# Deliverable 4.4

# Report on the model of sediment resuspension, particle size distribution and nutrient concentration behind towed demersal fishing gears.


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## SUMMARY

The report presented here covers three separately conducted significant areas of investigation: observed and modelled physical changes resulting from trawling across different types of sediments (section 1), experimentally constrained associated changes in biogeochemical parameters, such as oxygenation, pigment content, organic and inorganic nutrient concentrations and associated fluxes between the benthic and the pelagic system (section 2), and a theoretical comparison derived from observations and models on likely magnitude of resuspension impact compared to natural background processes (section 3). In bringing together the work across the different disciplines, an opportunity was created for shared learning and evaluation of likely signal transduction from physical seabed impact to resultant chemical re-distributions within the water-column and ultimately extrapolation of the likely consequences for the biological processes that form the basis of ecosystem interactions and productivity.

The work on the physical impacts of gear components emphasises the hydrodynamic nature of sediment mobilisation and the relationship found between the amount of sediment put into the water column and the hydrodynamic drag confirms the findings of O'Neill and Summerbell (2011). It is also demonstrated that the weight (and presumably the penetration) of a component does not influence the amount of sediment mobilised. This is especially interesting as it is often assumed that the amount of sediment put into the water column behind a gear component is directly related to the size of the trench/furrow/scour that it makes on the seabed.

Experimental resuspensions were conducted using fresh sediments collected from four contrasting sites in the Irish sea representing a gradient from fine muddy to coarser sandy sediments. The sites were selected to have equivalent water depth and temperature regimes and were characterised in terms of their oxygen penetration depth and apparent Redox Potential Discontinuity (aRPD) and also nutrient porewater profiles. Collected sediments were were analysed for particle size distribution, organic carbon and nitrogen concentration.The release of porewater nutrients (ammonium, nitrate, nitrate, phosphate and silicate) from sediment aliquots resuspended in bottom water was studied in detail over 24 hours. As expected, nutrient concentrations were much higher in the finer sediments and their associated porewaters. The experimental resuspensions, increased in particular silicate and to some extend phosphate concentrations in the water column, with concentrations significantly exceeding those expected from dilution of the porewater into the receiving bottom water. Silicate increases were continuous over the incubation period consistent with on-going dissolution of silicatious material from phytodetritus, resulting in concentration increases of up to 100 % from the fine and 50 % from the coarser sediments. Phosphate release was more pronounced immediately after resuspension and levelled out after the first hour of incubation. Signals were less clear for the three nitrogen containing nutrients, and only a limited decline was observed in the oxygenation levels, though these findings might have in part be influenced by the low temperatures chosen for the incubations to match observed *in situ* conditions in March. The experimental work clearly demonstrates significant changes in selected nutrient concentrations and ratios and the influence of sediment type on the signals observed.

Early indications from the calculations estimating nutrient fluxes due to trawling induced resuspension relative to natural background flux values, are that the effect is less pronounced for the two chemical species investigated (nitrate and ammonium) than suggested in earlier

SEVENTH FRAMEWORK PROGRAMME

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studies, though further investigations of other parameters, such as phosphate and silicate, might modify this finding. It is further of note that the presented estimates were based solely on physical resuspension and associated change in chemical concentrations, and not on coupled biologically mediated processes which could accompany trawling pressure, i.e changes in rates of sediment nutrient processing and resulting benthic-pelagic fluxes post resuspension and resettling of the disturbed bed. Effects of the physical impact and the instant change in oxygenation status and chemical environment experienced by the sediment biota (macro-, meio- and microbenthos) during a gear pass, might longer term be additionally significant in shifting cycles of nutrients, carbon and oxygen, than the instantaneous changes in concentrations and nutrient availability alone. So while the expected resuspension related chemical fluxes might only be of a comparable order of magnitude to the natural flows, the effect on the system might be significantly different, as organisms adapted to anaerobic conditions or a strongly reducing environment are suddenly exposed to completely different conditions as found in the water-column. And post re-settling of the suspended sediment, new gradients will establish with potentially altered chemical fluxes. Differentiating between acute effects and longer-term consequences of the short term disruption of the established chemical gradients will require further work. Links across to other efforts, such as the work on chronic effects of fishing, will be essential in enabling a more coherent evaluation of the various levels of systematic change experienced.

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# Introduction

Towed demersal fishing gears interact with the seabed on which they are towed. On soft sediments their physical impacts have been classified as being either geotechnical or hydrodynamic. Penetration and piercing of the substrate, lateral displacement of sediment and the influence of the pressure field transmitted through the sediment can be considered geotechnical; whereas the mobilisation of sediment into the water column can be considered hydrodynamic (O'Neill and Summerbell, 2011). These physical impacts have broader ecological, environmental and biological effects and towed fishing gears have been shown to damage habitats, cause benthic mortality, resuspend phytoplankton cysts and copepod eggs and release nutrients (Kaiser et al., 2006; Dounas et al., 2007; Gilkinson et al., 1998; Brown et al., 2013; Drillet et al., 2014; O'Neill et al., 2013).

Here we focus on the immediate nutrient fluxes into the water column, which are likely to be related to both the mobilisation of sediment caused by trawl gears and the penetration into the seabed of these gears (Pilskalin et al., 1998; Duplisea et al., 2001). These nutrient fluxes may fuel pelagic production, alter the water-column light climate, potentially accelerate nutrient recycling and result in an overall increase in primary productivity as well as altering oxygen cycles and organic carbon export rates (Dounas et al., 2007). There remain relatively few studies of the effects of fishing disturbance on nutrient fluxes in soft-sediment communities (Falcao et al., 2003) and yet all the evidence suggests that such effects may have a profound influence on the marine ecosystem. As a wide-spread impact, which contrasts from ambient sediment fluxes and storm effects, the physical effect of trawl gears on soft sediments can alter the resupply of nutrients to the water column, N:P:Si ratios and therefore potentially the magnitude and type of water-column production (Coughlan et al., 2011).

To fully understand how fishing can alter and contribute to changes in nutrient and carbon fluxes from the sediment and consequently how it may affect primary production, eutrophication etc, it is necessary to have a good understanding of the penetration depth of a gear, the amount of sediment it mobilises and the initial substrate chemistry. Here we address these issues by investigating further the individual and combined physical and chemical impacts of towed gears.

The report comprises three sections:
In the first section we extend the physical impacts study of O'Neill & Summerbell (2011) who have demonstrated that, for a given sediment type, there is a relationship between the hydrodynamic drag of the gear element and the mass of sediment entrained behind it. We carry out additional experimental trials to measure the hydrodynamic and the sediment mobilised by a wider range of gear components/elements than have been examined so far. This provides a more in depth and broader understanding of how the individual gear components of a demersal trawl can affect the soft sediments on which they are towed.

In the second section we report on laboratory experiments that look at the temporal dynamics of nutrient release using resuspensions of Celtic Sea sediment. Instantaneous and longer-term sediment oxygen demand is tracked as well as instantaneous and longer term net addition/removal of nutrient forms via sorption/desorption and scavenging reactions.

And in the third section the physical resuspension studies are combined with the nutrient information to obtain estimates of benthic-pelagic nutrient fluxes due to trawling. These are then put in context by comparing them to ambient fluxes to begin to assess their importance on an annual and regional basis.

# Section 1 – the hydrodynamic drag of towed fishing gear components and the mobilisation of sediment.

## 1.1 Introduction

Here we carry out experimental trials on a range of cylindrical and rectangular shaped objects that are in contact with the seabed and extend the approach of O'Neill and Summerbell (2011) who investigate the sediment mobilised in the wake of some of the elements of a demersal trawl on a range of soft sediments that are classified as being sand, muddy sand and sandy mud (Folk description). They demonstrate that there is a relationship between the hydrodynamic drag of the gear element and the mass of sediment entrained in its wake, and that the finer the sediment the greater the mass of sediment mobilised. In their trials the towing speed was kept constant and the hydrodynamic drag of the gear elements was estimated from experimental measurements on similar shaped objects that have been compiled by Hoerner (1965)
In this study we make (i) direct measurements of the hydrodynamic drag and calculate the hydrodynamic drag coefficient for a range of gear elements that are in contact with the sea bed; (ii) we measure the concentration and particle size distribution of the sediment mobilised in the wake of these gear elements (at a range of towing speeds) and demonstrate that as the hydrodynamic drag increases the amount of sediment mobilised also increases; and (iii) we vary the weight of the elements and show that this does not influence the amount of sediment mobilised.

The results provide insights into physical and mechanical processes that take place when a towed fishing gear interacts with the seabed and allow us to develop empirical models of the hydrodynamic drag of the fishing gear components that are in contact with the seabed and of the quantity of sediment mobilised in the turbulent wake behind towed fishing gears.

## 1.2 Experimental trials

### 1.2.1 Towed sledge and instrumentation

Experimental sea trials were carried out on the RV Alba na Mara during October 2013 in the inner Moray Firth, Scotland (**Figure 1.1)**.

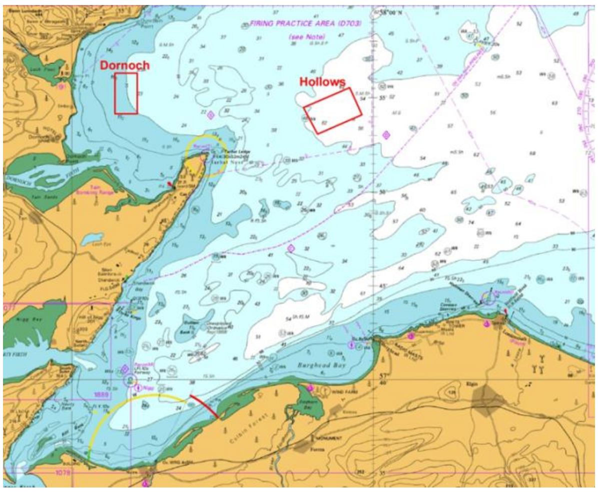



***Figure 1.1.*** *The inner Moray Firth where the trials took place.*

A towed sledge, of height 0.9m, width 2.1m, length 3.0m and weight 530kg was used to tow a range of cylindrical and rectangular objects supported on an axle, which were chosen to simulate a range of gear elements that are in contact with the seabed (groundgear, doors, clumps etc) (**Figure 1.2**). The full range tested is presented in **Figure 1.3** and includes disks and cylinders of diameter 200, 300 and 400mm, and rectangular doors of width 600mm and height 200, 300 and 400mm. In total 14 different configurations were examined, eight different cylinder designs, three configurations of separated disks and three of rectangular doors. These were fixed onto an axle that is 1.3m long and of 63mm in diameter and Strainstall 500kg X-Y load cells were fitted at each end of the axle to measure forces in the horizontal plane at a rate of 10Hz. The axle was attached to a framework (via the load cells) that was free to move in the vertical direction (**Figure 1.4**). Hence, the vertical forces the gear elements exerted on the sea bed were the gravitational forces associated with the gear element and that part of the supporting framework that was free to move. It was also possible to increase the applied vertical forces by attaching weights to the framework and each of the configurations was tested having vertical weights (in water) of approximately 60, 120 and 180kg. During each deployment the speed at which the sledge was towed was increased incrementally over a thirty minute period from 1 to 2 m/s. The vessels GPS recorded the speed of the sledge over the ground at a rate of 1Hz. A LISST 100X was positioned centrally 1.9m behind the axle, with the sampling head 35cm off the seabed to measure the concentration and particle size distribution of the sediment mobilised in the wake of the gear components. The LISST 100X uses the laser diffraction principle to measure the concentration of particles in 32 logarithmically increasing size ranges between 2.5 and 500 µm and was set to take measurements at a rate of 1Hz.

All drag, speed and concentration data were time-averaged into 10s intervals and it is these data that are examined in the following analyses. Two types of experiments were carried out: the first set were related to measuring the hydrodynamic drag, during which the elements were not in contact with seabed; while during the second set the elements were in contact with the seabed, and the geotechnical forces and the mobilisation of sediment were investigated.

To classify the sediment on which the trials took place, 15 grab samples were taken with a modified Day grab and the top 2.5 cm sampled and frozen. Subsequently these were defrosted and dried and the particle size distribution of each sample was analysed using a Malvern Instruments Mastersizer E Particle Size Analyser. An average was then taken to characterise the particle size distribution at the site. To allow comparison with the measurements from the plume, particles in the size range 2.5–500 µm were categorised in the same 32 logarithmically increasing size ranges as the LISST 100X measurements.

***Figure 1.2.*** *The towed sledge used to tow the range of cylindrical objects supported on an axle.*

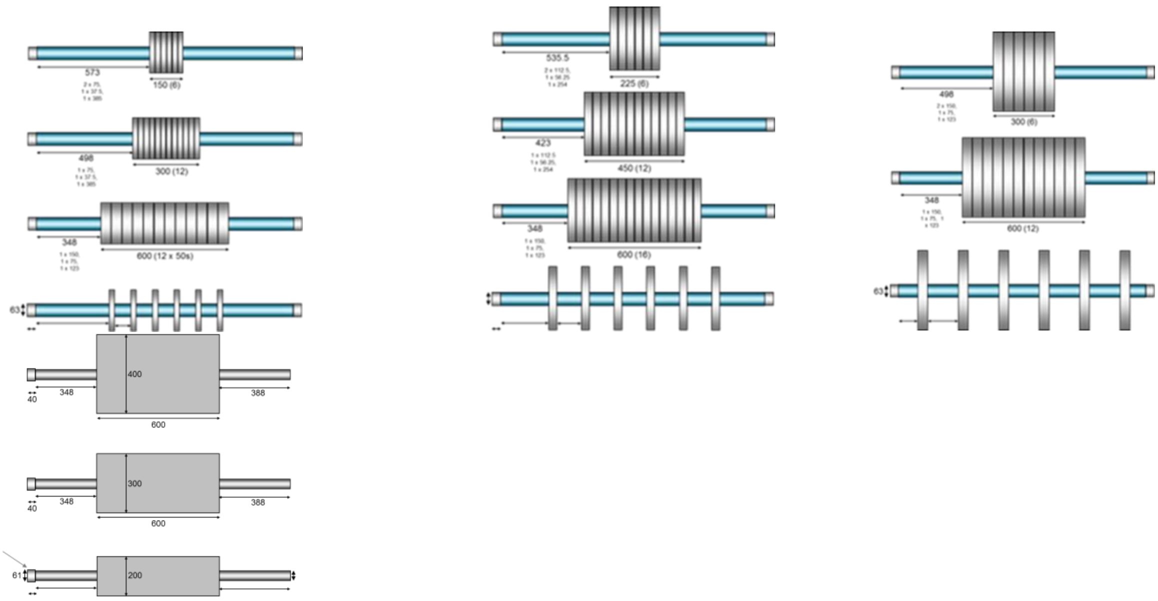



***Figure 1.3.*** *The range of gear components chosen to simulate some of the groundgears, clump weights and doors used in demersal fisheries comprising disks, cylinders and doors of diameter/heights 200, 300 and 400mm.*

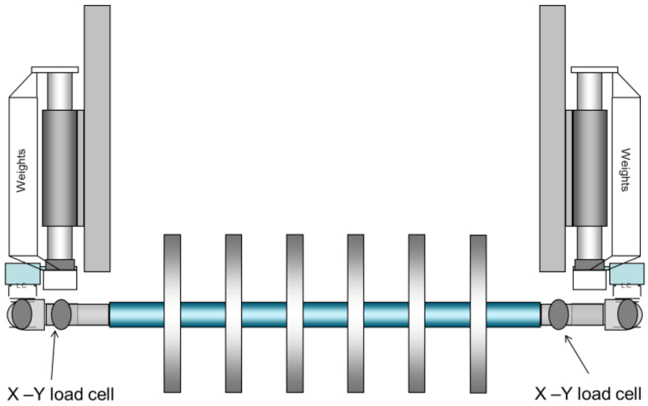



***Figure 1.4.*** *The framework to which the gear components and axle were attached showing where the additional weights were fitted and the position of the two Strainstall 500kg X-Y load cells.*

### 1.2.2 Hydrodynamic drag

In the first set of experiments, in order to estimate the hydrodynamic drag acting on them, the elements were held between 2 and 5 cm above the seabed and towed at speeds of between 1 and 2 m/s. The hydrodynamic drag, *D* (N), on a body is usually expressed as

$$D = 0.5\rho A_d U^2 c_d$$

where $A_d$ ($m^2$) is the frontal area, $U$ ($ms^{-1}$) is the flow or towing speed, $\rho$ ($kgm^{-3}$) is the density of water, and $c_d$ is the hydrodynamic drag coefficient of the body, a dimensionless quantity that characterises the drag on a body. Here we assume that the hydrodynamic drag comprises the drag of the gear element and the drag of the exposed part of the axle. Hence we fit a curve of the following form to the hydrodynamic drag data

$$D = 0.5\rho A_{elem} U^2 c_d + 0.5\rho A_{axle} U^2 c_{axle}$$

where $A_{elem}$ is the frontal area of the gear element and $A_{axle}$ is the exposed frontal area of the axle. $c_d$ represents $c_{cyl}$, $c_{disk}$ or $c_{door}$, the hydrodynamic drag coefficients of the cylinders, the circular disks and the rectangular doors respectively and which along with $c_{axle}$ , the hydrodynamic drag coefficient of the axle, are the four unknowns that need to be estimated. Hoerner (1965) collates data from a number of studies and demonstrates that as the diameter (or height) to breadth ratio (*d*/*b*) increases, the drag coefficient for (i) truncated cylinders, goes from having a value of about 1.17 (and being fully two dimensional in nature) to having a value of about 0.67 for *d*/*b* > 0.33 and (ii) rectangular plates, goes from a value of about 2.0 to 1.18 for *d*/*b* > 0.33. **Figure 1.5** reproduces the figure from Hoerner (1965) where he presents these data which we have summarised using exponential curves. Given that the *d*/*b* values of the cylinders, disks and doors we are dealing with are ≥ 0.33, the analysis we carry out assumes that we have a common $c_{cyl}$ coefficient for the eight cylinders, a common $c_{disc}$ coefficient for the three configurations of separated disks and a common $c_{door}$ coefficient for the three rectangular doors. It considers the $c_{axle}$ coefficient in two ways, in the first instance, it is assumed that it varies between the three gear element categories, and in the second, that it has a single common value for all fourteen data sets.

