the effect of sediment disturbance on the occurrence and distribution of toxic algal cysts and the conditions under which the toxic algae would thrive.

Two further objectives were added after the project had commenced:

13. To support the EU-funded FP6 COBO project (COBO: towards a Coastal Ocean Benthic Observatory), which commenced in March 2004, consisting of a consortium of 12 partners from 6 countries;
14. To undertake a review of existing information and conduct additional research into environmental conditions on and around the Souter Point disposal ground off the NE coast of England. This was prompted by a proposal to conduct a sediment capping trial of contaminated sediment dredged from the Tyne estuary, and required additional funding in 2 tranches.

All the objectives were met, with differing degrees of scientific certainty, and the methods and results are summarised below. Additional contract reports, peer-reviewed publications and other outputs from the project are listed in section 9. These should be consulted where more detailed information is required.

Methods and Results

The relative magnitude of sediment disturbance due to natural (storms and tides) and human (dredging, fishing and construction) activities, at both local and regional scales (objective 2)

The specific objective was to quantify the relative maximum spatial extent of impact for 3 human activities (dredge disposal, aggregate extraction, trawling) in the North Sea for 2001 and 2002. The areas and tonnages involved in dredge spoil disposal were obtained from a database held within CEFAS under FEPA legislation (Food & Environmental Protection Act). Information on the area and rate of aggregate extraction was supplied by the Crown Estate from their Electronic Monitoring System (EMS) records of dredger activity. Data on fishing effort were obtained from the VMS database held by Defra, after removing information covered by the Data Protection Act. This contains information from overflights by fisheries protection airplanes up to 2000, and satellite GPS data (every 2 hours) from 2001, when vessels > 24m were required to have automatic positioning systems fitted. Data were also obtained for non-UK (mainly Dutch) registered fishing vessels. The advantage of the satellite data is that they provide much higher spatial and temporal resolution. A disadvantage is that smaller inshore vessels are not monitored. For this reason we used both types of data. Satellite data were appropriate for looking at variability in the OSP but the Thames embayment was characterised by smaller vessels so the overflight data were used there, aggregated from 1990-2000 (SPUE – sightings per unit effort). To calculate the spatial extent of fishing pressure both the minimum (straight line vessel track method) and maximum (ellipse method) potential areas impacted were estimated based on VMS locations and speed information (Aldridge et al., in prep). The spatial extent of trawling disturbance far exceeded that of the 2 other relatively major human activities in the southern North Sea (Table 1). However, the distribution was not uniform (Fig 1) and, at OSP, varied between years.

Table 1: Spatial extent of human activities over the southern North Sea in 2001/2002.

Activity	Coverage 2001 (km^2)	Coverage 2002 (km^2)	% of southern North Sea
Aggregate extraction (< 1hr)	96	99	0.08
Aggregate extraction (> 1hr)	9.3	9.2	0.01
Dredge disposal	52	38	0.03 – 0.04
Trawling (beam)	78400	75100	64 - 67

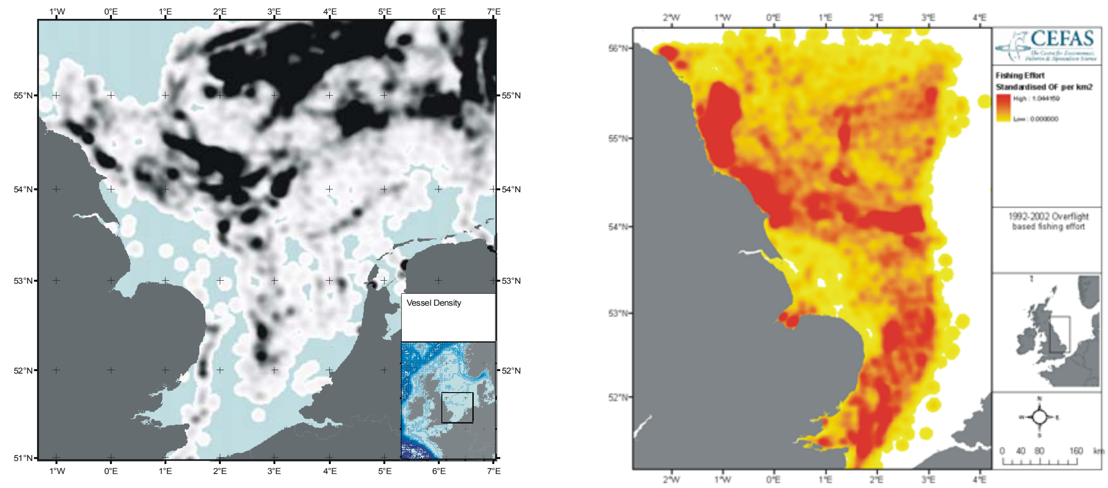

Figure 1 The distribution of fishing effort in the North Sea: a) satellite observations indicating vessels >24m (2002); b) overflight observations, 1990-2000, including inshore vessels.

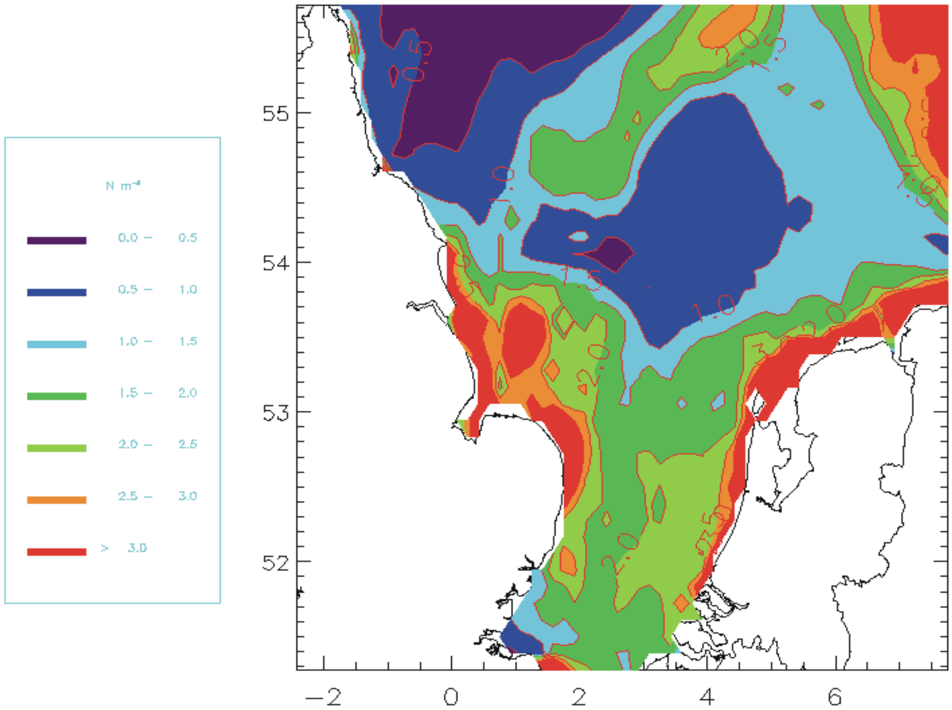

Figure 2. Peak tide-wave stress (N m^{-2})