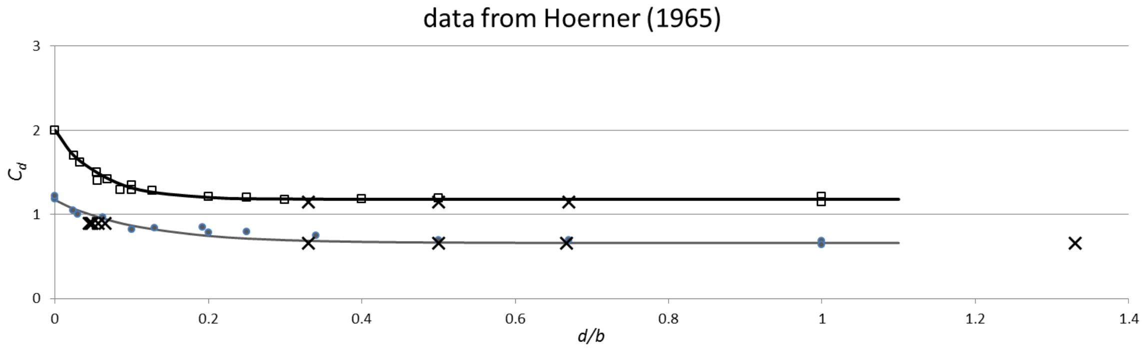



***Figure 1.5.*** *The hollow rectangles and grey circles are the hydrodynamic drag coefficient measurements collated by Hoerner (1965) for rectangular plates and circular cylinders respectively and plotted against d/b, diameter (or height) to breadth ratio. The curves are exponential functions we have fitted to these data and the black crosses are hydrodynamic drag coefficients we estimate for the gear components tested here when we assume a common drag coefficient value for axle for all fourteen data sets.*

### 1.2.3 Mobilisation of sediment

In the second type of experiment, the objects were in contact with the seabed. The trials were carried out with vertical force loadings of approximately 60, 120 and 180kg and at speeds of between 1 and 2 m/s. During these experiments the LISST 100X measured the concentration and particle size distribution of the sediment mobilised in the wake of the gear components. O'Neill and Summerbell (2011) find a relationship between the hydrodynamic drag of a gear element and the amount of sediment mobilised in its wake. We explore this relationship here by plotting the mass of sediment mobilised per unit width against the hydrodynamic drag per unit width where again the hydrodynamic drag was estimated using the equation above. We also investigate whether the amount of sediment mobilised depends on the weight of the gear component by plotting for each component the mass of sediment mobilised at each of the three vertical force loadings.

## 1.3 Results

The analysis of the day grab sediment samples classified the experimental sites (using the Folk description) as being very fine silty sand. **Figure1.6** contains a detailed description in terms of the percent volume in each particle size bin. The silt and clay component (% of sediment < 63 µm) is 12% and the d50 is 100 µm.

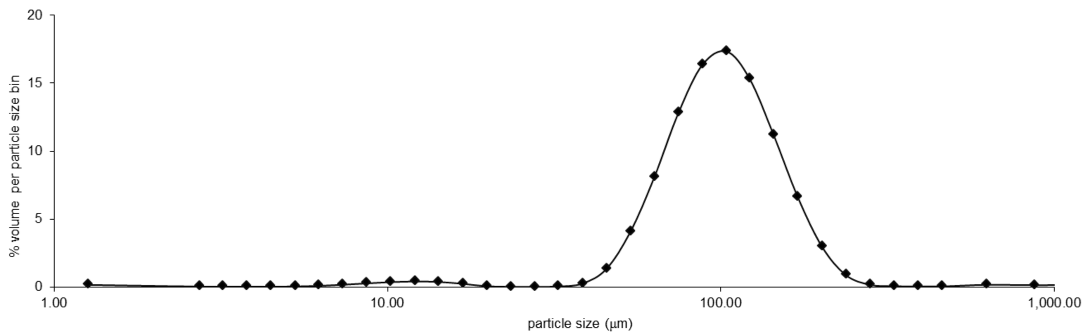



***Figure 1.6.*** *The particle size distribution of the sediment on which the trials took place presented in terms of the volume concentration in 32 logarithmically increasing particle size bins.*

### 1.3.1 Hydrodynamic drag

Figure 1.7 contains the hydrodynamic drag data of the each tow of a gear element and the supporting axle when the element is held clear of the seabed. The grey curves are the regressions to the data when it is assumed that $c_{axle}$ varies between the three gear element categories and the black curves when it is assumed to have a common value for all fourteen data sets. The corresponding drag coefficients are presented in **table 1**. Although, the additional flexibility offered to the regression by assuming that $c_{axle}$ varies between gear elements provides a slightly better fit, in general there is very little difference between either approach. Hence in the forthcoming analysis we assume the simpler form which assumes a common $c_{axle}$ value for all fourteen data sets. Furthermore, as can be seen in **Figure 1.5**, the resulting drag coefficient estimates using this approach are more consistent with those presented by Hoerner (1965).

**Table 1.** The drag coefficients of the cylinders, disks and doors when it is assumed that $c_{axle}$ varies between the three gear element categories and when it is assumed to have a common value for all fourteen data sets.

| | $c_d$ | $c_{axle}$ | $c_d$ | $c_{axle}$ |
|---|---|---|---|---|
| Cylinders | 0.63 | 0.92 | 0.66 | 0.85 |
| Disks | 1.00 | 0.73 | 0.89 | 0.85 |
| rectangular door | 1.28 | 0.45 | 1.15 | 0.85 |

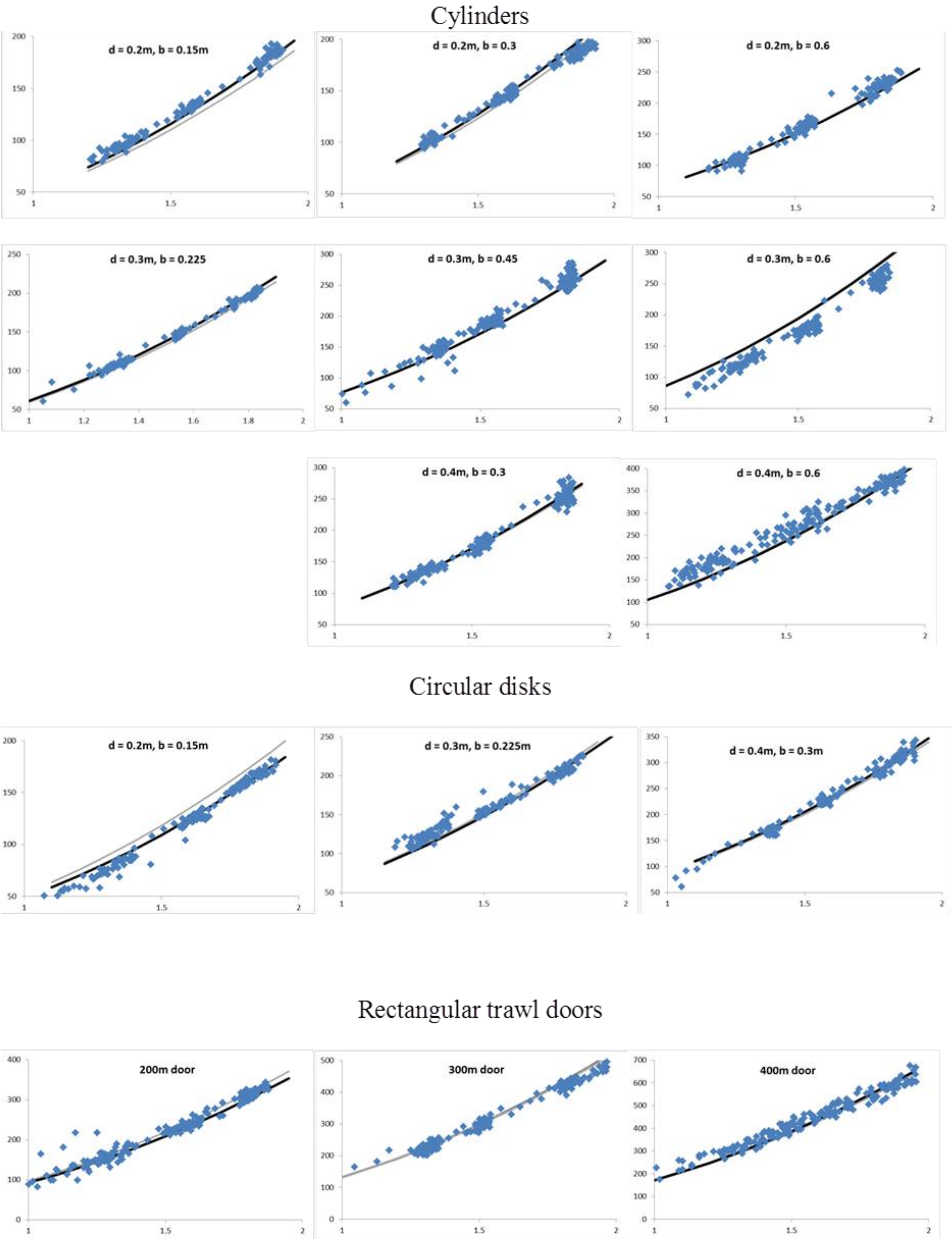



***Figure 1.7.*** *The hydrodynamic drag data of each gear element and the supporting axle. The grey curves are the regressions to the data when it is assumed that $c_{axle}$ varies between the three gear element categories and the black curves when it is assumed to have a common value for all fourteen data sets.*

## 1.3.2 Mobilisation of sediment

**Figure 1.8a** demonstrates that the mass of sediment mobilised in the wake of the cylindrical components (rolling and fixed) and the rectangular doors increases as the hydrodynamic drag per unit width increases. The black lines are linear regressions to three data sets. There is a lot of variability in these data which reflects the turbulent nature of the plume. Similar quantities of sediment are put into the water column behind the rolling and fixed cylinders, however less is mobilised behind the rectangular doors, which may reflect differences in the nature of the turbulence behind these two sets of geometric objects. **Figure 1.8b** plots the same data but this time the thicker black line is the linear regression to all the data combined and the thinner line is the prediction of sediment mobilised from the expression given by O'Neill and Ivanovic (2015) where the silt fraction is assumed to be 12%. It is clear there is very good correspondence between the two.

**Figures 1.9a and b** replot these data, but in this case as a function of the weight per unit area exerted by each component on the seabed. It is clear from these figures that, for a given component, there is no relationship between the amount of sediment mobilised and the pressure force exerted (and presumably the penetration made) by a component.

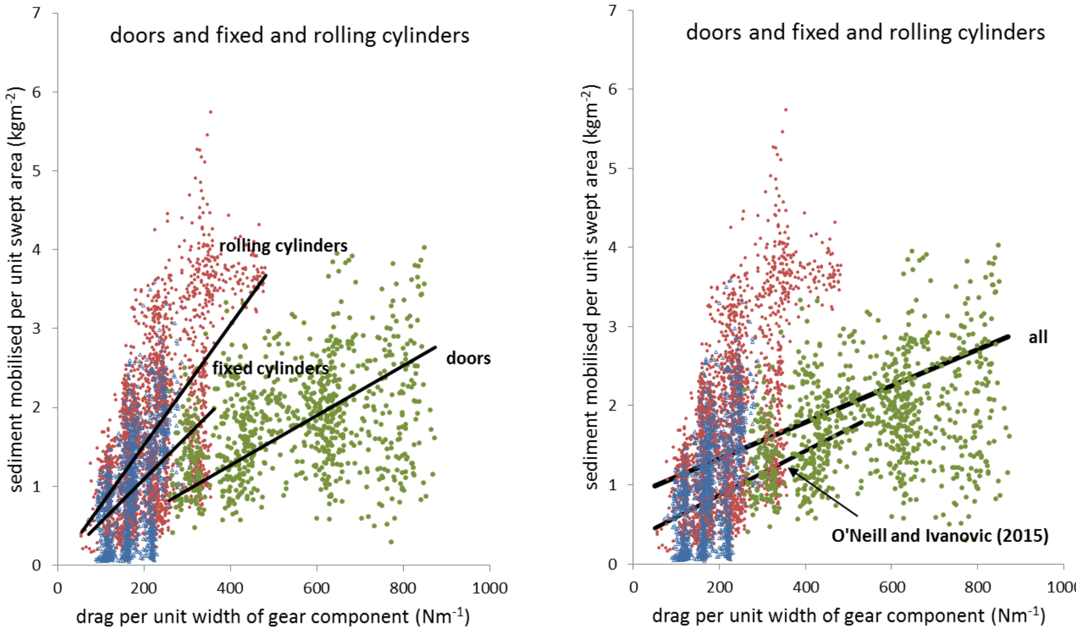



***Figure 1.8. (a)** The sediment mobilised in the wake of the cylindrical components (rolling and fixed) and the rectangular doors plotted against the hydrodynamic drag per unit width. The black lines are linear regressions to three data sets. **(b)** The same data but where the thicker black line is the linear regression to all the data combined and the thinner line is the prediction given by O'Neill and Ivanovic (2015) for sediment with a silt fraction of 12%.*

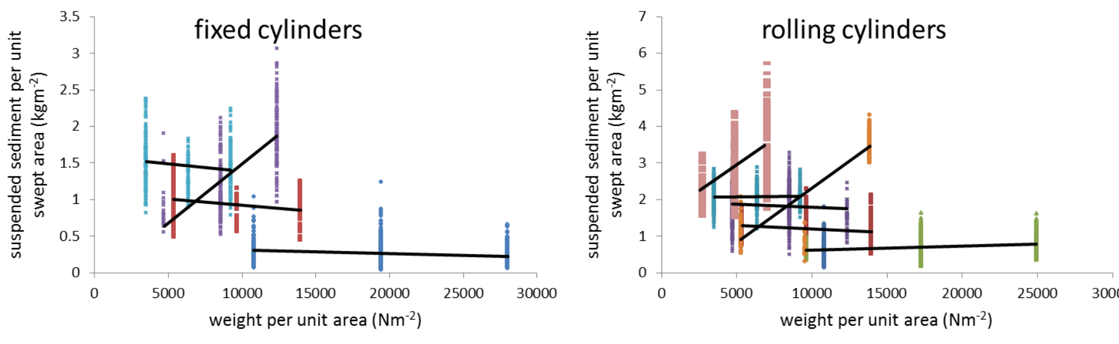



***Figure 1.9.** The mass of sediment mobilised in the wake of **(a)** the fixed and **(b)** the rolling cylindrical components plotted against weight per unit area.*

## 1.4 Conclusions

These results highlight the hydrodynamic nature of sediment mobilisation. The relationship found between the amounts of sediment put into the water column and the hydrodynamic drag confirms the findings of O'Neill and Summerbell (2011). In their experiments the hydrodynamic drag of the gear elements was estimated from results in the literature (Hoerner, 1965) and the towing speed was kept constant. Here we further test this relationship by making direct measurements of the hydrodynamic drag for a range of gear components that were towed at speeds between 1 and 2 ms-1 and obtained results which are consistent with those complied by Hoerner (1965). We also demonstrate that the weight (and presumably the penetration) of a component does not influence the amount of sediment mobilised. This is especially interesting as it is often assumed that the amount of sediment put into the water column behind a gear component is directly related to the size of the trench/furrow/scour that it makes on the seabed (Churchill, 1989). The absence of a dependency on gear component weight again emphasises the hydrodynamic nature of sediment mobilisation and also identifies the possibility of reducing this type of impact by using more streamlined components.

# Section 2: The biogeochemical effects of trawling (penetration and resuspension) on nutrient fluxes:

## 2.1 Introduction

Shelf sea productivity is maintained by strong benthic-pelagic coupling, particularly of nutrients. Nutrient flux rates from the seabed to the water column occur as a result of carbon remineralisation and recycling. The natural ambient fluxes (diffusional/advective) of nutrients across the Sediment-Water Interface (SWI) can be controlled in differing locations by seabed chemistry and the activities of benthic fauna. Disturbances such as storms and other physical impacts such as trawling have been shown to directly alter the timing and magnitudes of these fluxes (Coughlan et al., 2011; Diesing et al., 2013; Tengberg et al., 2003). Although some work has been undertaken to address chemical fluxes induced by storm resuspension (Coucerio et al., 2012), the understanding of the effect of demersal gears on long-term release of nutrients remains poorly constrained.

As described in section 1 of this report, demersal gears are designed to impact the seabed by a combination of hydrographic and geotechnical processes, and have been shown to disturb large amounts of sediment either by resuspension or turning and ploughing the seabed (O'Neil et al., 2008; O'Neil et al., 2011; 2013 and 103b, O'Neill and Ivanovic, 2015; Pilskalin et al., 1998, Palanques et al., 2001; Palanques et al., 2014;) depending on gear type and location of impact. Aside from changing the inorganic suspended particulate matter concentration and distributions above the bed as resuspended plumes, these impacts can also stir and turn the bed to expose new sediment from depth or redistribute sediment pore-waters during pressure changes above the sediment water interface and within the sediment associated with the gear passage. Various studies have focused on the effects of gears passing on the inorganic suspended load or on changes in the geochemical bed composition (Trimmer et al., 2004; Pusceddu et al., 2005). However, this impact on the bed also has the capacity to alter the chemical connectivity of the sediment-water column (benthic-pelagic coupling) depending on the mode of action of the gear, sediment type and initial sediment chemistry. This can shift the rate, timing and magnitude of resupply of chemical species such as nutrients, carbon fractions and contaminants from the bed into the water-column, and thus alter ecosystems processes affected by benthic-pelagic exchanges.

Limited work has been done on the chemical changes which occur once sediment is released from the bed into the water column and subsequent net input or removal of chemical species such as nutrients into bottom waters. Past studies have tracked nutrient releases using trawl gear or *in-situ* devices (Durrieu de Madrona et al., 2005; Dounas, 2006) or forced resuspensions in laboratory mesocosms (Tengberg et al., 2003; Percival, 2004). Others have developed methods to track plume sediment and nutrient concentrations and calculate release via a closed budget type approach (Durrieu de Madron et al., 2005; Coughlan et al., 2012). These studies have shown that changes in fluxes and the nutrient ratios of release can be significantly different, especially for nutrients generated deeper in the bed (i.e.silicate or phosphate) or which have low oxidation/scavenging behaviour (i.e. nitrate).
However, these methods are limited in their ability to reproduce a realistic trawl impact on the sediment in terms of depth or scale whilst in mesocosms or restricted to linking instantaneous chemical measurements (derived from within a plume or from the bed) to calculate nutrient release/flux without information on subsequent chemical processing such as oxidation or scavenging (particularly relevant for nutrients such as ammonium and phosphate). There is therefore a need to quantify sediment and nutrient partitioning changes and kinetics under

different sediment resuspension scenarios which are consistent with trawling disturbances and track overall changes in nutrient fluxes (+ or -) from ambient conditions.