To compare the relative impact of trawling with disturbance due to waves and tides, the data were gridded (~ 11km grid). Sediment turnover from trawling was estimated from the calculated spatial extent from all vessels within a given time period, and assuming a depth of penetration of the gear of 4-10cm. To calculate the effect of natural disturbance we used the results of combined tide and wave modelling supplied by the Proudman Oceanographic Laboratory (Osuna & Wilf, 2004), with wave data from the period September 1999 to September 2000. This was used to estimate bed stress (Figure 2) from which a calulation was performed to estimate the depth to which the sediment would be disturbed by real waves and tides in different regions. The factors which were included were: bed stress; wave current interaction in calculating threshold conditions; bedform prediction formulae; orientation of waves and tides; proportion of the area covered by megaripples and other features. A full description of the methods is provided by Aldridge et al. (in prep.).

The results showed that reworking of the top 1-2cm was dominated by natural processes at most locations in the North Sea. At depths comparable with trawl gear penetration, 4-10cm, it is likely that the southern North Sea continues to be dominated by natural reworking due to megaripple migration. In wave dominated regions in the northern North Sea uncertainties in wave ripple prediction make it difficult to assess the relative importance of natural verses anthropogenic impacts. Intermediate between these two regions, beam trawling is likely to be the main process for rapid reworking of the bed at depths below 4cm. However, it was concluded that further basic research on ripple and megaripple generation is required before these issues can be answered with a greater degree of certainty.

The effect of sediment disturbance on the biogeochemical functioning of coastal marine sediments (objective 3)

Marine sediments are important for the cycling of carbon and nutrients. Sediment disturbance may result in changes in the rates of biogeochemical cycling, due to: physical stirring or resuspension and oxidation (e.g. due to trawling); changing the sediment size spectrum or organic content (e.g due to aggregate extraction or dredge material disposal); and, through the impact on the benthos which can mediate sediment geochemistry through bioturbation and bioirrigation processes. Such changes must be set in the context of natural disturbance, due to tidal currents and waves. This study was designed to look at the impact of disturbances on sediment biogeochemical function and also the associated faunal community which mediates it. Three case studies were selected based on sediment type, water depth, natural tidal bed stresses, trawling intensity and disposal ground extent: coastal waters off the Tyne (TY: disposal ground, intermediate natural disturbance); Outer Silver Pit (OSP: trawling gradient, low natural disturbance); Thames Embayment (TH: trawling gradient, high natural disturbance). Three cruises were undertaken in the southern North Sea in October 2001, July 2002 and July 2003, visiting 4 to 6 sites within each study area. The sites were selected on the basis of sediment type, bathymetry and natural tidal bed stresses, along gradients of human imapact. At each site a common suite of measurements was made, within a circle of 100m radius (Parker et al., 2003):

- side-scan sonar to 'ground-truth' trawling intensity and bedforms;
- oxygen profiles using microelectrodes;
- sediment process rates: oxygen uptake; sulphate reduction (turnover of radio-labelled ^{35}S); denitrification (using stable ^{15}N);
- nutrient fluxes and pore water profiles;
- epi- and infaunal assemblages: using a Jennings beam trawl and Hamon grab respectively;
- sediment properties: particle size, chlorophyll, organic carbon, porosity;
- water column characteristics: CTD, dissolved nutrients, dissolved oxygen, chlorophyll, suspended particulate.

In addition, a survey was conducted in 2003 of the Tyne disposal ground using a Sediment Profile Imagery (SPI) camera system (Birchenough et al., 2004). This is a relatively rapid technique which reveals the depth of the apparent redox discontinuity and can provide information about the status of the benthic assemblage (Germano, 2003). The results of the field measurements have been reported in detail (Parker et al., 2004, submitted; Trimmer et al., in press).

The water column in Tyne and Thames areas is well-mixed throughout the year, whereas thermal stratification develops at OSP during the summer. The nutrient and chlorophyll measurements were consistent with seasonal nutrient utilisation, sources and production. Considering biogeochemical processes in the seabed, trawling appeared to have a different impact in the Thames and OSP. The relatively high degree of natural disturbance in the Thames led to a high degree of variability in sediment characteristics, which effectively masked potential effects due to fishing effort. In contrast, increasing trawling effort at OSP was accompanied by an increase in sulphate reduction but a reduction in coupled denitrification. In addition, there was a decrease in the median particle size, although the causal relationship has not been established. The Tyne sediments had a relatively high organic carbon content, although there was a significant contribution from hydrocarbons which may have lower bioavailability. Sediment process rates in October 2001 were consistently lower than in July 2002, and this difference tended to exceed the inter- and intra-site variability.

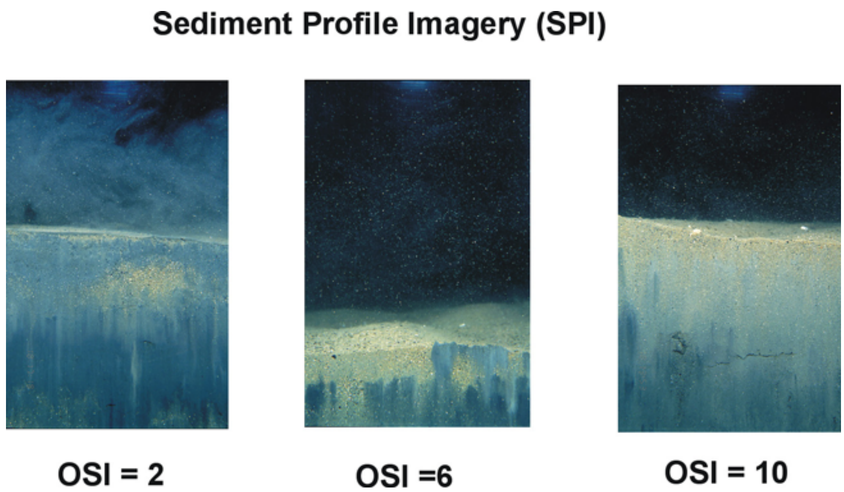

Figure 3. SPI images from the Tyne disposal ground, showing progressive change from high impact, high organic load, low benthic status (OSI = 2) towards more oxygenated and more diverse benthic status (OSI = 10).