The experimental work described below was designed to provide information on the net release of different nutrients immediately after resuspension and also investigate how this release changes with time after a trawl pass i.e. longer-term changes in water chemistry following an acute disturbance. The overall aim was to provide a mechanistic approach to assess net nutrient release with respect to variable gear disturbance depth and evaluate resulting concentrations and nutrient specific, post-resuspension chemical processing within any associated plume. Experiments were run for differing depth of sediments (in relation to differing gear penetrations/disturbance horizons) and also different types of sediments (to reflect differing plume locations or concentrations and hence particle/dissolved phase interactions). By tracking differing nutrient flux behaviour, initial substrates and depths it was envisaged to develop a systematic approach to describing nutrient releases associated with gear disturbance (penetration or resuspension) for a discrete period post trawl.

# 2.2 Material and Methods:

## 2.2.1 Sediment sampling and site characterisation

**January 2014: North Sea**

Three sites in the North Sea were selected for sampling on a routine Cefas /Defra cruise. These sites (North Dogger, Oyster Grounds and Sean Gas Field) have been extensively studied previously (Marine Ecosystem Connections Programme 2007-2012, Defra contract ME3205) and would have enabled building future work on a good understanding of sediment biogeochemistry and natural / storm fluxes in these locations. Unfortunately severe weather conditions for the whole of the 2 week cruise prevented any coring or experimental work.

**March 2015: Celtic Sea**

Intact box-cores were taken from four locations in the Celtic Sea during a cruise in March 2015, associated with the UK NERC Shelf Seas Biogeochemistry (SSB) Programme (cruise DY021). The location of the study sites (Boxes A, G, H and I, representing main SSB process sites) are marked on **Figure 2.1** below.

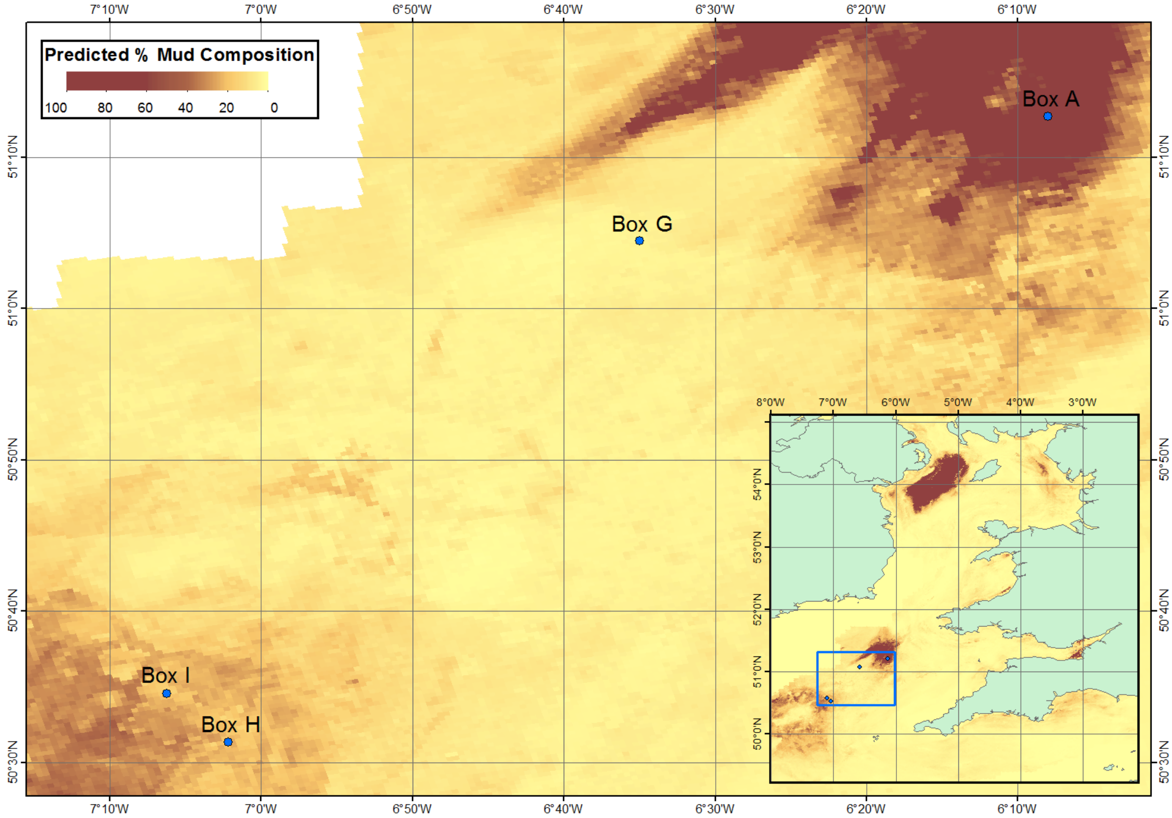



***Figure 2.1:*** *Map of site locations for sediment samples collected for resuspension experiments during March 2015 cruise plotted on a predicted % mud layer (data used to create this layer is published at [http://doi.pangaea.de/10.1594/PANGAEA.845468](http://doi.pangaea.de/10.1594/PANGAEA.845468); Stephens and Diesing (submitted).*

The sediment types were selected on the basis to cover a spectrum ranging from mud to sand, specifically:

**Box A= mud**
**Box G = sand**
**Box H = muddy sand**
**Box I = sandy mud**

In selecting the sampling sites, it was considered important that sediments were collected from locations with similar depth (approximately 100 m) and bottom water temperature regimes to minimise the influence of these critical environmental parameters on sediment biogeochemistry.

Sediment Profile Images (SPI) were obtained using the Cefas SPI camera at all four sites to visually characterise the sediment types under investigation and deduct apparent Redox Potential Discontinuity (aRPD) (Teal et al., 2010).

To recover fresh sediment from the four sites, coring was carried out using a NIOZ box corer. Resuspension samples were taken from a single NIOZ core at each site, along with other supporting measurements to enable site characterisation (see **Figure 2.2**). These included a sub core for oxygen microelectrode profiling, a sub core for both coarse scale particle size analysis (PSA) and total organic carbon and nitrogen (OCN) slicing (0-5cm and 5-10cm bulked samples).

Nutrient pore water profiles at up to ten depths between 1cm and 20cm were collected by a sipper system (Sivyer, 1999). The sippers were inserted into NIOZ cores and a vacuum applied to withdraw samples, which were usually collected within 15mins of the core arriving on deck. The extracted water samples were filtered at 0.2 µm and analysed for nitrate, nitrite, silicate, phosphate and ammonium using a scalar auto-analyser (Kirkwood et al., 1996).

Oxygen profiles were determined on-board ship in intact sub cores using glass microelectrodes (Unisense) according to Rabouille et al. (2003).

Total Organic Carbon (TOC) was analysed using broadly similar methodology to that described by Verado et al. (1990). Samples were freeze-dried and then ground to homogenise the sample. Inorganic carbonate was removed from a subsample using sulphurous acid to excess. Sub-samples (~0.5 g) were then weighed into tin cups and analysed using a Carlo Erba EA1108 Elemental Analyser.

The resuspension samples were collected in triplicate using modified plastic syringes (from BD Plastipak). Three different sized syringes were used to gather sediment from different depths, while maintaining a similar total sediment volume and therefore similar concentration within the resuspension experiments were achieved. The resuspension samples were as follows:

0-2cm depth: 60ml syringe, diameter 27mm, sediment volume 10 ml
0-4cm depth: 20ml syringe, diameter 19mm, sediment volume 12 ml
0-6cm depth: 10ml syringe, diameter 14mm, sediment volume 10 ml

A full set of resuspension experiments was undertaken with sediments from each site as described in **section 2.2.2** below.

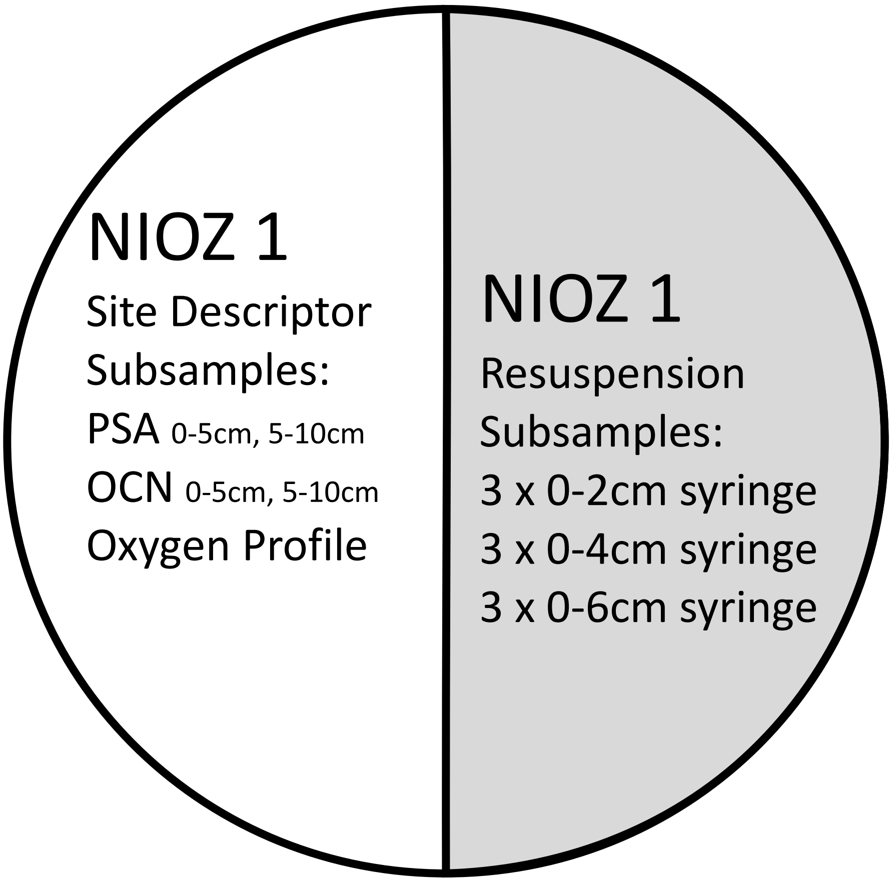



***Figure 2.2:*** *An overview of the sampling regime from each NIOZ core, left hand side dedicated to gathering site characteristics, right hand side to gathering sediment for use in the resuspension experiments.*

### 2.2.2 Experimental Set-up for resuspension

A water-filled incubation tank was set up in the ambient temperature wet lab on board the RRS Discovery. The tank water temperature was set to 9°C (close to the ambient bottom water temperature at time of sample collection as measured by Conductivity Temperature Depth CTD instrumentation), with water continuously being circulated around the tank and through a chiller. Twelve individual magnetic stirrer plates were placed inside the tank and firmly held in position below the water using a thick sheet of foam with holes. A plastic bottle-rack on stilts provided support for 12 separate 2 l sample bottles when placed on the submerged stirrers. Incubation took place in the dark with light excluded from the tank using floating plastic balls and black plastic sacks.

12 hours prior to the coring activity, a CTD profile was carried out and bottom water was collected. A 30 litre carboy filled with bottom water was placed in the Control Temperature (CT) laboratory. This water was aerated and kept in the dark, to ensure suitable water was available for sediment plugs suspension. Before the coring activity started the carboy of bottom water was retrieved from the CT room. The 2 litre experimental bottles were rinsed with bottom water, before being completely filled. A magnetic stirrer was added and the bottles closed. The bottles were then placed into the incubation tank to equilibrate and the stirrers activated. See **Figure 2.3** for an overview of the tank layout and **Figure 2.4** for a cross-section of the tank.

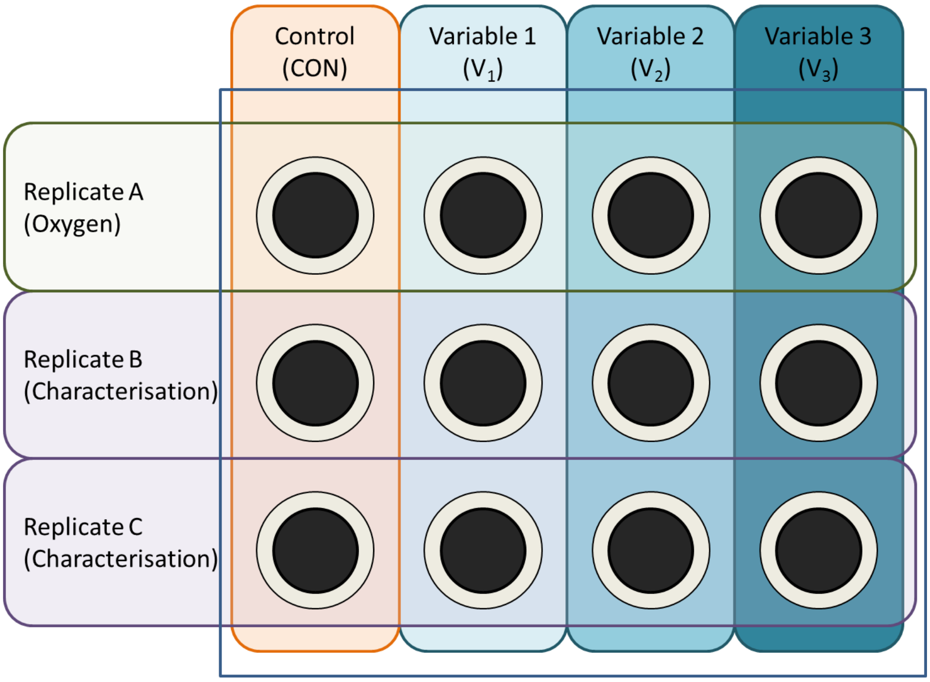



***Figure 2.3:*** *Schematic of incubation tank layout for resuspension experiment (top view with sample ID)*

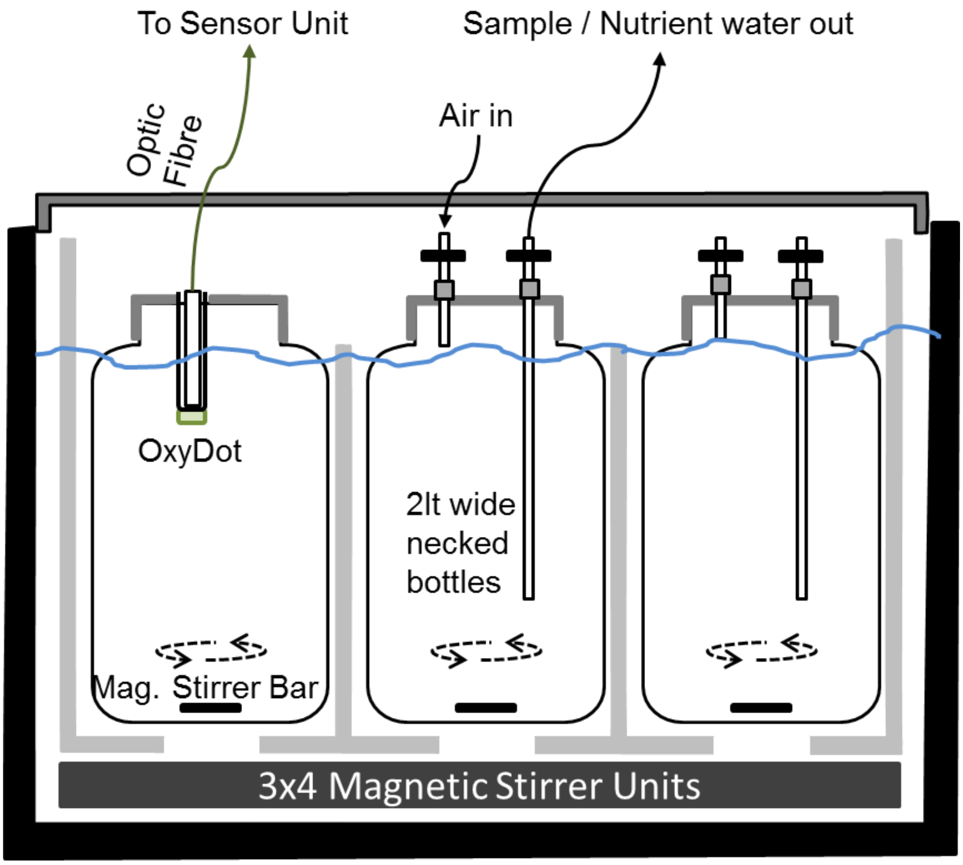



***Figure 2.4:*** *Schematic of incubation tank (cross section)*

Once all experimental bottles were filled, the remaining water in the carboy was used for the time-zero time point samples. Sub-samples were taken for nutrient, chlorophyll and SPM analysis and processed using the following methods:

*Nutrients*
A 20ml sample was hand filtered through a 0.2µm pore size disposable polycarbonate syringe filter. The filtered water sample was stored in the fridge at 5°C until on board analysis (conducted by Malcolm Woodward from PML onboard the RV Discovery in the context of the NERC/Defra Shelf Sea Biogeochemistry Programme).

*Chlorophyll*
A 250ml sample was filtered using ~0.7µm pore size GF/F over a vacuum pumped filter rig. The filter paper wrapped in tin foil before being stored at -80°C before later analysis (using fluorescence measurements according to Tett, 1987) at Cefas .

*Suspended particulate matter (SPM)*
A 1l sample was filtered using a pre-weighed 0.4µm pore size polycarbonate filter over a vacuum pumped filter rig. The filter paper was then placed in a plastic Petri dish and stored at room temperature for analysis back at Cefas.