The SPI survey revealled changes to the depth of redox discontinuity, fauna and sediment type as a result of disposal operations, which were not apparent from the sediment rate measurements (Figure 3). However, the relatively small ‘footprint’ of the activity (Table 1) means that the overall impact on sediment functioning at a regional scale is likely to be low

In the Thames there was no clear distinction between sites within an area of high fishing intensity and those in areas of low intensity in terms of percentage abundance of major epi-faunal taxa, i.e. the Thames samples showed no tendency for similar species compositions to occur within impact categories. It is likely that this may be due to the naturally variable nature of the seabed environment in the Thames resulting from high natural disturbance. Significant differences in species diversity and abundance were observed between low and high impact sites at OSP. Overflight trawling intensity best matched the pattern seen in the epifauna (correlation = 0.838). Low impact sites in 2002 showed a tendency to dominance by Echinoderms (primarily the brittle Star *Ophiura albida*) which was not so apparent at high impact sites. At the Tyne there was there is a notable difference in the abundance of major taxa from the sites outside the dredge disposal sites and from those within. Crustacea (*Crangon allmanni*) numerically dominated the two low impact sites and the stations within the disposal site had much higher proportions of Mollusca and Echinodermata. These findings were confirmed by significant separation of the species abundance MDS plots for high and low impact sites from the OSP and Tyne, but lack of separation of high and low impact areas in the Thames. The variability both between and within sites was high in the Thames suggesting patchiness on a relatively small scale.

SP02 JB Abund, MDS, factor = overflight (no stn 3D)

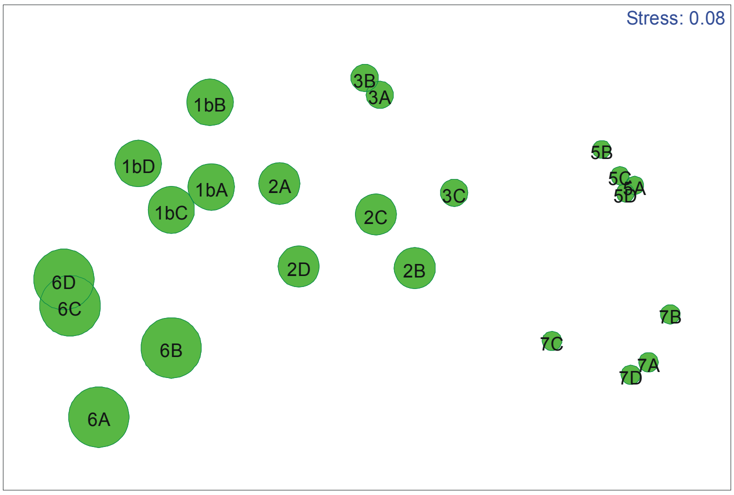

Figure 4. Multi-dimensional scaling (MDS) species abundance plot of Bray-Curtis similarity for the Outer Silver Pit, showing sample number with circle size proportional to overflight fishing intensity.

The percentage abundance of major in-fauna taxa from Hamon grabs indicated that all three areas surveyed during the cruises had different community structures, suggesting the importance of species function for future intra-area comparisons. In the Tyne and Thames this difference in community structure could be attributed to impact. In the Tyne the low impact areas had ~50% of their community structure characterised by 4 species (*Thyasira flexuosa*, *Nucula nitidosa*, *Abra alba* and *Nephtyidea*) and high impact sites had 50% of community structure characterised by *Pectinariidea*, *Dosinia lupinus*, *Nucula nitidosa* and *Circomphalus casin*. These dominant species did vary somewhat with season. The sites in the Thames were much more variable both within and between impacts, although this is expected due to the high degree of natural disturbance.

A Bioturbation Potential Index (BPI) was developed in an attempt to quantify the effect of faunal bioturbation and bio-irrigation on geochemical processes. In- and epifauna data were categorised using two criteria: abundance; and, bioturbation potential using biomass and function. Functional attributes (mobility and habit) were scored, based on Swift (1993), more recent literature (Bremner, *et al.,* 2003) and expert knowledge. The BPI was calculated for individual species and communities: BPI (f) = biomass *(Activity* Habit). We consider this to represent a useful indicator of benthic functioning but further development is required until it can be used routinely.

The effect of sediment disturbance on contaminant (PAHs, TBT, Cu and other metals) bio-availability and toxicity (objective 4)

Sediments in industrialised estuaries in the UK tend to have a high contaminant loading, including organometallic and hydrophobic organic contaminants (Law and Biscaya, 1994; Unger et al., 1988). This partly is due to the process of flocculation which occurs when saline and freshwaters mix and fine sediment becomes deposited (Clark, 2001), combined with relatively high direct and riverine inputs, and the legacy of past industrial practises. The disturbance which occurs when the sediments are dredged and then dumped at offshore disposal sites has the potential to release a proportion of the sediment-bound contaminant load. A literature review was conducted to ascertain what was known about contaminant release when sediments were disturbed (Eggleton & Thomas, 2004). It became evident that there were significant gaps in knowledge, including the release of organometallic compounds from sediments during resuspension and their bioavailability. This led to the setting up of a laboratory-based experiment to provide information relevant to this project.

The study was designed to investigate whether anoxic re-suspended sediment from the Tyne estuary affects the feeding habits and condition of the blue mussel (*Mytilus edulis*), and to find out how much contaminant is bioavailable. Mussels are considered to be good bio-indicators since they are sessile, non-selective, filter-feeders, which can sequester lipophillic contaminants and have limited metabolic degradation of PCBs (polycyclic biphenyls), PAHs (polyaromatic hydrocarbons) and TBT (tributyltin) (e.g. Fung et al., 2004). Increasing sediment loadings within the water column can lead to a decrease in their ability to filter food. PCBs, PAH and TBT are also readily accumulated in mussel tissue and can reduce the mussels rate of feeding (e.g. Widdows and Page, 1993). The river Tyne in the North East of England is one of the most heavily polluted watercourses in the British Isles (Matthiesen and Law, 2002). It has a long history of industrial and urban development and its estuarine sediments, and biota, are known to contain high levels of PAH and other industrial organic chemicals (e.g. Law et al., 2002; Thomas et al., 2002). Full details of the analytical methods and experimental set-up are provided by Tolhurst et al. (2004, submitted).

There was a positive correlation between increasing suspended solids and TBT, DBT and PAH accumulation in *M. edulis* (Figures 5 & 6). Mussels did not accumulate PCBs to any great extent, possibly due to the relatively low concentrations in the sediment. PAH accumulation was low relative to PAH found in the sediment. This reduced bioavailability of PAH may be due to dissolved organic matter within the pore water (Knutzen, 1995). PAH bioavailability is also affected by sediment grain size (Harkey et al., 1994) and organic carbon content (Zhang et al., 2004).

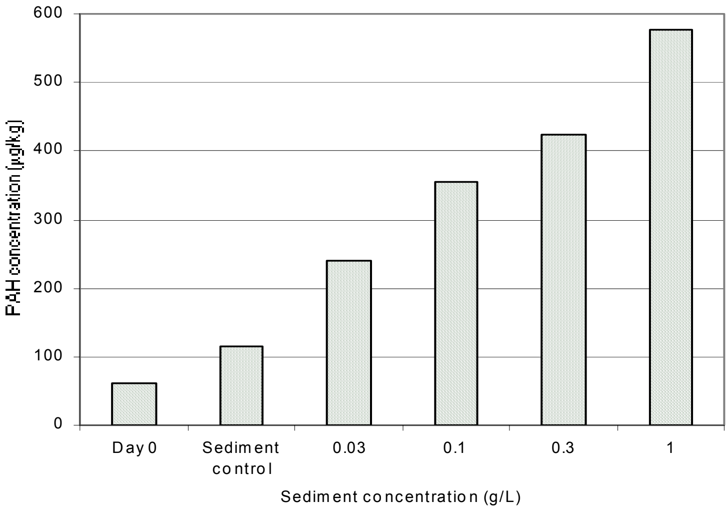

Figure 5. ∑PAH found in mussel tissue at 21 days

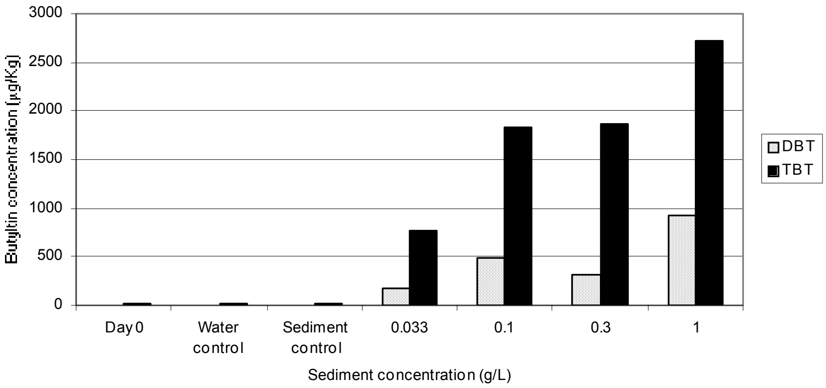

Figure 6. Butyltin found in mussel tissue at 21 days

Uptake of TBT and DBT into mussel tissue would have most likely occurred through both water column and particulate matter due to the mussel's mode of feeding. TBT and DBT desorb in seawater (Hoch et al., 2003) allowing for uptake through the gills where most organotin compounds are found (Page et al., 1995). However, desorption is not complete in marine conditions, particularly in the presence of paint flakes (e.g. from cleaning vessel hulls) so uptake through the sediment is possible. The resuspension of contaminated anoxic sediment, from the Tyne estuary, did result in a reduced feeding rate and increased contaminant bioavailability to mussels. But we are not able to distinguish the relative importance of sediment and contaminant loading on the clearance rate, and there was no statistically significant reduction in the mussels' condition index. The Tyne sediments are contaminated with a wide variety of potentially toxic substances and it is not possible to draw conclusions about the impact of individual contaminants using sediment collected from the field.

The effect of sediment disturbance on the occurrence and distribution of coastal algal toxicity concerns (objective 5)

Around the UK there have been persistent and diversifying difficulties associated with marine microalgae over the last four decades. These are manifested in a number of ways: as unsightly scum or water discolouration, death of fish or other marine organisms, in shellfish contaminated with algal toxins (e.g. Lewis, 1996). Certain of the microalgae that give rise to these problems (in particular the dinoflagellates) have resting stages that spend most of the year in the sediments. The question that has been increasingly asked of regulatory agencies is: if we remove sediment or disturb sediment from this site will this exacerbate or cause a problem with regard to microalgal phenomena? The broad aim of this workstrand was therefore to assess the effect of sediment disturbance on the occurrence and distribution of coastal algal toxicity concerns.

In order to address this aim one needs to consider the distribution of algal cysts in the sediments and the germination potential of those cysts. One of the most potentially severe problems around Britain is Paralytic Shellfish Poisoning (PSP) the vector for which, in these waters, is the dinoflagellate genus *Alexandrium*. *Alexandrium* is amongst the dinoflagellates that produce a long-lived sexual resting stage or cyst. This genus therefore provided a specific focus for this project. At the time of starting the project there was also a growing interest in the diatom genus *Pseudo-nitzschia*, the vector for amnesic shellfish poisoning (ASP) so this was included in the initial objectives. Additionally there was great interest in the Thames area, an area that had not been investigated with regard to its recent dinoflagellate cyst content. As a result of this the initial specific objectives of the project were to:

- Review the literature covering issues regarding resting stage biology likely to be relevant to the study.
- Conduct a field survey of Thames embayment to map distribution of dinoflagellate cysts and *Pseudo-nitzschia* in surface sediments including detailed analysis of selected sites with regard to depth distribution of dinoflagellate cysts and *Pseudo-nitzschia.*
- Arrange for collection and analysis of samples from Belfast Lough for comparative purposes (with 1992 data set).
- Carry out a laboratory–based investigation of germination potential of target species with regard to original depth in sediment; temperature; salinity and oxygen concentration.
- Develop inputs and structure for modelling and provide data for model.
- Carry out a desk study to investigate the relationship between particle size and cyst distribution using existing data sets.

All of these objectives have been addressed and have described in Contract Reports, a PhD thesis (Pérez Blanco, in prep) and in papers submitted for peer-reviewed publication. The literature review (Lewis, 2002; Lewis & Pérez Blanco 2002) was carried out and extensive references consulted regarding encystment and excystment in dinoflagellates and the methodologies that have been used to investigate them (Montesor & Lewis, in press). The key outcomes from this review were the identification that the same species from different parts of the world can have different autecological characteristics. This means it is necessary to conduct experiments on the populations of interest rather than simply extracting data from the literature. The review also established a robust methodology for germination experiments.

The survey of the Thames revealled that the dinoflagellate cyst population in the Thames estuary was negligible, so an alternative site for the project (the Fal estuary) was identified, to provide suitable sediments for the germination experiments using *Alexandrium minutum*. This site was chosen because of its history of shellfish toxicity and the synergy of another project being carried out in the area. This led to additional survey work Pérez Blanco 2003) (above that originally anticipated) and this combined with the time consuming nature of the germination experiments led to a reduction in the scope of some of the objectives attempted. It was concluded that the *Alexandrium minutum* cysts in the Fal estuary are a likely source for the population causing PSP in the estuary

Belfast Lough was the site of an intensive survey for *Alexandrium* cysts in 1992. The *Sea Cat* service, which has been running since that time, causes extensive sediment disturbance in the shallow regions of the Lough and some changes in sediment deposition have been noted. *Alexandrium* occurrence in the water column has been monitored since that time in the Lough. With this background a repeat cyst survey was made in October 2003 to investigate whether there had been any major changes in *Alexandrium* occurrence in the Lough sediments. Figure 2 shows the distribution of *Alexandrium* cysts in the Lough. This can be compared with Figure 3 that shows the distribution in 1992. Broadly the number of *Alexandrium* cysts in the Lough has reduced. Analysis of *Alexandrium* production is being carried out to investigate possible causes of this change of distribution.