*Continuous Oxygen recording*
To enable continuous observation of the oxygen concentration for the duration of the resuspension experiment, a FireSting Optical Oxygen Meter (OxyDot) was set up next to the incubation experiment. Before each experiment the OxyDots were calibrated using a two point calibration system: at 100% and 0% saturation. For 100% saturation in situ sea water was aerated to the 100% saturation point and for the 0% saturation a solution of ascorbic acid and sodium hydroxide in Ultrapure water was used. The OxyDot probes were inserted into the four Oxygen Replicate bottles without re-opening the bottles, as an OxyDot sensor spot was pre-attached to the end of a small glass tube, held in suspension within the 2l bottle (see **Figure 2.4**). The optical cable was inserted into this glass tube until it touched the bottom. This enabled oxygen to be measured optically while maintaining a sealed environment.

Once collected, the sediment samples (for differing depths) were added to the incubation vessels. The samples were carefully extruded from the syringes directly into the relevant experimental bottles. This was done without removing the bottle from the incubation tank to ensure the magnetic stirrer was not disturbed. Bottom water was used to top-up the experimental bottles to ensure they were completely full before being re-sealed.

Each experiment was considered to have started once the sediment samples were added to their relevant bottles and the OxyDots attached to the FireSting meter with the software started recording. Samples for nutrients, chlorophyll and SPM were collected from each of the Replicate 2 and Replicate 3 sample bottles at pre-defined time intervals (see **Table 2.1** for sampling details) over a 24 hour period and processed as described previously for the bottom water analysis. The only difference was that lower sample volume was needed for SPM (~100ml) due to the high suspended sediment content. For the final time step at the end of the experiment, all bottles were sampled including the sealed Oxygen replicates.

**Table 2.1:** Overview of the sampling regime for each 24 hour resuspension experiment (T shows time since start of experiment, with T=0 being the starting point post sediment addition; Nut = nutrient analysis sub-sample, Chl = combined chlorophyll and phaeopigment sub-sample, SPM = suspended particulate matter subsample; O2 = bottle dedicated to continuous oxygen recording, R2 and R3 are the two replicates for subsampling, V1-V3 denotes the three depth variables with associated sediment quantities)

| | | **Experiment (Depth/Concentration)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Control** | | | **V1** | | | **V2** | | | **V3** | | |
| | | **n/a** | | | **0-2cm/10ml** | | | **0-4cm/12ml** | | | **0-6cm/10ml** | | |
| | | **O2** | **R2** | **R3** | **O2** | **R2** | **R3** | **O2** | **R2** | **R3** | **O2** | **R2** | **R3** |
| T=0 | Nut | ✓ | | | | | | | | | | | |
| | Chl | ✓ | | | | | | | | | | | |
| | SPM | ✓ | | | | | | | | | | | |
| T=1<br>15 mins | Nut | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ |
| T=2<br>30 mins | Nut | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ |
| T=3<br>1 hour | Nut | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | Chl | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ |
| T=4<br>3 hours | Nut | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ |
| T=5<br>6 hours | Nut | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ |
| T=6<br>12 hours | Nut | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ |
| T=7<br>24 hours | Nut | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Chl | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | SPM | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Nut Total | | 63 | | | | | | | | | | | |
| Chl Total | | 21 | | | | | | | | | | | |
| SPM Total | | 13 | | | | | | | | | | | |

At the end of one experiment, the final (T=7) samples were taken and the bottles were removed from the incubation tank. Any remaining sample was disposed of and the bottles were rinsed out with ultrapure (MilliQ) water.

## 2.3 Results

### 2.3.1 Collection site and sediment characterisation

For the purpose of this experimental study, it is important that the depth from which the NOIZ cores were recovered were broadly similar (site A: 111m, site G: 103m, site I: 113 m and site H: 109m) and that the range from mud to sand observed aligned well with the envisaged distribution of sediments ranging from fine/cohesive to coarse/advective, as can be seen from the PSA distributions detailed in **Table 2.2** below.

**Table 2.2** Particle size analysis (PSA) and sediment organic carbon and nitrogen content (OCN)

| Site ID | Gravel (%) | Sand (%) | Silt/Clay (%) | Total organic carbon (%) | Nitrogen (%) |
|---|---|---|---|---|---|
| **Box A, 0-5** | 0.03 | 34.46 | 65.50 | 1.23 | 0.14 |
| **Box A, 5-10** | 0.01 | 30.27 | 69.72 | 1.22 | 0.13 |
| **Box I, 0-5** | 0.03 | 67.02 | 32.94 | 0.68 | 0.09 |
| **Box I, 5-10** | 0.00 | 70.13 | 29.87 | 0.66 | 0.09 |
| **Box H, 0-5** | 0.22 | 74.73 | 25.05 | 0.46 | 0.08 |
| **Box H, 5-10** | 0.45 | 72.36 | 27.19 | 0.56 | 0.08 |
| **Box G, 0-5** | 0.98 | 94.68 | 4.34 | 0.12 | 0.05 |
| **Box G, 5-10** | 2.86 | 86.15 | 10.99 | 0.15 | 0.05 |

**Figure 2.5** shows the PSA distribution for each slice as a percentage split of gravel, sand and silt/clay fractions. To most accurately link with the resuspension experiment, where plugs of sediment were retrieved from depth of up to 2cm, 4 cm and 6 cm respectively, the following site characterisation is based on the surface slice (0-5cm):

Box A is characterised as containing 66% silt/clay = mud
Box I contains 33% silt/clay = sandy mud
Box H contains 25% silt/clay = muddy sand
Box G contains 4% silt/clay = sand

This confirms the site classifications by sediment type confirmed with the range targeted during the cruise programme and for the experimental design.

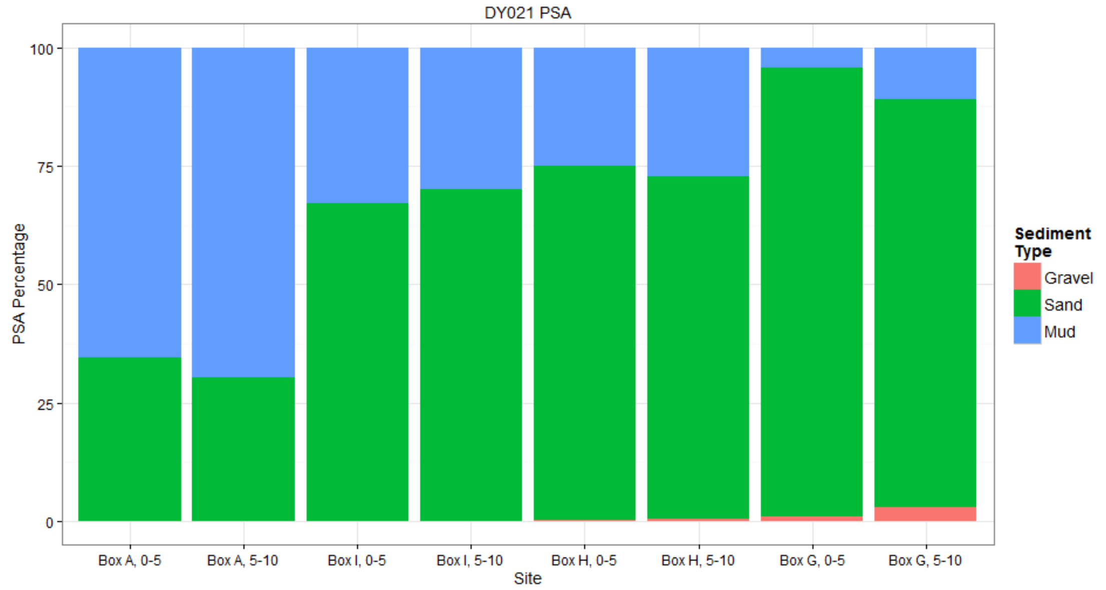
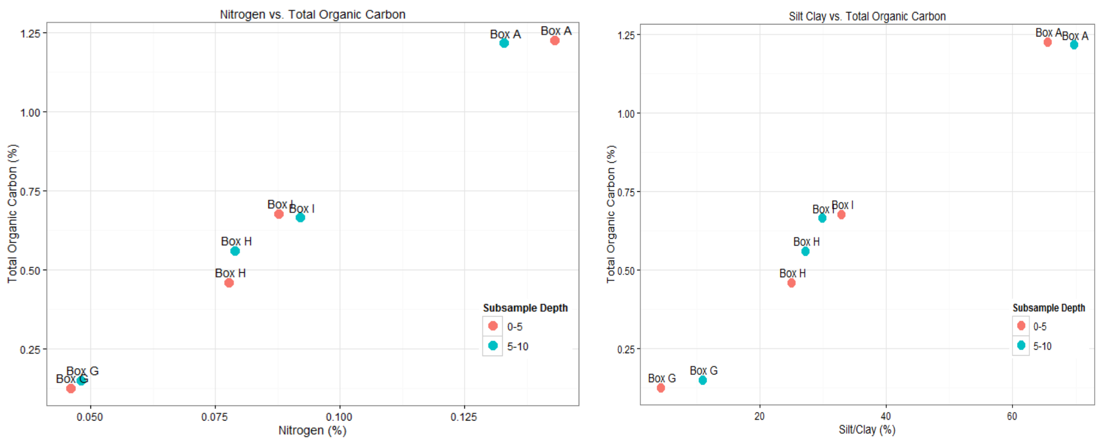



***Figure 2.5:*** *Particle size analysis results for two depth slices (0-5 cm and 5-10 cm) of sediment cores recovered from the four study sites (Boxes A, I, H and G)*




*a) TOC vs N* *b) TOC vs Silt/Clay*

***Figure 2.6:*** *Scatter plots showing the correlation between a) total organic carbon (TOC) and Nitrogen content and b) Total organic carbon and silt/clay fraction.*

In addition to PSA, all sliced sub-cores were analysed for organic carbon and nitrogen content (OCN). **Figure 2.6** shows the variation in total organic carbon (TOC) content of the sediment in relation to **a)** the nitrogen content and **b)** percentage silt/clay content.
The relationships shown in **Figure 2.6** illustrate that across the sites, organic carbon as well as nitrogen content increased with increasing silt/clay percentage.

The SPI images given in **Figure 2.7** show the visual differences between the four sediment source sites: ranging from the finest, muddiest substrate with clearly visible sub-surface reducing zones (grey black) characteristic of Box A to the coarse light brown sand found at site G, where a combination of shallower penetration of the camera prism and absence of sufficient fines mean no apparent Redox Discontinuity Depth (aRPD) is discernible.

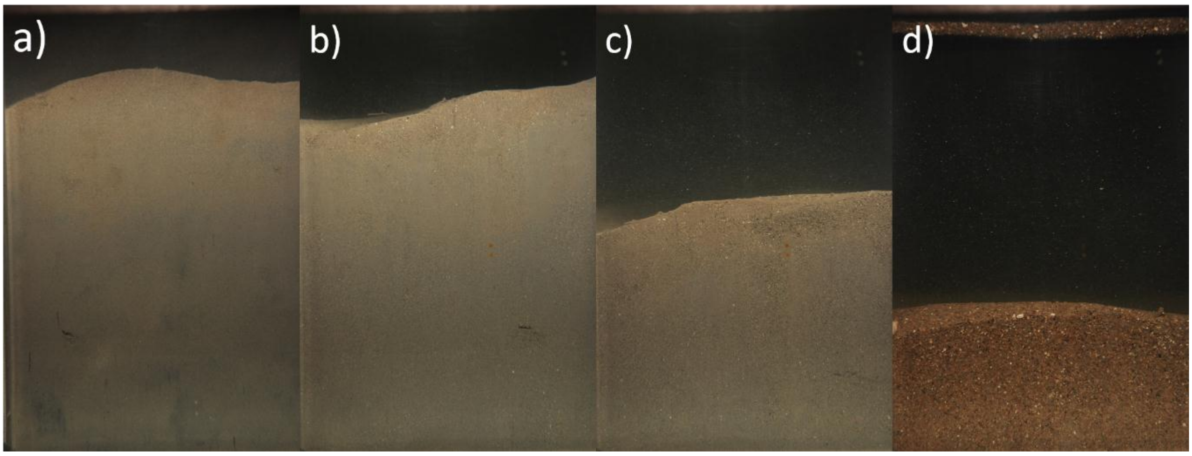



***Figure 2.7*** *Example sediment profile imagery (SPI) camera images from the 4 study locations: a) Box A: Mud; b) Box I: Sandy Mud; c) Box H: Muddy Sand; d) Box G: Sand*

Sediment site characteristics deducted from image analysis as described in Teal et al. (2010) are summarised in **Table 2.3**. Multiple SPI camera insertions were performed at each site. In addition to aRPD derived from sediment colour changes (brown to grey transition typical of the Iron reduction horizon), the average penetration depth of the prism is calculated and a measure of surface roughness provided.

**Table 2.3** Summary of apparent Redox Discontinuity Depth (aRPD), prism penetration depth into the sediment and surface roughness values as deducted from multiple SPI camera images recorded at stations Box A Mud , Box I Sandy Mud, and Box H Muddy Sand (Teal et al., 2010)

| Station Code | Replicate Hop | Comments | aRPD cm | Penetration cm | Surface Roughness cm | Average aRPD | STDEV |
|---|---|---|---|---|---|---|---|
| A5 | A | | 5.051 | 18.33 | 2.07 | | |
| A5 | B | Disturbed sediment surface - Burrow entrance? | 3.5852 | 15.71 | 6.56 | | |
| A5 | C | | 3.6814 | 16.45 | 1.54 | | |
| A5 | D | Difficult to discern - lighter sediment at depth on left of image | 3.1672 | 12.28 | 4.09 | | |
| A5 | E | | 2.957 | 14.71 | 1.74 | 3.69 | 0.82 |
| I1 | A | | 4.506 | 17.49 | 2.91 | | |
| I1 | B | Burrow at depth? | 4.733 | 17.37 | 2.23 | | |
| I1 | C | Burrow at depth? | 3.704 | 15.55 | 2.26 | | |
| I1 | D | | 3.829 | 15.03 | 1.64 | | |
| I1 | E | | 5.2109 | 17.66 | 2.77 | 4.40 | 0.63 |
| H3 | A | Difficult to discern - lighter sediment at depth | 3.6629 | 11.07 | 2.53 | | |
| H3 | B | Difficult to discern - lighter sediment at depth | 3.0135 | 12.09 | 2.18 | | |
| H3 | C | Difficult to discern - lighter sediment at depth | 3.6781 | 13.72 | 2.58 | | |
| H3 | D | Difficult to discern - lighter sediment at depth | 2.3395 | 12.74 | 3.50 | | |
| H3 | E | | 2.7087 | 12.75 | 1.39 | 3.08 | 0.59 |

*Oxygen profiles*

Oxygen data from microelectrode profiles collected at all four sites are shown in **Figure 2.8**. The derived oxygen penetration depth are as follows:

Box A - mud = 0.4 cm
Box I - sandy mud = 0.2 cm (both replicates)
Box H - muddy sand = 0.9 cm (both replicates)
Box G - sand = 5.5 cm (or even deeper; the coarse nature of the sediment prevented deeper profiling or replication and the value reached was only close to zero free oxygen)

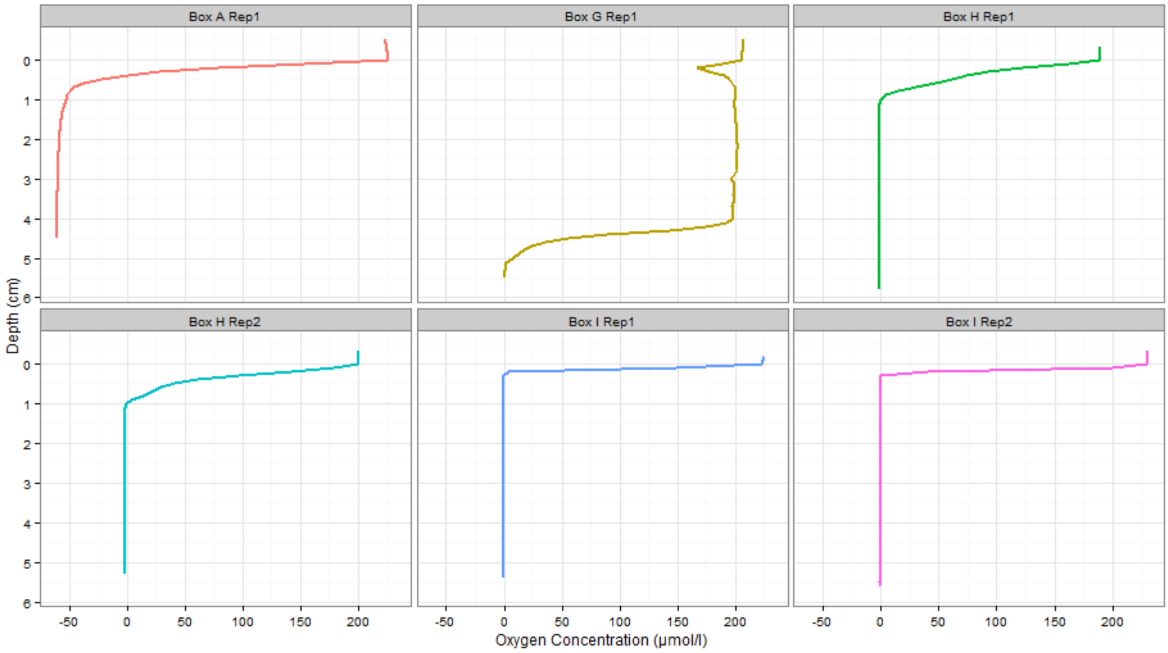



***Figure 2.8*** *Oxygen profiles recorded using Unisense microelectrodes*

The profiles are as would be expected from the sediment characterisation, showing a clear deepening of the horizon in which free oxygen is present as the grain size increases and the organic carbon content decreases. The slight anomaly that the muddy site (Box A) had a marginally deeper OPD then sandy mud is likely due to a degree of heterogeneity within cores; both sites can be described as having a very shallow layer of free oxygen.

*Porewater nutrient profiles*

The results from the porewater nutrient profiles obtained using a sipper system are detailed in **Figure 2.9.**

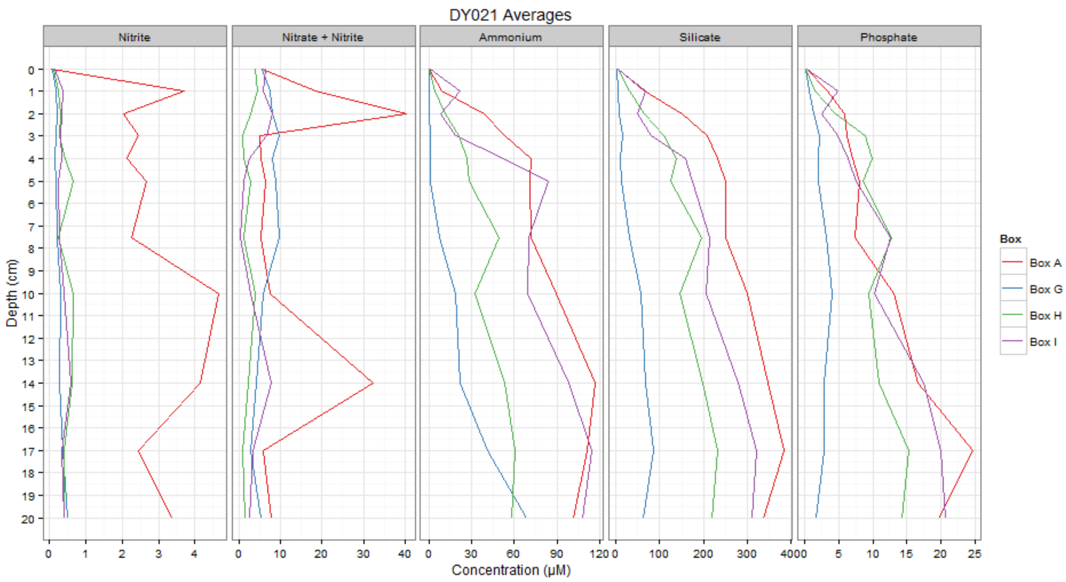



***Figure 2.9*** *Porewater nutrient profiles obtained at the 4 study locations: Box A: Mud, Box G: Sand, Box H: Muddy Sand and Box I: Sandy Mud.*

Higest nutrient levels across chemical species and depth were recorded in the fine sediments and lowest in the sand. The sandy site contained fairly constant nutrient concentrations with depth, consistent with a well flushed system in constant exchange with the water column, with a late increase in ammonium below 14 cm into the sediment and a gradual increase in silicate below about 5 cm. In contrast the three finer sites all have gradually increasing contents of ammonium, silicate and phosphate in the porewaters. Nitrate and nitrtite concentrations peak twice, once below the surface (nitrite and 1 cm and nitrate at 2 cm), and again at a depth of 10-14 cm, so well below the layer samples for the resuspension expriment.

### 2.3.2 Oxygen data from continuous recording

Oxygen traces from each of the four resuspension experiments are shown (combined per site) in **Figures 2.10 - 2.13**.

The vertical lines added to the figures correspond to the time points when the Replicates B and C were sampled, though the oxygen incubation bottles themselves were not opened. This is intended to enable easy visual identification of key experimental time points and to highlight occasions at which a degree of handling of bottles within the incubation tank might have led to disruptions in the readings (for example by temporarily dislodging OxyDot cable attachments).

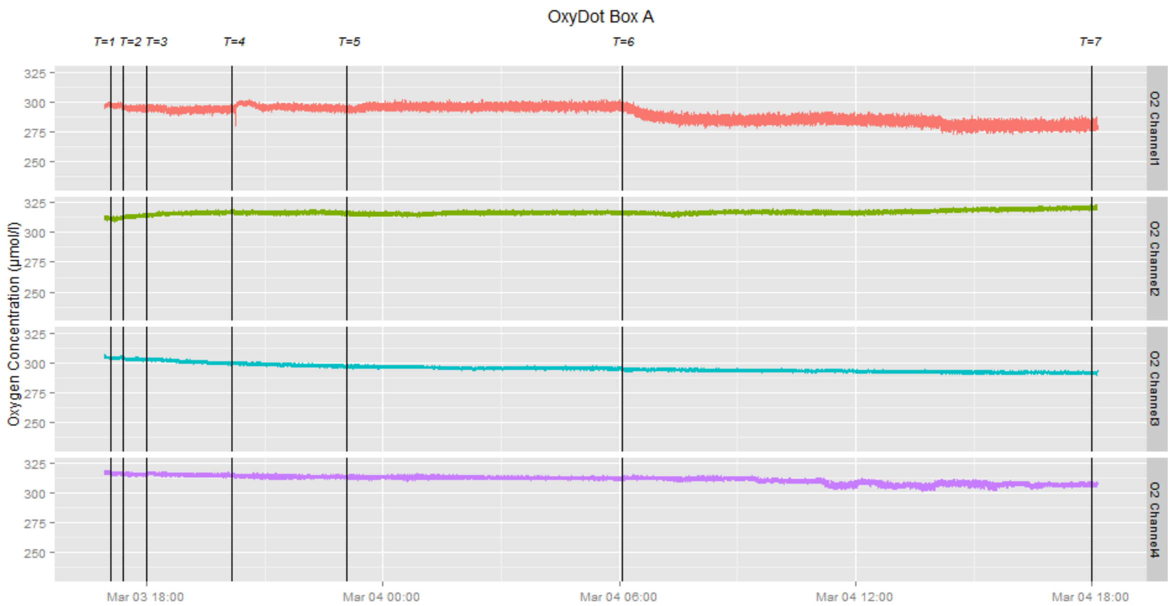



***Figure 2.10*** *Benthic A (Mud) OxyDot data; Channel 1 = Control, Channel 2 = V1 (0-2 cm), Channel 3 = V2 (0-4 cm), Channel 4 = V3 (0-6 cm).*

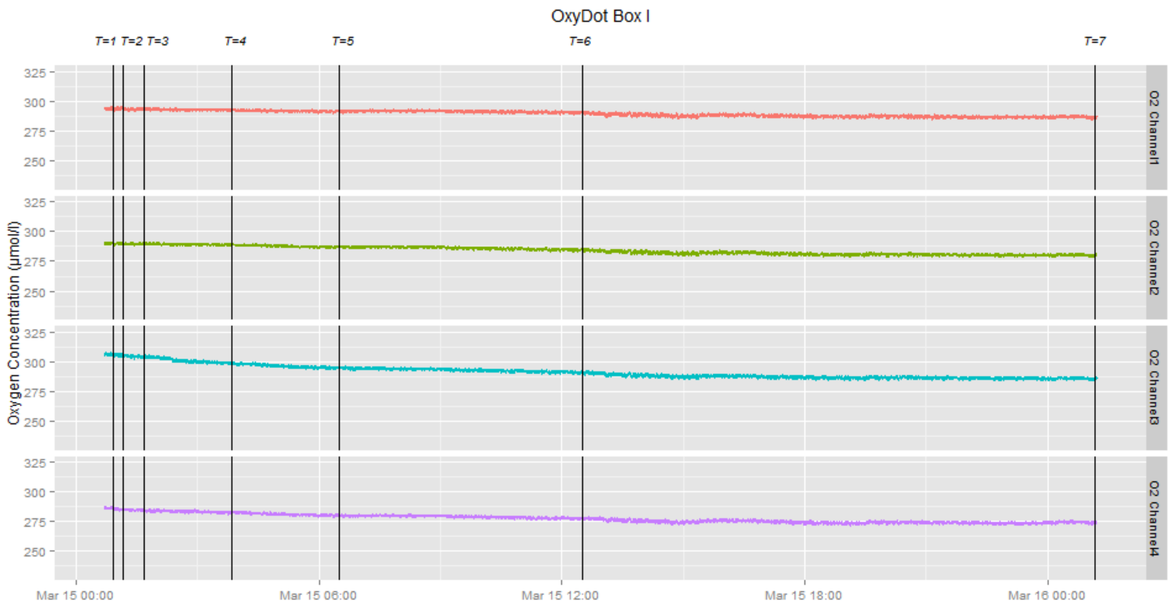



***Figure 2.11***: *Benthic I (Sandy mud) OxyDot data; Channel 1 = Control, Channel 2 = V1 (0-2 cm), Channel 3 = V2 (0-4 cm), Channel 4 = V3 (0-6 cm).*

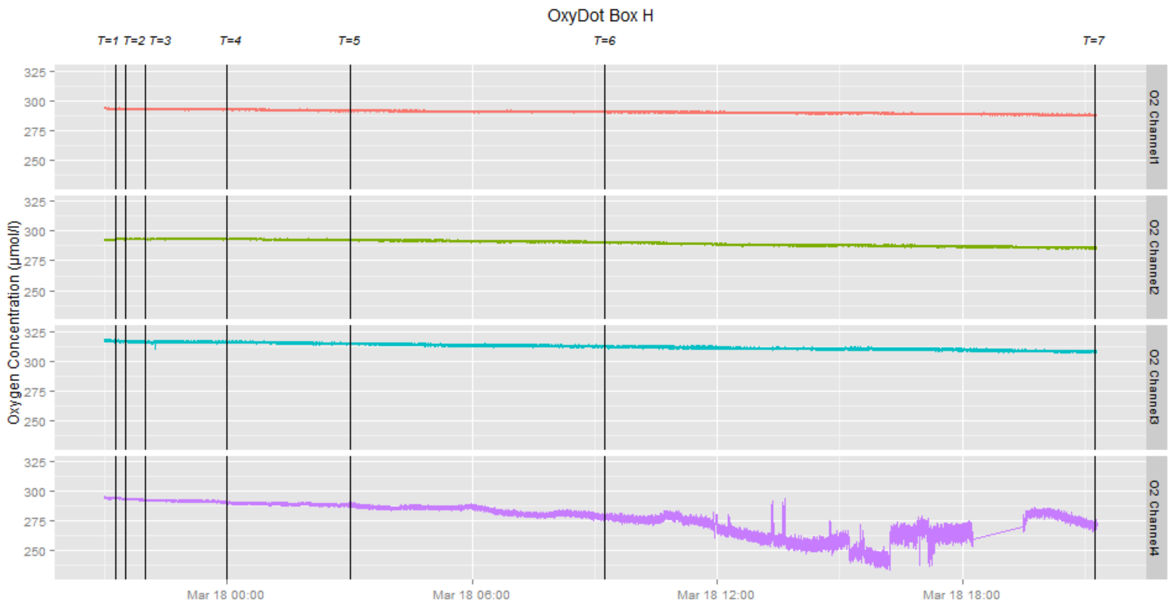



***Figure 2.12***: *Benthic H (Muddy sand) OxyDot data; Channel 1 = Control, Channel 2 = V1 (0-2 cm), Channel 3 = V2 (0-4 cm), Channel 4 = V3 (0-6 cm).*

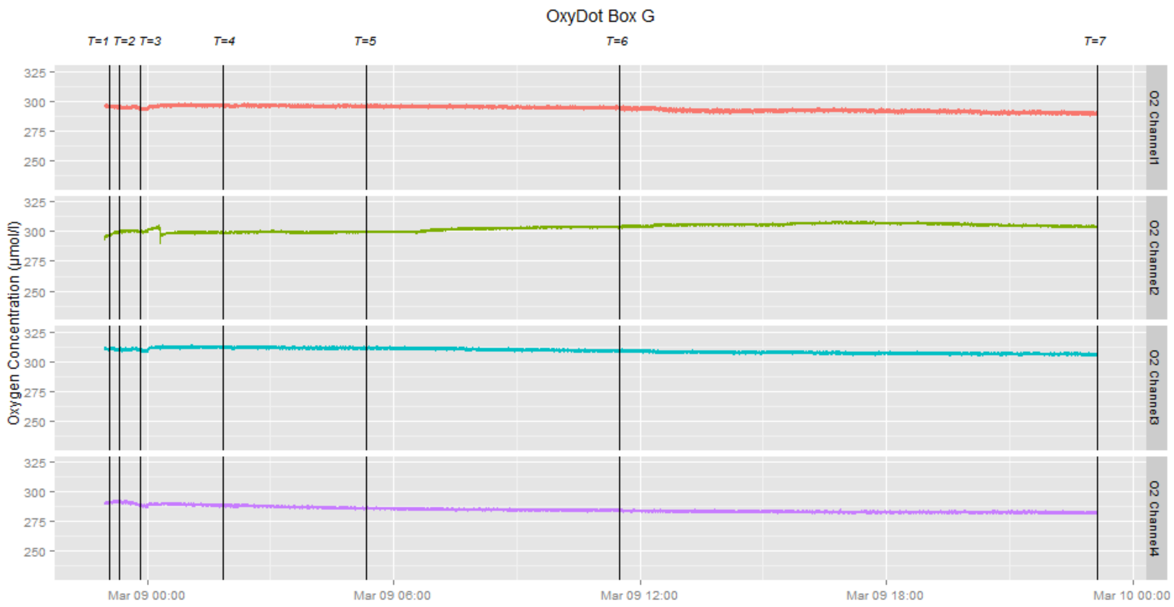



***Figure 2.13***: *Benthic G (Sand) OxyDot data; Channel 1 = Control, Channel 2 = V1 (0-2 cm), Channel 3 = V2 (0-4 cm), Channel 4 = V3 (0-6 cm).*

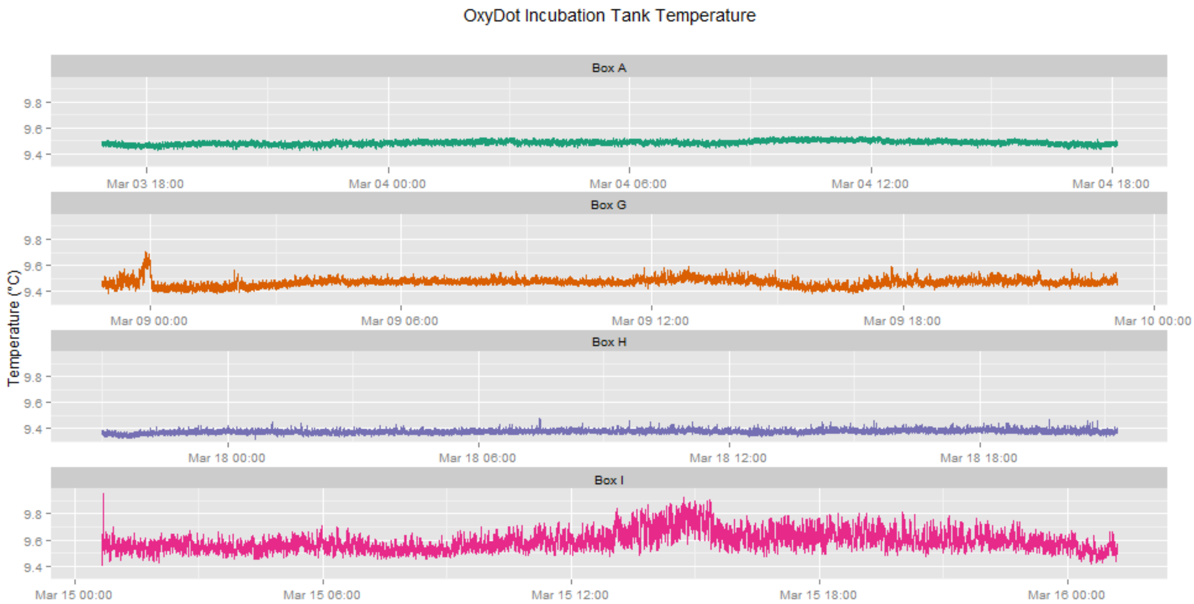



***Figure 2.14***: *Temperature recordings of incubation tank water during the four experiments.*

The temperature recording within the incubation tank water (**Figure 2.14**) shows the high degree of temperature control achieved within the experimental set-up (in most cases <0.1 $^{o}$C fluctuation).

Most traces, including the control (where no sediment was added to the collected bottom water), showed a gradual overall decline in oxygen over the duration of the experiments (24h). This was therefore indicative of chemical and/or biological oxygen demand. The rate of decline was variable, both between incubations and over the course of each individual experiment, and in two cases (i.e. the 0-2 cm sediment slice of both the mud and the sand) an increase in oxygen over the 24 h period of the experiment was recorded. The latter may have been caused by air

bubbles trapped in the bottles that were not identified due to the spatially constrained experimental set-up or may be indicative of a fault/leak in the incubation vessel.
Detailed analysis of the gradients of change in the oxygen signals with time might allow oxygen consumption rates to be calculated at differing time steps. Of particular interest here is the difference between the initial response to the sediment addition (steps between T0 and 3) and the effects of prolonged resuspension (T3 through to T7). Normalisation to suspended particulate matter values (as determined at T7) could be undertaken and might further improve comparison, as would correction for temperature fluctuations (though as stated above they were minor, thus temperature correction is unlikely to significantly alter conclusions). Some experimental constraints detailed in Annex III need to be considered during data interpretation.

### 2.3.3 Suspended particulate matter (SPM)

The range of suspended particulate matter concentrations determined for the collected bottom water and as a result of resuspending controlled sediment volumes determined at the end of the incubations are summarised for all sediment types in **Figure 2.15.** Further plots showing SPM concentrations recorded for each sediment type separately and resolved by resuspension depth are given in **Annex I**.