The species chosen for this was *Alexandrium minutum* and sediments from Percuil (Fal estuary) were used for a series of germination experiments. Detailed methodology is given in Pérez Blanco (2003). A range of temperatures (4-24°C), salinities (15-30psu) light (0-20 µmol of photons.$m^{-2}.s^{-1}$) and presence and absence of oxygen were used to examine the germination potential of this species. Time did not permit detailed examination of depth of burial on germination potential. Oxygen and more than 5 µmol of photons.$m^{-2}.s^{-1}$ light were required for germination. Results for temperature and salinity are summarised in Figure 7. Surprisingly, very little variation in germination rate was found at a variety of temperatures in this species. The implication is that within the temperature and salinity conditions likely to be found around the British coast this species (given sufficient light and oxygen) will be capable of excystment. Within the estuary it has been noted (Percy, unpubl. obs.) that paralytic shellfish toxins appear rapidly in shellfish. It seems likely that the source of the cells carrying these toxins might be germinating cysts which could produce reasonable numbers of cells in the water column relatively rapidly (as opposed to a more slowly developing population by growth within the water column).

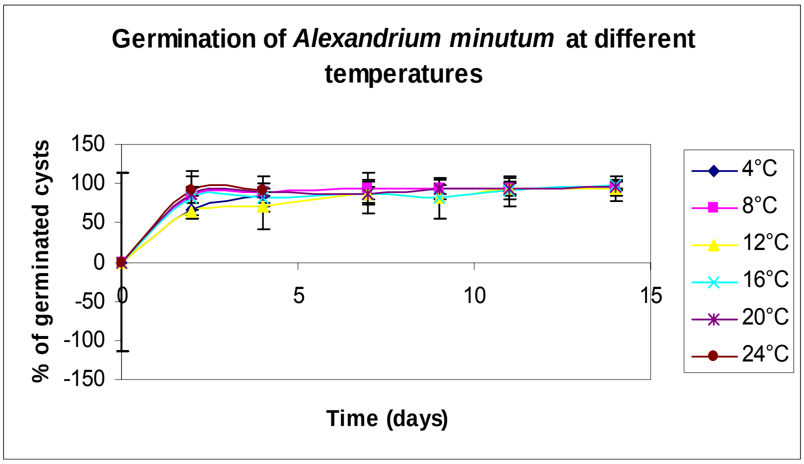

Figure 7. Germination of *Alexandrium minutum* from sediments from the Fal, cultured at six different temperatures (4ºC, 8ºC, 12°C, 16ºC, 20ºC, and 24ºC)

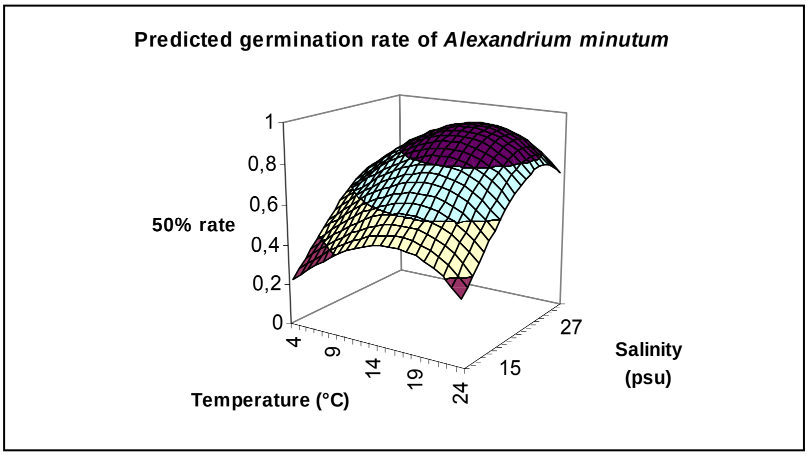

Figure 8. Predicted 50 % germination rate of *Alexandrium minutum* at any combination of a temperature range from 4°C to 24°C and salinity from 15 psu to 35 psu.

A module to predict the 50 % germination rate of *Alexandrium minutum* within a range of temperature and salinity conditions has been developed with the data obtained in the excystment experiments. This module can be included in a wider model assessing the movement of sediments to predict a likely inoculum of excysted cells to the water column. The module can be easily adapted to any surface (Figure 8) generated by excystment experiments. Thus the 50% germination rate of other species studied in the future can be predicted using this same module.

A conceptual model of the consequences of sediment disturbance to support impact assessments and the development of activity-related ecological targets (objective 1)

Although there have been many studies of each of the specific disturbance issues (mainly targeted towards impact on benthos) there are few conceptual frameworks or models that can be used to bring together all the relevant information in a form to permit impact assessment and investigation of management options (ecological targets) at appropriate spatial and temporal scales. A GIS-based framework was used to underpin the conceptual models and facilitate scenario testing. The main aim was to develop an improved method for conveying information on impact assessment to regulators, policy makers and the public. A full discussion of the rationale behind the conceptual framework is given in Parker et al. (2003).

The GIS assessment tool consists of four components:

- Overall conceptual framework - DPSIR (**D**river, **P**ressure, **S**tate, **I**mpact, **R**esponse – Figure 9)
- Parameterisation of disturbances – Driver, Pressure (natural, anthropogenic, single, composite, timing, real/scenario) (Objective 2)
- Impact models - describe the effects of physical disturbance on the ecosystem (sediment geochemistry / benthic fauna, algal cyst viability, contaminant release) components as derived within independent workstrands - State, Impact. (Objectives 3, 4 and 5)
- The integrating framework (GIS based) - allows analysis of spatial information, derivation of cause/effect models and testing of models in a spatial matrix with respect to impact questions (Response).

Three applications were developed and tested (Parker et al., 2004, in prep), providing examples on a regional, coastal and estuarine scale:

- Regional - Impact of redistribution of trawling fleets on sediment biogeochemistry in the OSP;
- Coastal – Contaminant remobilisation and bioavailability - Investigation of TBT remobilisation due to disturbance around the Tyne disposal sites;
- Estuarine - Algal Cyst viability – Testing of scenarios to examine the impact of dredging activities on algal cyst viability in the Fal Estuary.