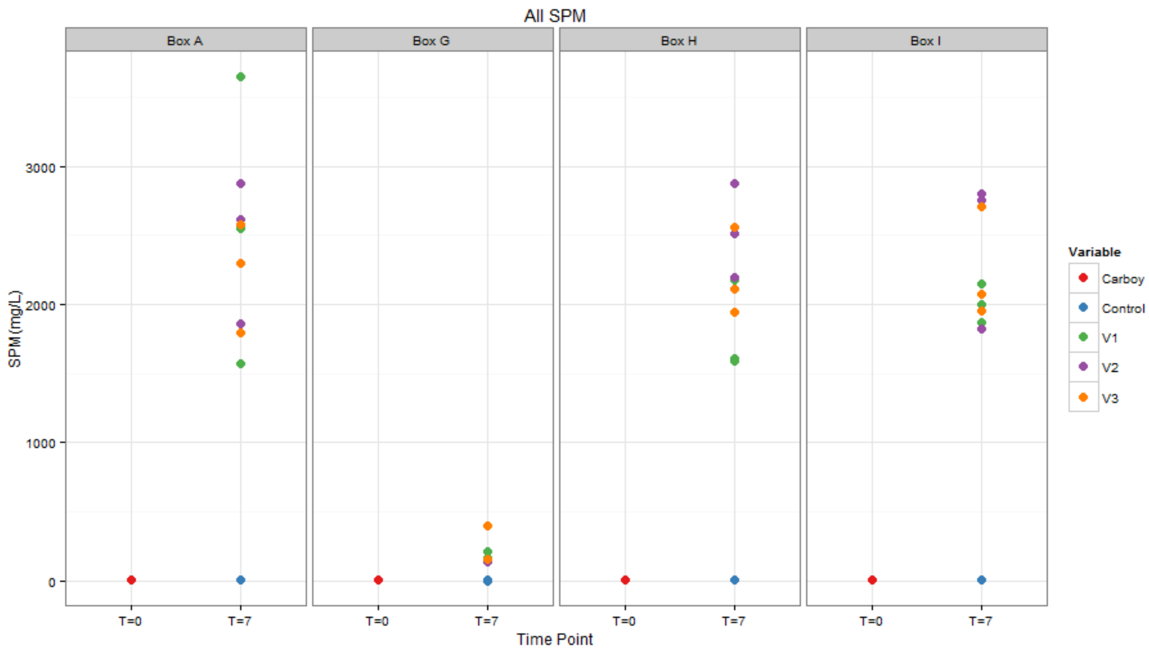



***Figure 2.15:*** *Suspended particulate matter results from all incubations (Box A = mud, Box G = sand, Box H =muddy sand, Box I = sandy mud)*

The results illustrate the absence of any significant quantities of suspended particulate matter from the bottom water (control), though the presence of some fine particles or colloids can not be excluded. Comparable ranges of SPM were present in three sites (A, H and I). The low values recorded from the incubations with coarses sediment from site G have to be regarded as a method artefact. The heavier sediment particles had a tendency to re-settle between virogous shaking of the incubation vessel and decanting. Thus it is not recommended to us the Box G SPM values.

### 2.3.4 Chlorophyll and phaeopigments

**Figure 2.16** shows the concentrations of chlorophyll and **Figure 2.17** phaeopigment concentrations at different time intervals during the incubations.

Chlorophyll and its degradation products (i.e. phaeopigments) are indicative of the labile carbon sources present in the sediments. In the bottom-water control, the measured chlorophyll concentration was stable and phaeopigments were low, as would be expected for undisturbed waters. All of the sediment additions resulted in significant release of chlorophyll and also phaeopigments, into the water column showing the introduction of additional carbon and nutrient sources into the pelagic system. An increase in both parameters was observed at T3, within 30 minutes of sediment addition, and even higher values were recorded at T7, i.e. at the end of the 24h incubation. Plots detailing the values recorded for all sediment types and depth as well as the observed relationships between suspended particulate matter and pigment concentrations are given in **Annex II**.

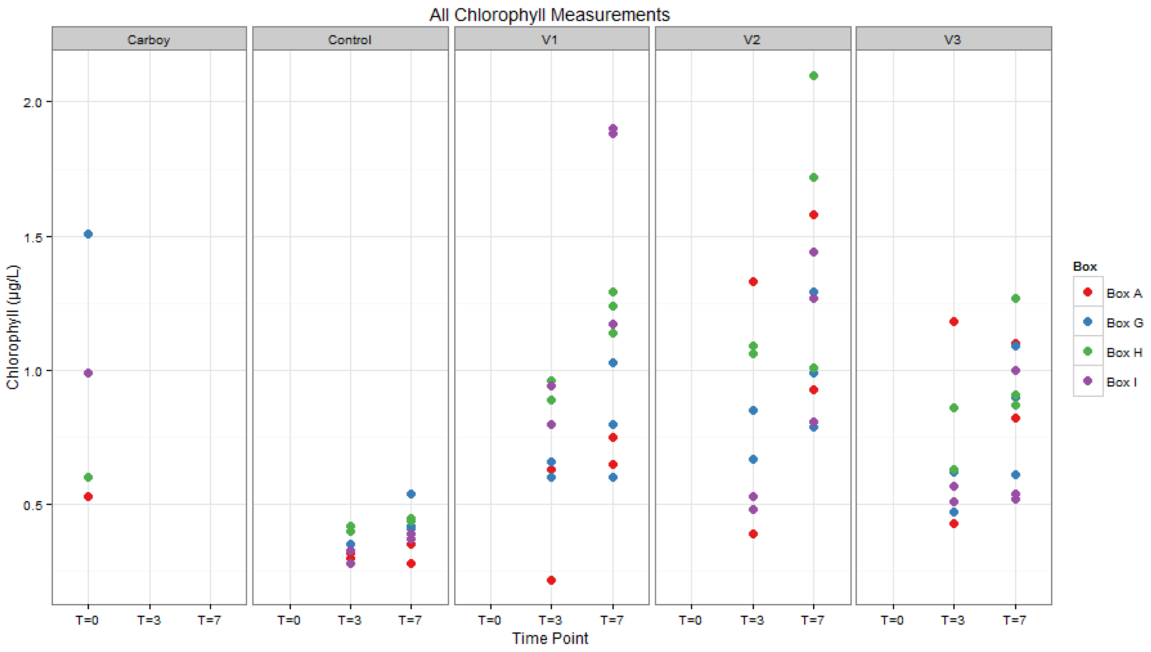



***Figure 2.16*** *Chlorophyll concentrations from all sediment types and replicates*

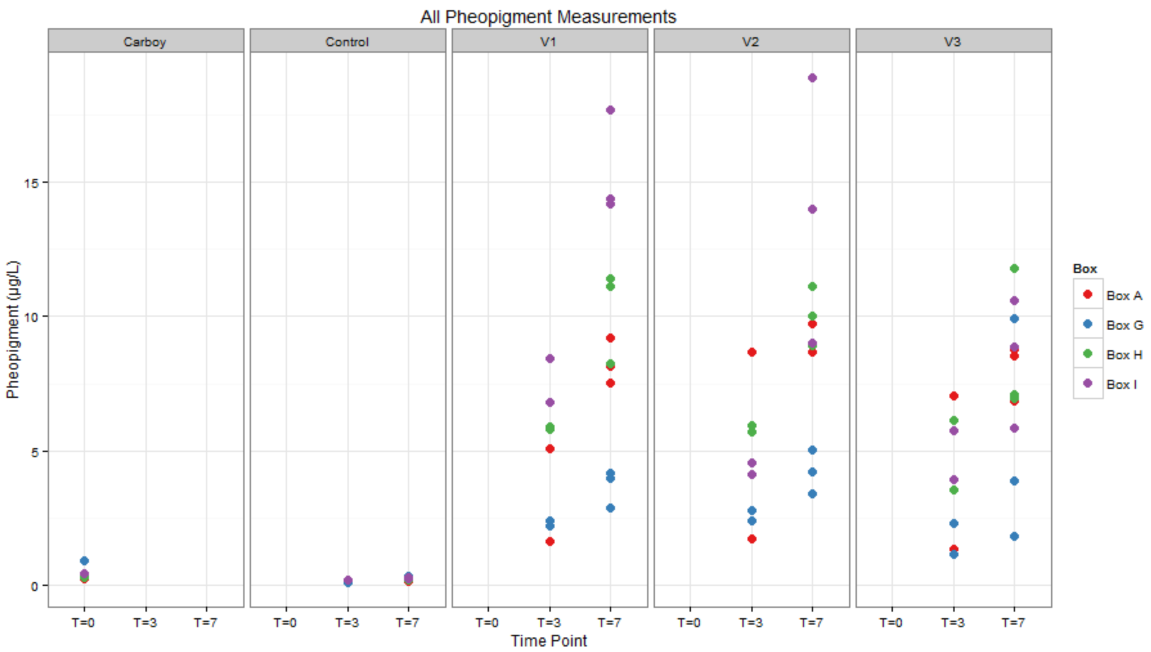



***Figure 2.17*** *Phaeopigment concentrations from all sediment types and replicates*

### 2.3.5 Inorganic Nutrients (nitrate, nitrite, phosphate, silicate and ammonium)

Nutrient data has been worked up as part of the SSB programme by another institute (PML) and is detailed in Figures 2.18 – 2.37 below.

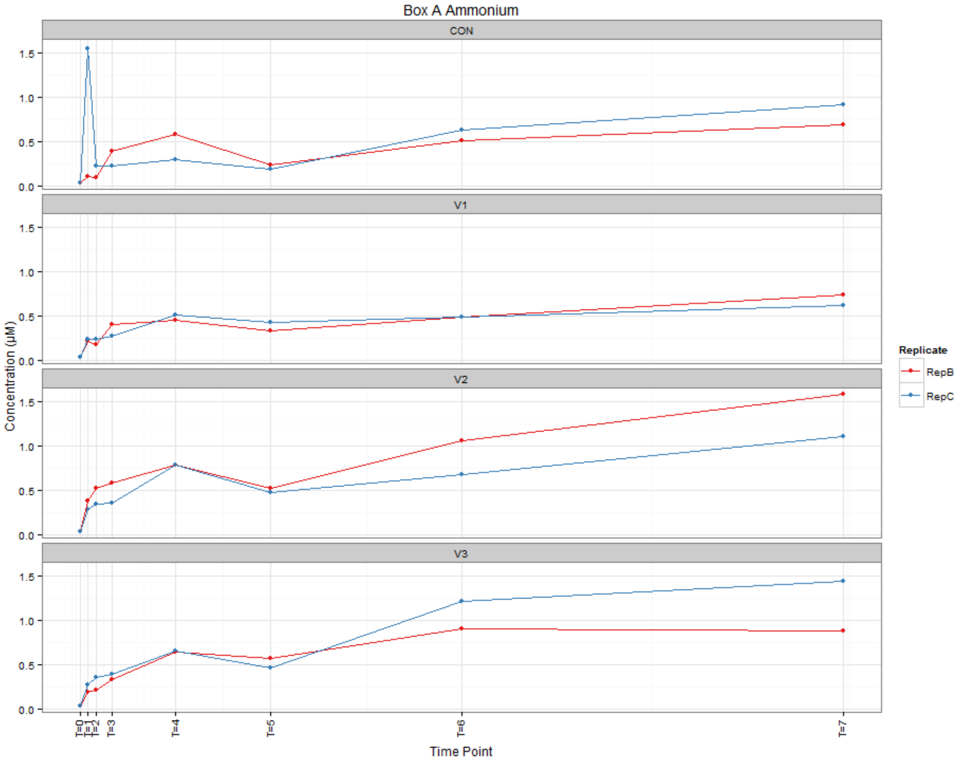



***Figure 2.18*** *Ammonium concentartions during resuspension of Box A (mud). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

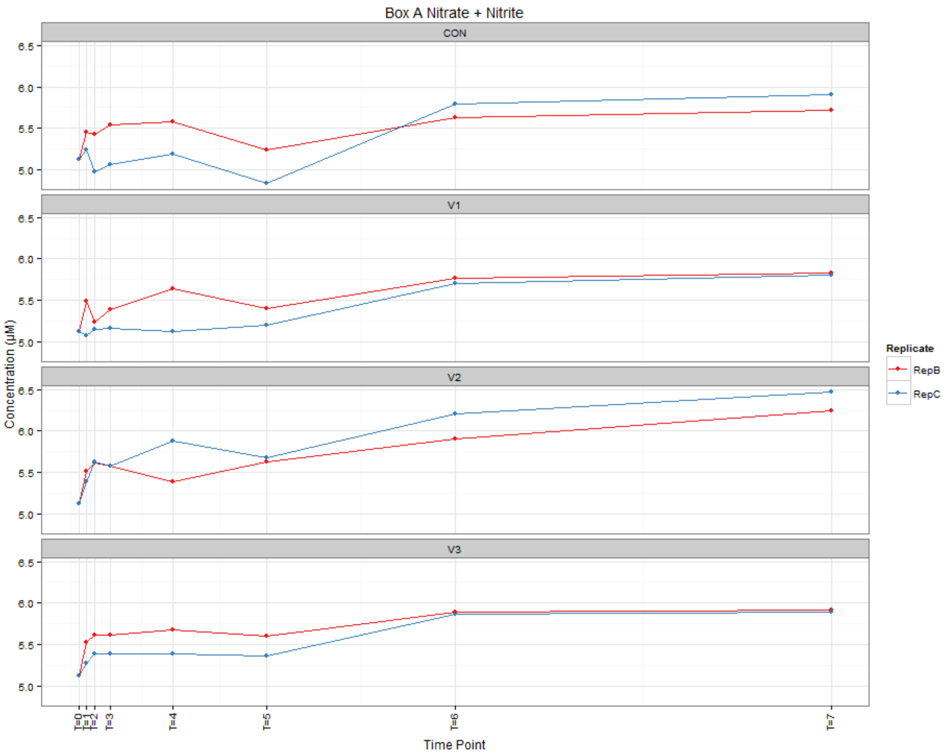



***Figure 2.19*** *Nitrate and nitrite concentartions during resuspension of Box A (mud). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

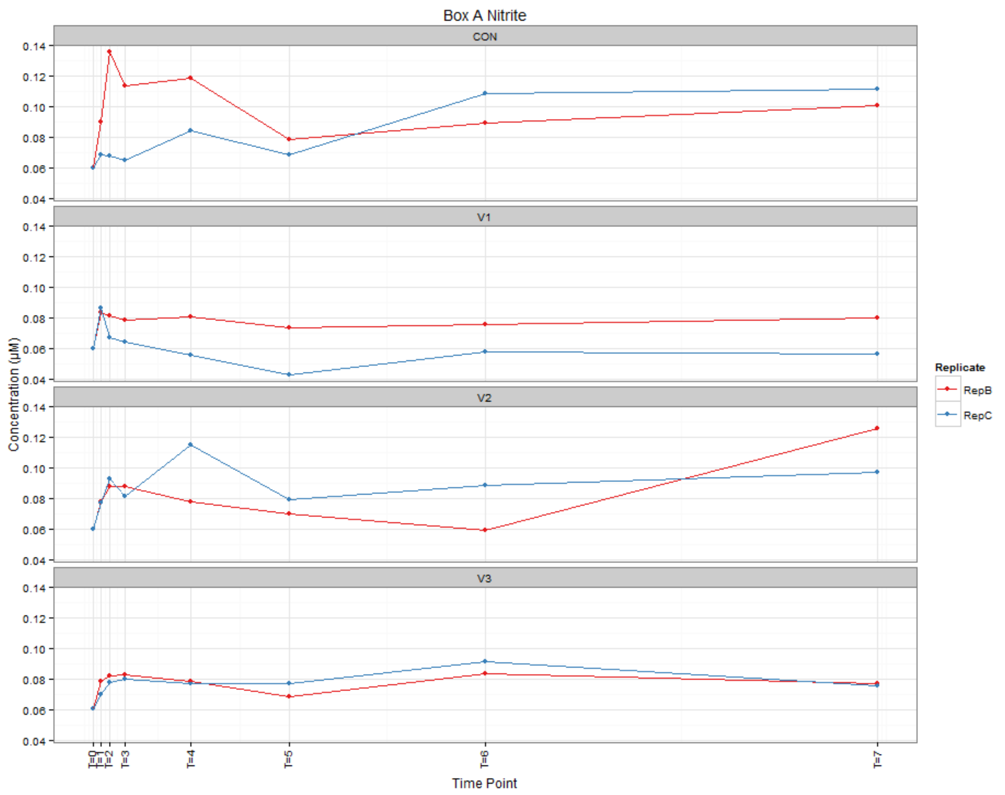



***Figure 2.20*** *Nitrite concentrations during resuspension of Box A (mud). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

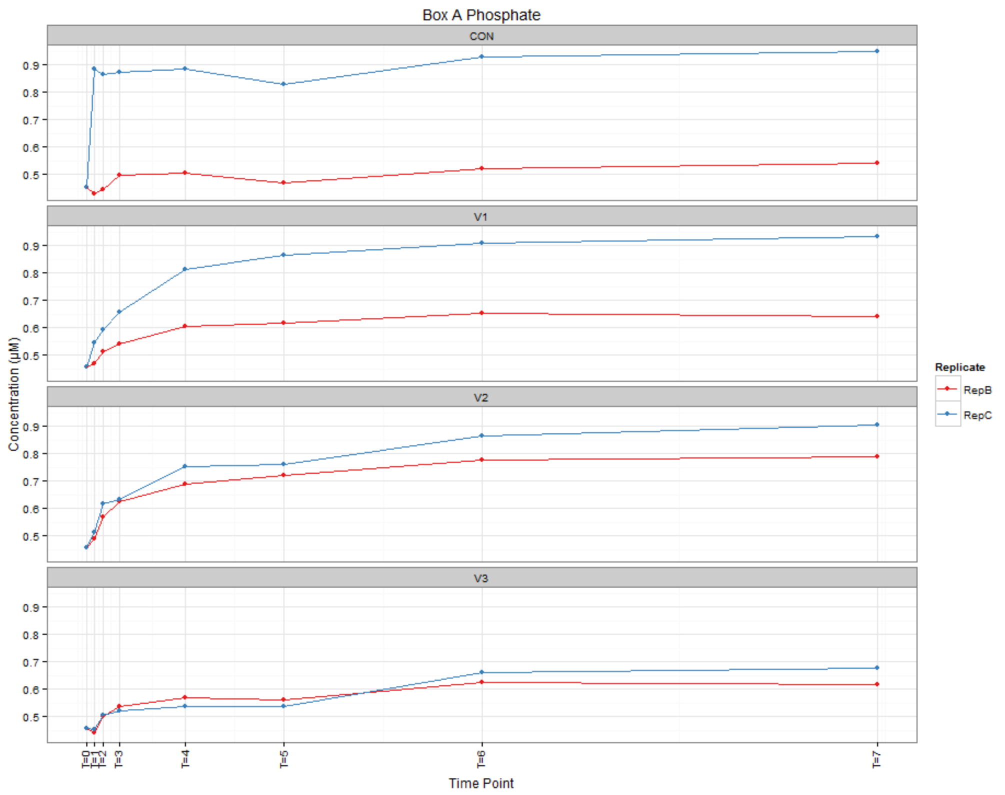



***Figure 2.21*** *Phosphate concentrations during resuspension of Box A (mud). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