One example is described here, examining the impact of changes in trawling effort on carbon remineralisation, in the OSP, between 2001 and 2002,. This used 2 empirical models, developed during the project, describing the impact of trawling pressure on coupled denitrification and sulphate reduction (Trimmer et al., in press; Parker et al., 2004). Both sediment biogeochemical models described a change in carbon remineralisation through the nitrogen and sulphur cycles with increasing trawling impact. For coupled denitrification the model illustrated a decrease in Dn with increasing trawling pressure, as determined from sediment rate measurements along a gradient of satellite-derived trawling pressure. The Dn/trawling model is described by the equation:

$$\text{Coupled Dn } (\mu\text{mol N m}^{-2}\text{ h}^{-1}) = 36.248e^{-1.866x} \qquad (1)$$

where x = fishing effort

This relationship may be driven partly by seasonal variations in rates, but we were unable to quantify this (Trimmer et al., in press). In contrast, sulphate reduction increased with increasing trawling pressure, as derived from long-term overflight data (SPUE – sightings per unit effort). The equation for this sulphate reduction/trawling linear model is given by:

$$\text{Sulphate reduction } (\mu\text{mol SO}_4\text{m}^{-2}\text{ h}^{-1}) = 396.48x + 15.32 \qquad (2)$$

The main layers and models used within the DPSIR framework were:

- **D**riving force: Distribution of trawling in OSP
- **P**ressure: Annual intensity of trawling derived from satellite/overflight data
- **S**tate: Spatial application of impact models to provide a state map .
- **I**mpact: Modelled changes in coupled denitrification or sulphate reduction with trawling intensity (i.e. estimating the difference between 2001 and 2002 states, assuming either even or patchy effort distribution, using a CutFill GIS method).
- **R**esponse: this was not investigated explicitly, but the output could be used, for example, to inform managers on the potential impact of changes in the distribution of fishing effort.

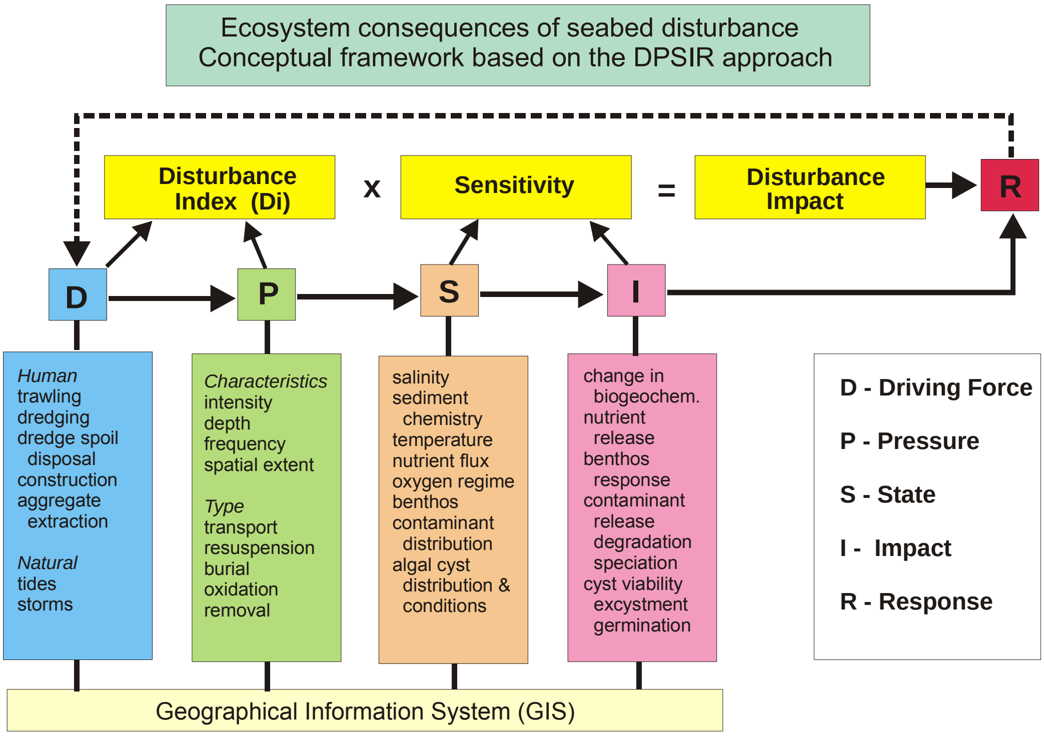

Figure 9. Conceptual framework for the assessment of the impacts of seabed disturbance using the DPSIR approach.

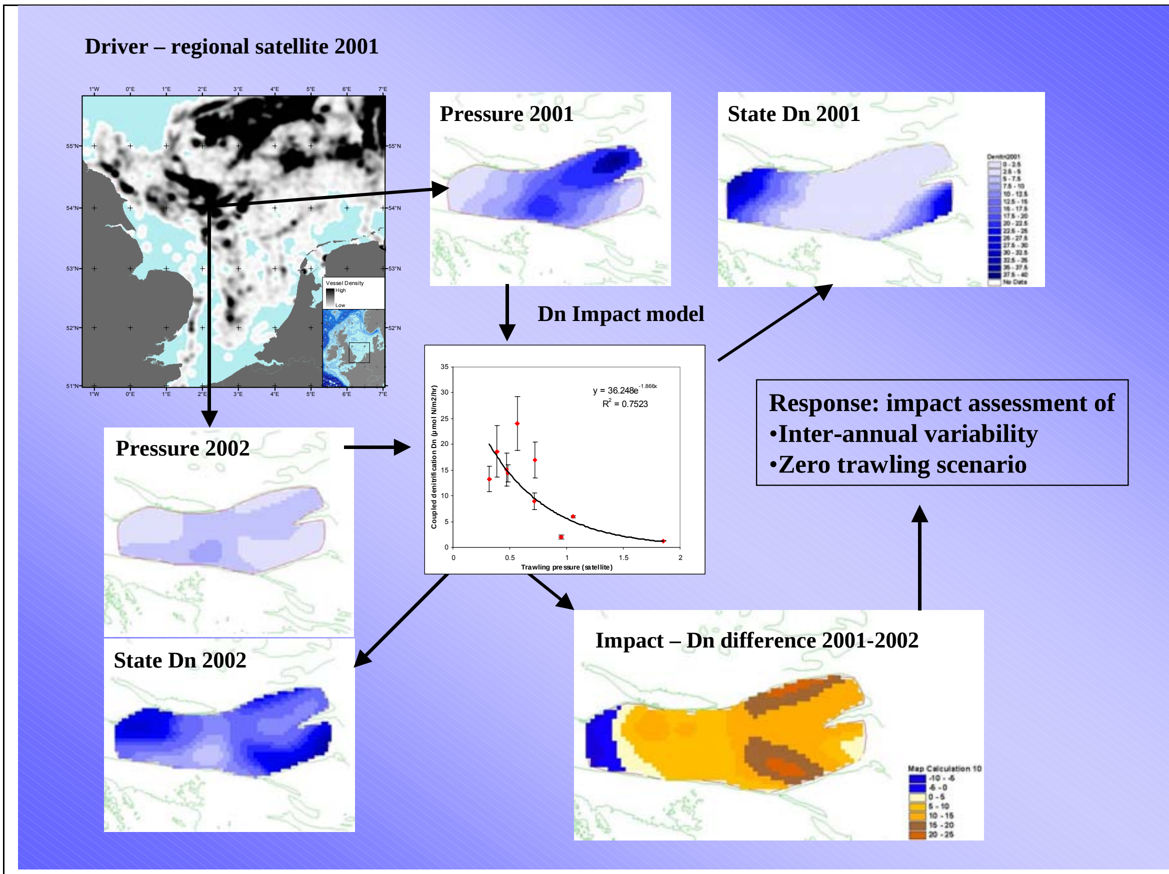

Figure 10. Estimating the impact of variable fishing effort on coupled denitrification (Dn)