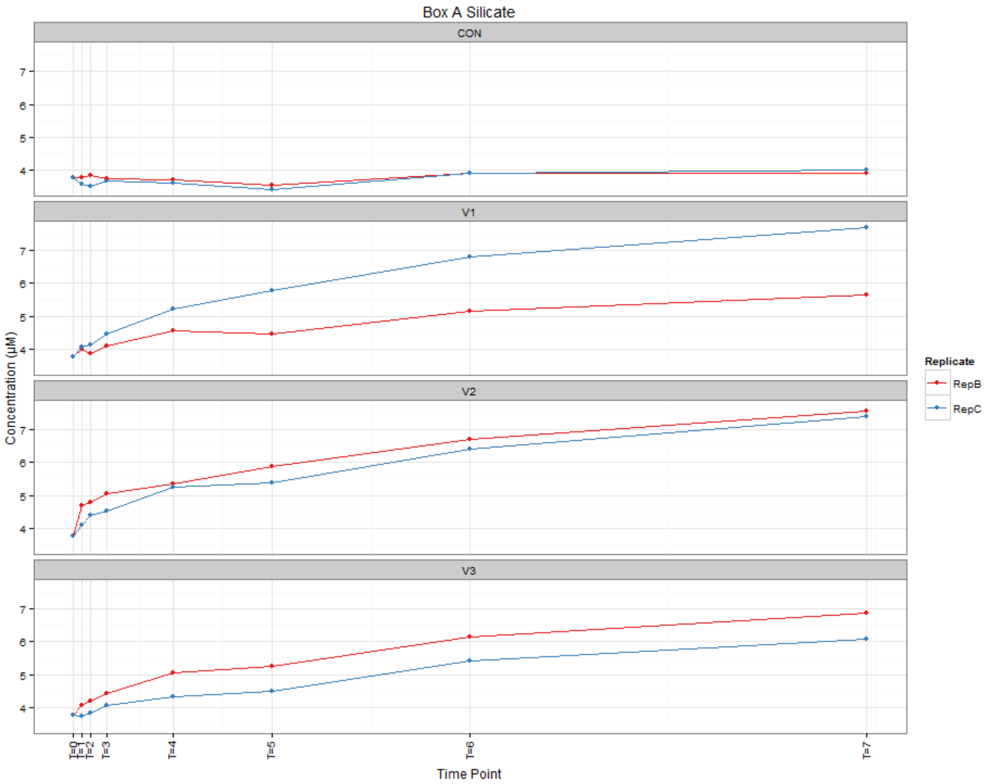



***Figure 2.22*** *Silicate concentrations during resuspension of Box A (mud). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

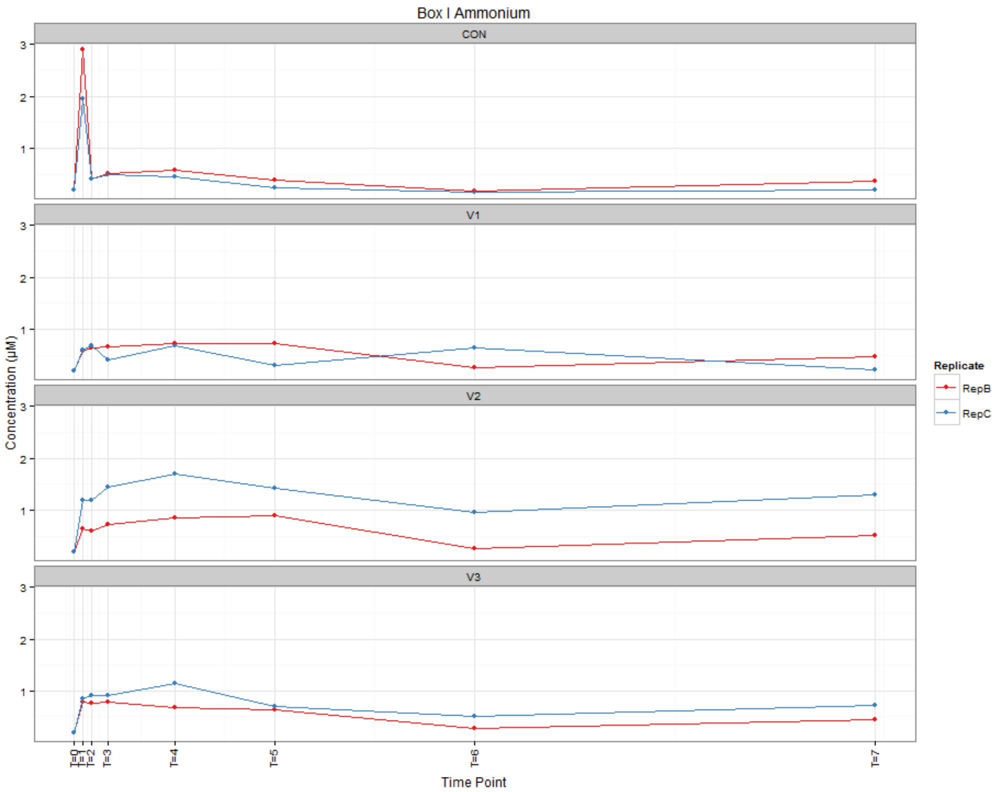



***Figure 2.23*** *Ammonium concentrations during resuspension of Box I (sandy mud). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

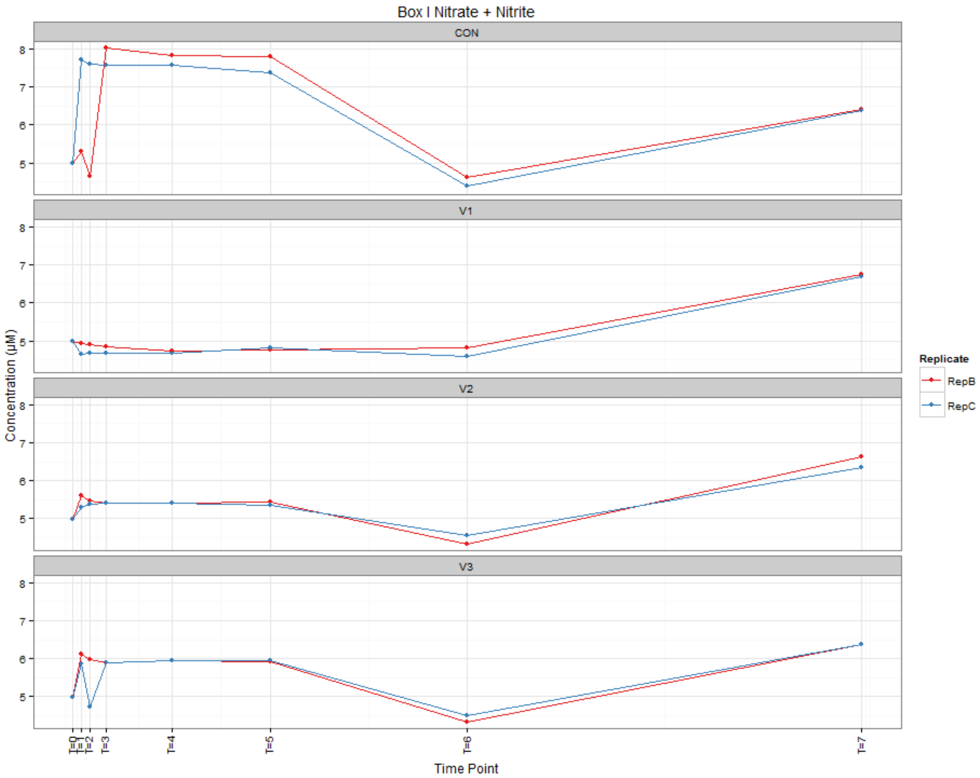



***Figure 2.24*** *Nitrate and nitrite (ToxN) concentrations during resuspension of Box I (sandy mud). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

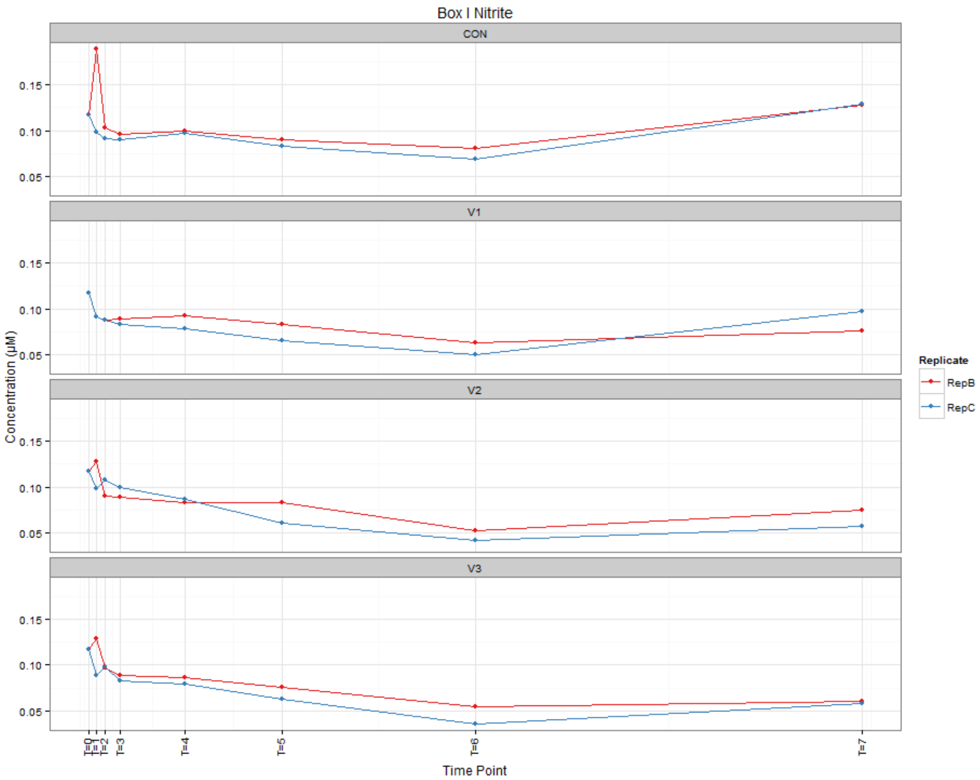



***Figure 2.25*** *Nitrite concentrations during resuspension of Box I (sandy mud). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

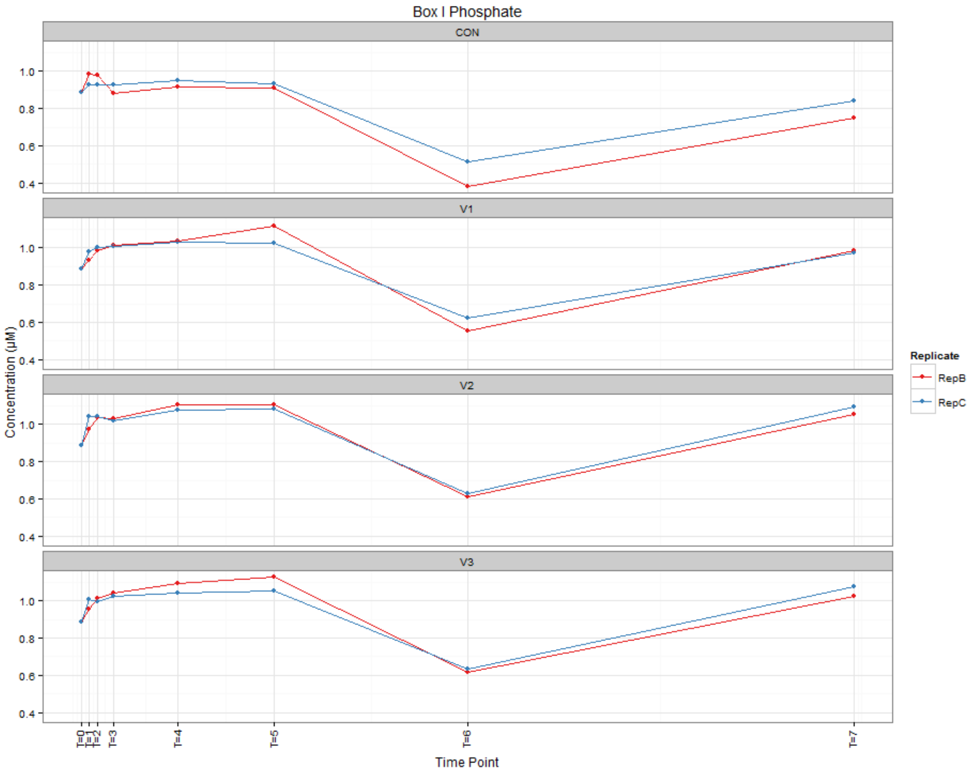



***Figure 2.26*** *Phosphate concentrations during resuspension of Box I (sandy mud). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

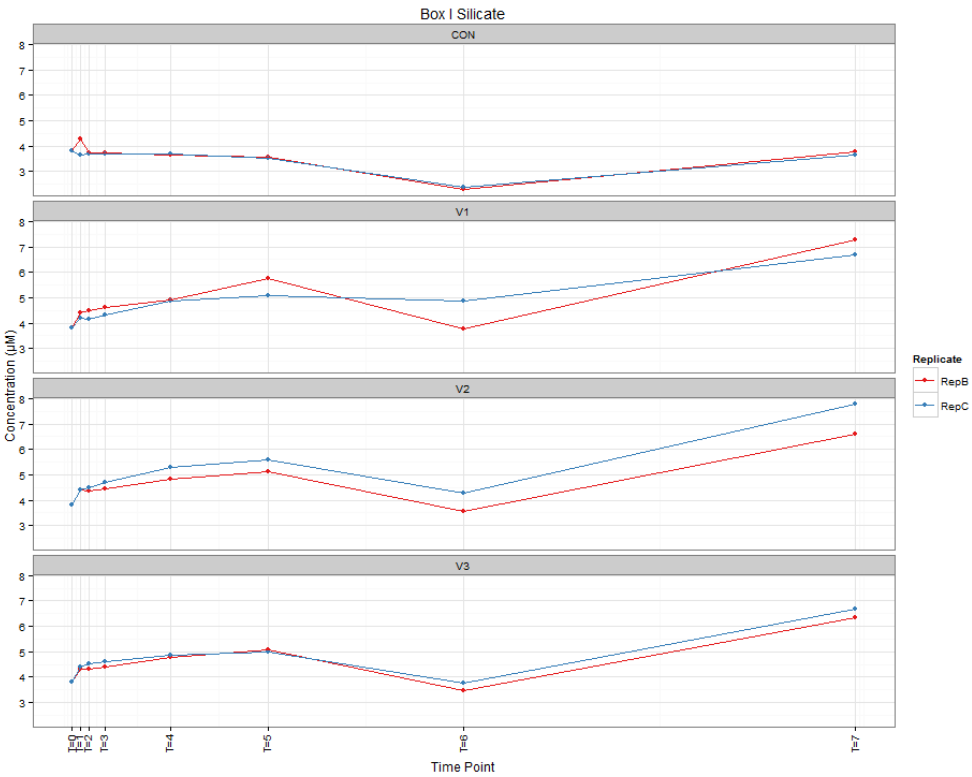



***Figure 2.27*** *Silicate concentrations during resuspension of Box I (sandy mud). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

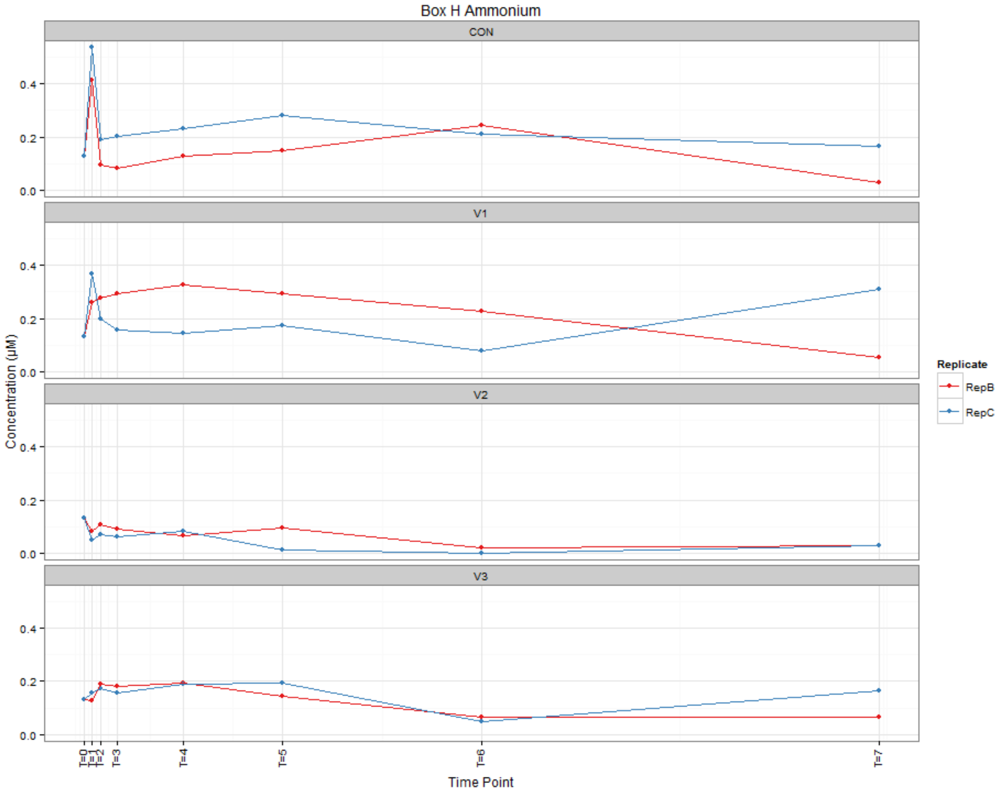



***Figure 2.28 Ammonium*** *concentrations during resuspension of Box H (muddy sand). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