The impact models were used to investigate two trawling scenarios in the OSP: interannual variability of distribution and magnitude of trawling effort; and, the effect of even vs. patchy effort distribution for a given total pressure over an equivalent area. There was a significant interannual variability in the distribution and magnitude of trawling effort. The total amounts of Dn for the OSP region in 2001 (high intensity) and 2002 (low intensity) were estimated, using this tool, as 993 and 2415 tonnes N a^{-1} respectively (Table 6). This suggests an increase of 1422 tonnes a^{-1} or ~ 240% from 2001 to 2002. Application of the impact model to a zero trawling level over the same region gave a Dn of 4990 tonnes N a^{-1} suggesting that present day trawling impact is significantly decreasing Dn in this region by between 52 and 80%. A similar application of the sulphate reduction impact model (Eqn 2) with an averaged fishing pressure GIS layer (1992-2002), predicts that trawling has increased sulphate reduction within this region by at least on order of magnitude (~900% from a zero trawling state scenario).

Table 6: Total Dn (2001/2002) and SO4 reduction (1992-2002) for the Outer Silver Pit region

	Dn (tonnes N / yr	Dn % of zero	SO4 (tonnes SO4/year)	% of zero
2001 (high, patchy)	993	20	-	-
2002 (low even)	2415	48	-	-
OF 1992-2002	-	-	158000	990
Difference 2001/02	1422	28	-	-
Zero effort	4990	100	14500	100
Even effort	99	2	158000	990
Difference (Zero vs. even)	4891	98	144000	890
(patchy 2001 vs. even - difference)	849	18	None	None

A change in the distribution of fishing effort was investigated. For sulphate reduction, changes in the distribution of effort did not alter the estimated total amount of carbon remineralised through this route, due to the linearity of the model applied. However, for coupled denitrification there was a significant effect and if the total effort for 2001 is distributed evenly the total denitrification within OSP was decreased from 993 to 99 tonnes N a^{-1}, a decrease of 90% (but to 18% of zero trawling). The results suggest that a patchy fleet distribution, as occurs at present, has less impact on Dn than an even distribution of similar effort.

Support for COBO: towards a Coastal Ocean Benthic Observatory (objective 6)

It was agreed that A1224 should provide part of the matching funds required to support the COBO programme (www.cobo.org.uk). This Strategic Targetted Research Programme (STREP), under the EU 6th Framework Programme, was conceived after A1224 began. Defra is providing additional support for technical developments (contract C2152). After protracted contract negotiation the programme started on 1st March 2004 and will run until 28th February 2007. Its aim is to promote the development of technologies for making *in-situ* observations of the seafloor, including conditions in the upper 10s of cm of the seabed. A critical objective is the integration of technologies. CEFAS is providing the lead in the development of a ‘smart’ datalogger, an X-Y-Z drive for accurately positioning and operating sensitive probes, and a control box to allow controlled disturbance experiments and associated sampling. This builds and extends our existing expertise in lander development and in-situ technologies, provides access to the leading European groups in the field, and will deliver cutting-edge equipment on which to develop evidenced-based advice. The first integrated field campaign is planned for April 2006, in Loch Creran, a sealoch near Oban on the west coast of mainland Scotland. A longer term field experiment will be conducted in the autumn of 2006. The project website has public access.

Souter Point review & research (objective 7)

The variation to the contract agreed in late 2003 allowed additional work to be carried out on physical and chemical factors asssociated with the North Tyne and Souter Point disposal grounds, stimulated by an application by Port of Tyne to dispose highly contaminated sediment (i.e. > Action Level 2). The intent was to provide improved data for simulating the impact. In turn this was incorporated into the CEFAS response, led by Chris Vivian (Burnham-on-Crouch Laboratory), to the application in late 2003 by Port of Tyne to carry out a capping trial of the same material. To put this in context, in 2002 over 410,000 tonnes of dredge spoil from the Tyne estuary was placed in offshore dumping grounds as a result of routing maintenance dredging (S. Blake pers.comm. 2004). Following a challenge to the advice CEFAS was providing, a modelling exercise was conducted to simulate the behaviour of contaminated sediments, in particular TBT, based on an existing sediment transport model (Aldridge et al., 2003). This highlighted deficiencies in our knowledge of TBT behaviour. As a result a review was undertaken to provide appropriate parameter values, should further modelling be required (Tolhurst et al, 2004). It was concluded that TBT degradation and sorption are very much dependent on physical environmental conditions, including salinity, pH, POM (particulate organic matter), suspended load, degree of resuspension and redox conditions. The degree to which TBT is bound to paint particles is highly significant. Conditions in individual estuaries, certainly around the UK coast, are highly variable, and it follows that TBT behaviour will differ from location to location. The data collated by this exercise, to provide parameter values recommended for modelling, should be treated with caution. For robust predictive purposes the behaviour of TBT should be investigated using site-specific information.

Additional fieldwork planned for model validation was modified to reflect the new capping proposal (locations, timing, duration). This reflected discussions which took place between the applicant, the applicant’s consultants, Defra, CEFAS (under contract BA001) and the other consenting organisations, with due regard to the recommendations of the US Army Corps of Engineers Guidance on capping assessments. Three MiniLanders were deployed in spring

2004, across the Souter Point region, to measure the current near the seabed, the suspended sediment concentration at two levels near the seabed, current profiles through the water column and the wave height and period. The suspended sediment sensors were calibrated in a turbidity tank using sediment from Booner tubes (passive sediment traps) mounted on the MiniLander frame and from sediment samples taken nearby at the beginning and end of each deployment. From these raw parameters the bed shear stress was be estimated for calibration /validation of the numerical sediment transport model. An incident with a fishing vessel resulted in one of the landers (including the wave sensor) being recovered inadvertently. This matter has been the subject of legal action and we await being given access to the equipment. This has hampered our advice to MCD regarding the wave climate at the capping site. However, the additional information gained during the review and fieldwork greatly improved the overall advice CEFAS was able to provide.

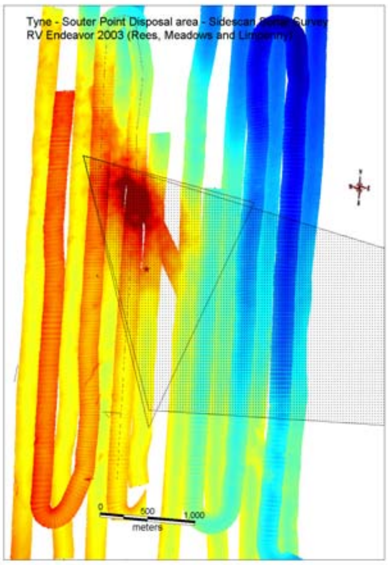

Figure 11. Swathe bathymetry mosaic from Endeavour cruise in 2003 showing the site of the active disposal in the north west corner of Souter disposal site (shown at intensive red “mound”).

Main Implications of the Findings

A novel approach to impact assessment has been developed which combines GIS-based disturbance information and pressure-impact models within a DPSIR framework. It can be applied at various spatial scales and to a range of human activities, and has potential for helping to select reference areas for establishing EcoQOs (Ecological Quality Objectives). The impact assessment approach is quick to apply given availability of the right data and an appropriate impact model (empirical or conceptual). Consequently, it can be used as a screening tool to identify limitations in scientific knowledge or help decide if a full modelling exercise is required. In this way, existing impact models can be applied within a GIS environment to give some preliminary assessment of potential effect in terms of: the sensitivity to changing disturbance distributions (management scenarios); investigations of critical model criteria (environmental conditions); or by combinations of information layers to provide risk assessment. In the present study the approach was applied to three case studies: the impact of trawling on sediment biogeochemistry; the potential impact of disturbance of toxic dinoflagellate cyst viability; and, the behaviour of TBT at the Tyne disposal site.

About 70% of the seabed in the southern North Sea Natural is physically impacted by human activities (aggregate extraction, dredge disposal, trawling). Natural disturbance and fishing impacts are of most importance on a regional scale whilst aggregate extraction and disposal are spatially restricted (<0.1%) but intense. The spatial distribution of the trawling fleets is patchier than originally thought with significant inter- and intra- year variations in impact intensity which can be linked to management actions (i.e. closure of the Cod Box in 2001).

Natural disturbance appears to mediate the sediment type and mobility, redox state and hence associated rate processes, to a significanr extent, based on a combination of field measurements and modelling techniques. The continuum from low natural disturbance (diffusional) to high natural disturbance introduces an increasing degree of natural variability against which human impacts are difficult to detect. High natural disturbance drives high sediment mobility, increased sediment oxygen, high advective pore water fluxes, quicker C recycling and lower associated anerobic processes and C storage. Conversely, in areas where there is low natural disturbance, biogeochemical rates are driven by diffusional processes or mediated significantly by the biota, which generally makes impacts of human activities easier to detect. However, the parameterisation of some disturbances remains problematic, and is reliant on a number of assumptions and simplifications. Further field and modelling work would be beneficial.

In terms of field observations, the SPI camera proved to be a relatively cost-effective and rapid method for assessing the impact of dredge spoil disposal on the benthic fauna and general sediment characteristics. Some of the sediment process measurements are costly and time-consuming, which may impose limits on their use. The EU COBO programme will provide a range of novel in-situ technologies which will complement the more conventional methods.

The behaviour of contaminants when sediments are disturbed remains poorly described. The review of TBT behaviour indicated site-specific information is required if reliable predictions of impact are to be made. In the UK context, and probably elsewhere, the preservation of paint chips in harbour sediments, from former practises, ensures a continuing supply of organotin compounds to coastal waters as a result of dredge spoil disposal. We have shown that TBT, and other contaminants, is bioavailable when sediments are disturbed. This reinforces the need to take post-disturbance behaviour into account when assessing the implications of such activities.

The work on algal cysts illustrated the patchy distribution of particular species. The assumption that the Thames embayment would contain significant quantities was ill-founded. The experimental work allowed the conditions for excystment to be explored, generating a modelling module for inclusion in the GIS framework and providing a predictive capability of the conditions under which a toxic bloom might occur. The model requires additional refinement and experimental data on other problem species.

Possible Future Work

There are several areas which we believe warrant further research effort, building on the developments and increased understanding delivered as part of this project. It is clear that, in terms of ecosystem impact, it is the regional-scale disturbances (natural and trawling) which have the biggest potential to influence sediment biogeochemistry, contaminant movement and algal cyst redistributions, although cotaminants and cysts may have a more local distribution and therefore be more susceptable to smaller-scale events. Given the complexity of space- and time-scales influencing the impact on sediment processes, we consider that a cost-effective approach would be to build on the disturbance overview, process work and GIS tool, and to link these with process-based numerical models that can look at appropriate temporal/spatial changes and feedback mechanisms. Particular attention should be directed at measuring the changes in fluxes across the sediment/water interface and how large-scale processes may effect this. This would require work on resuspension events, which will influence nutrient fluxes and pelagic production.

It would be desirable increasing the number of measurements for selected parameters, to make the pressure-impact models more robust, given the relatively restricted number of measurements which could be taken within the biogeochemical workstrand. This should include coarser sediments, which were not targeted in this project but which represent the bulk of sediments on the UK shelf and may be important for carbon cycling. The mediation/response links between the faunal community and biogeochemical changes are difficult to establish, but are likely to be significant, as is the rate of post-impact recovery. The BPI has provided a good starting point to describe the functioning of the benthic community, but this needs to be refined and validated, for example by using mesocosm experiments with specific organisms and i*n-situ* techniques such as time-lapse SPI.

Additional 'activities' (e.g. oil/gas installations, pipelines, high-speed ferries, other constructions) should be considered to complete the overview of seabed disturbance, and address the need to manage cumulative impacts from mutliple activities, within marine spatial planning. This is needed to define the total impact on an area (linked to sensitivity) but also to improve the provision of advice on indicators, EcoQO reference areas and holistic MPAs (Marine Protected Areas). Some of these data (especially trawling) have restricted availability outside UK waters which inhibits achieving a truly regional and ecosystem approach to impact assessment.

The current models of contaminant behaviour following disturbance are insufficiently robust and rely on assumptions due to lack of site specific information. This needs to be recognised with the implied need for appropriate field and experimental data, to cover the range of sites, contaminants and biota which will be encountered.

The work on algal cysts would benefit from additional experiments on a wider range of organisms, to provide basic information on the conditions for excystment and encystment, cyst viability and probability of toxic events, from oceanogrpahic observations combined with improved modelling descriptions.

Actions Arising from the Research

The results of this project will be taken forward in a number of ways. A major new R&D proposal has been submitted to Defra, with the working title: Marine ecosystem connections – essential indicators of healthy, productive and biologically diverse seas. It is intended that this will build on the GIS-based approach, but will be extended to look at exchanges across the sediment-water interface and pathways to higher trophic levels. The project will provide support to the COBO programme and take advantage of the the technologies which are developed to allow in-situ observations over extended timescales and at precise spatial scales. The results will be fed into a number of on-going Defra projects, including the development of indicators of ecosystem health and promoting the ecosystem approach to environmental management. It will inform our input to a number of international collaborations and advice fora, including OSPAR, ICES (www.ices.dk)and the Marbef Network of Excellence (marine biodiversiy, www.marbef.org). The work on the Tyne disposal site will be used to develop improved assessment techniques and monitoring strategies at this and other sites.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

Publications arising from the project:

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