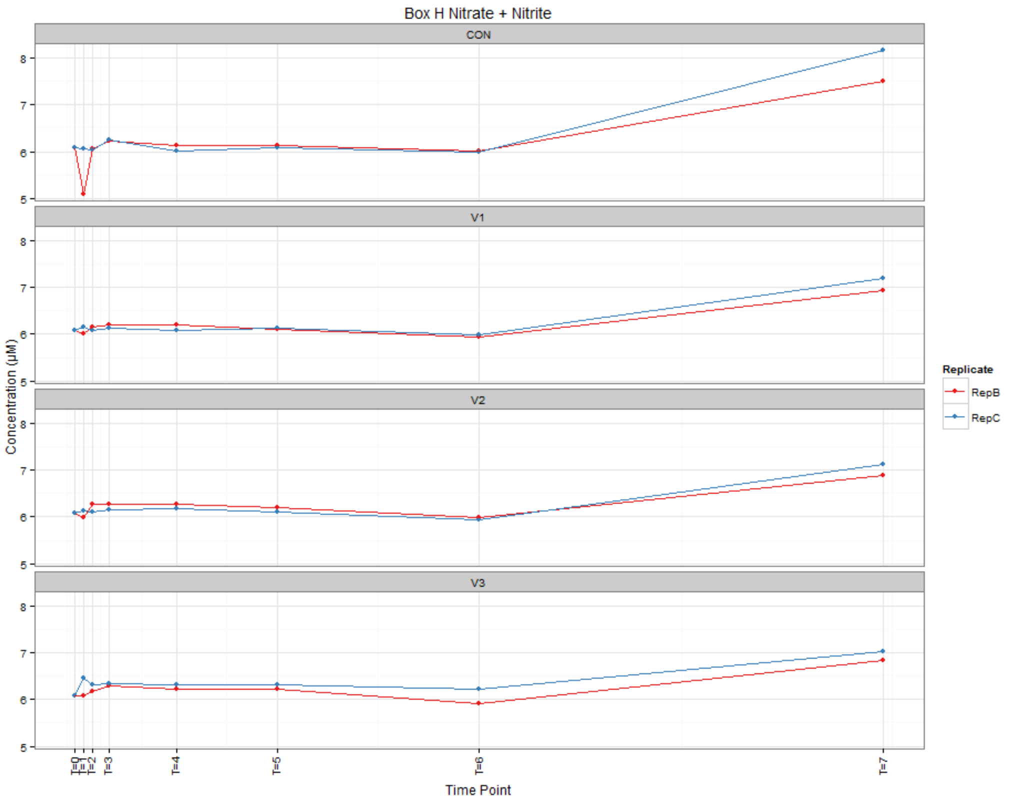



***Figure 2.29*** *Nitrate and nitrite (ToxN) concentrations during resuspension of Box H (muddy sand). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

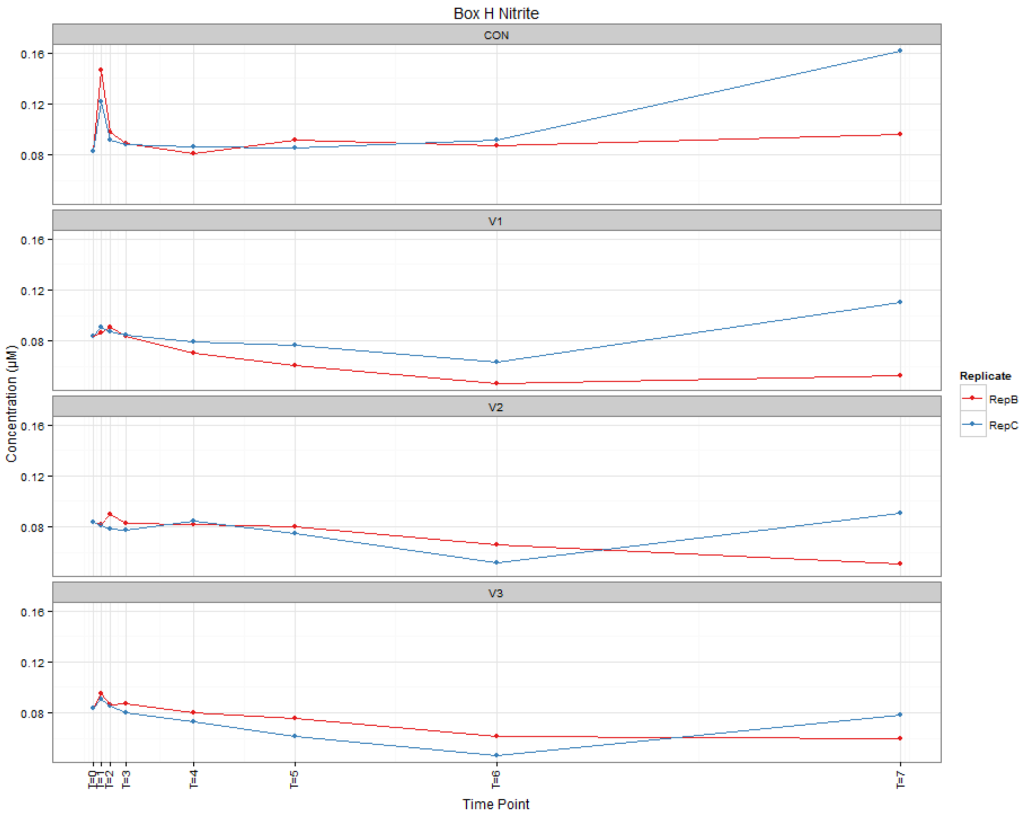



***Figure 2.30*** *Nitrite concentrations during resuspension of Box H (muddy sand). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

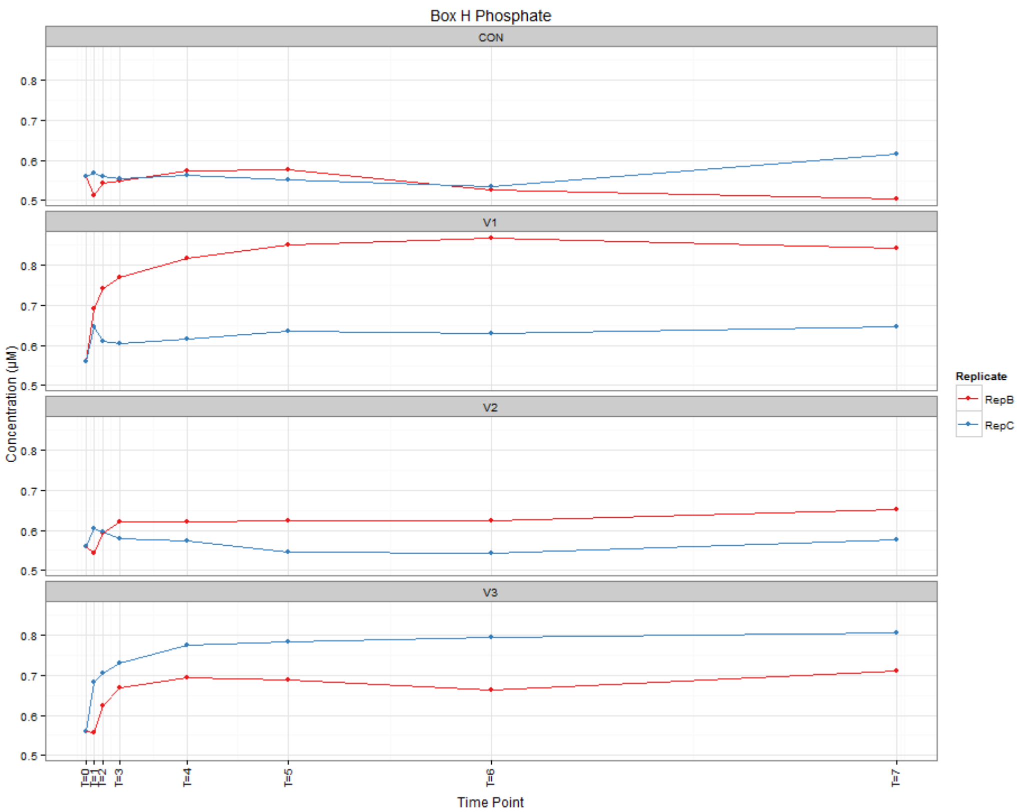



***Figure 2.31*** *Phosphate concentartions during resuspension of Box H (muddy sand). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

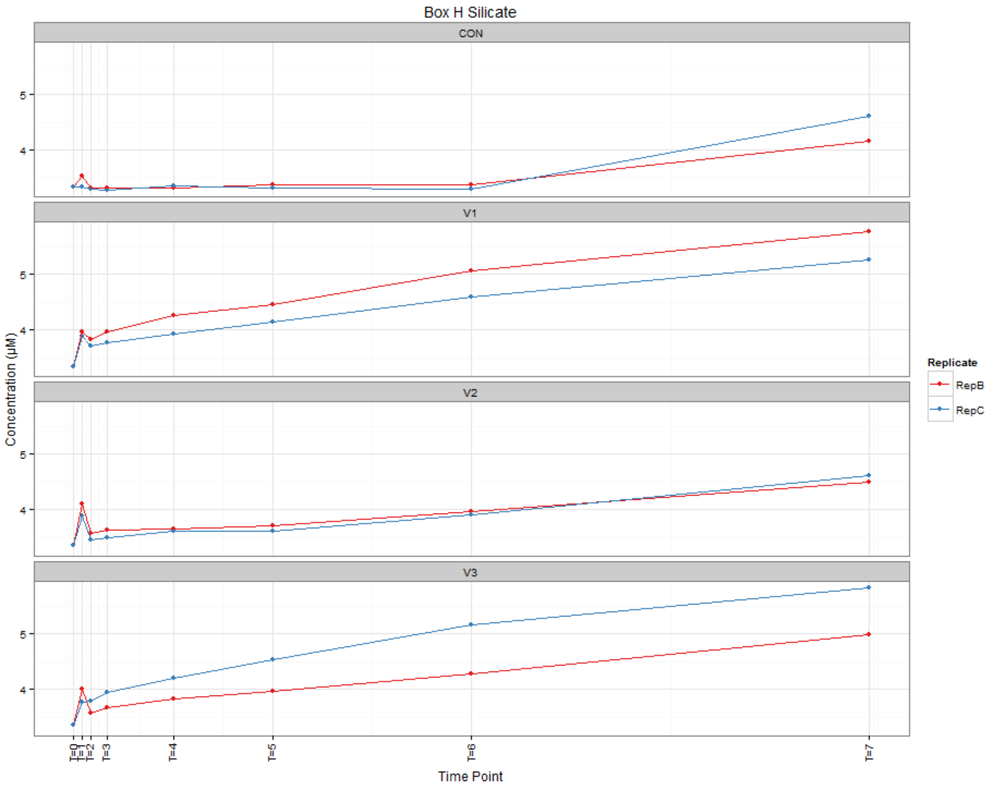



***Figure 2.32*** *Silicate concentrations during resuspension of Box H (muddy sand). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

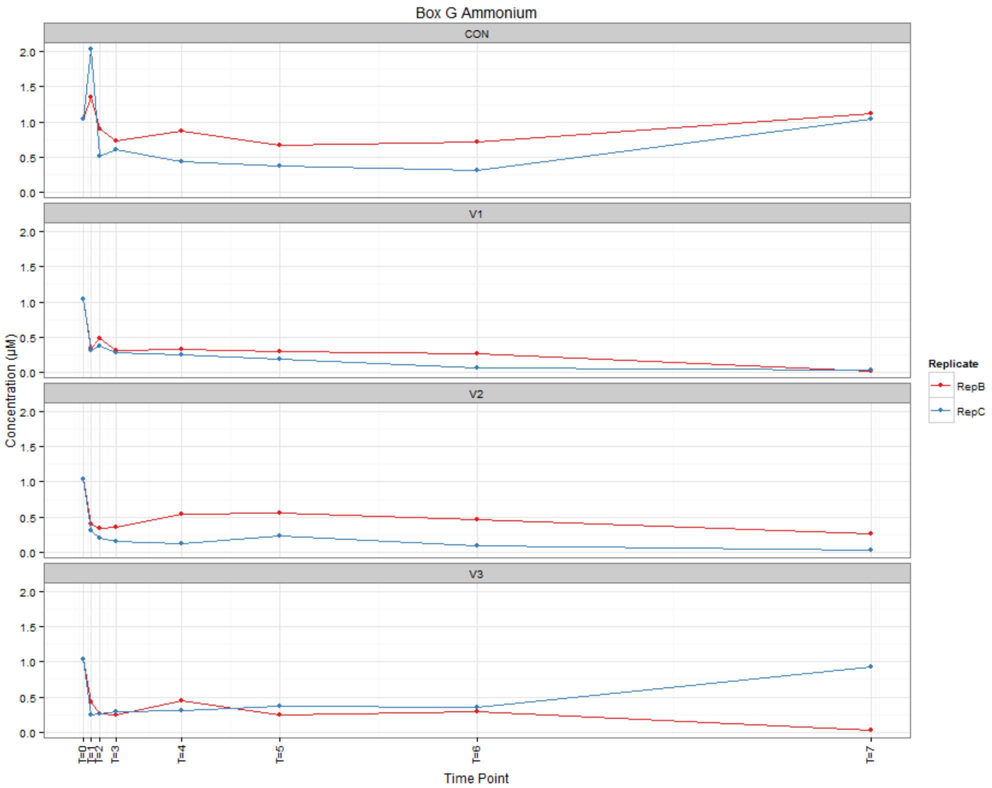



***Figure 2.33*** *Ammonium concentrations during resuspension of Box G (sand). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

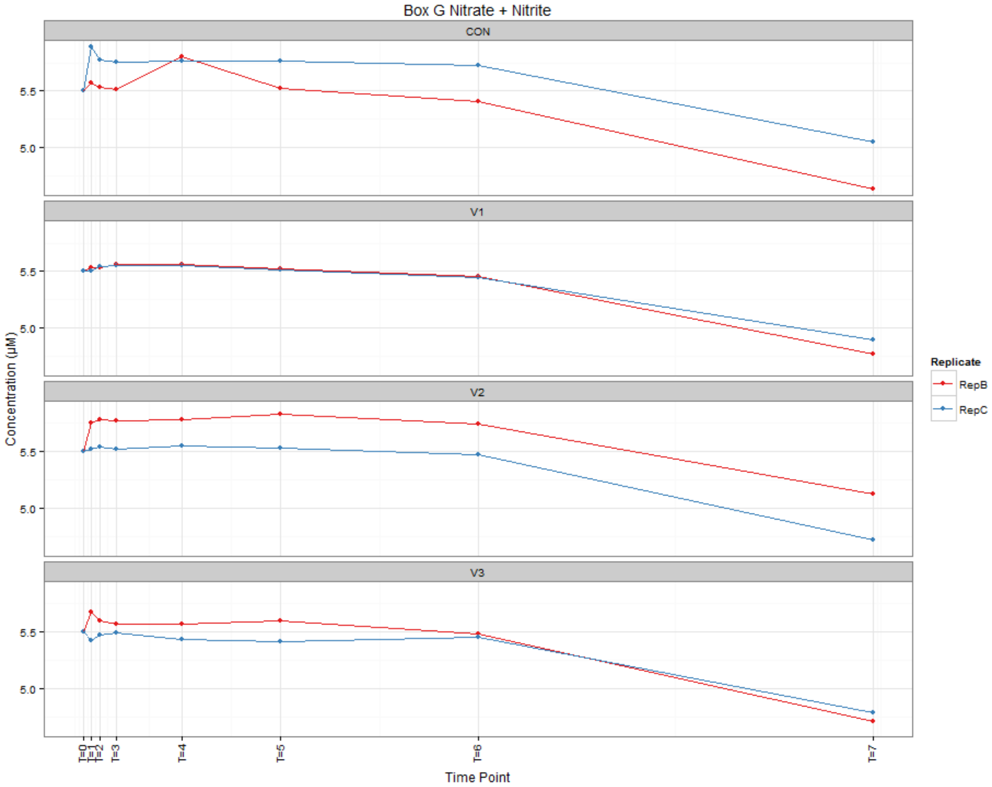



***Figure 2.34*** *Nitrate and nitrite concentrations during resuspension of Box G (sand). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

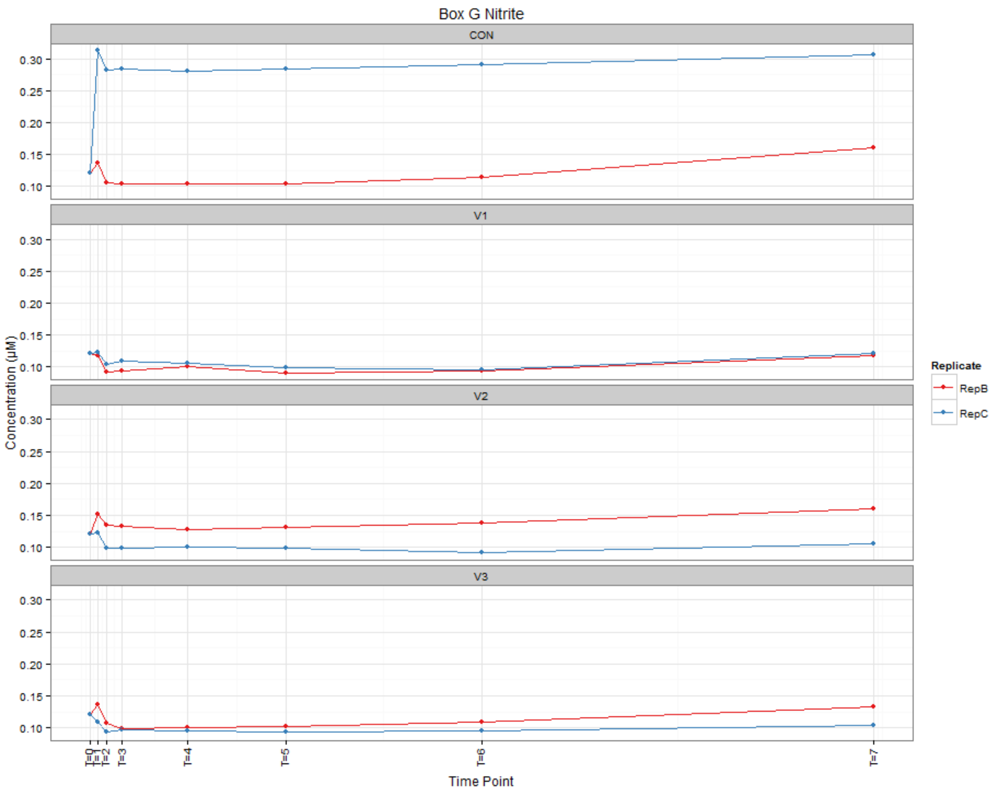



***Figure 2.35*** *Nitrite concentrations during resuspension of Box G (sand). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

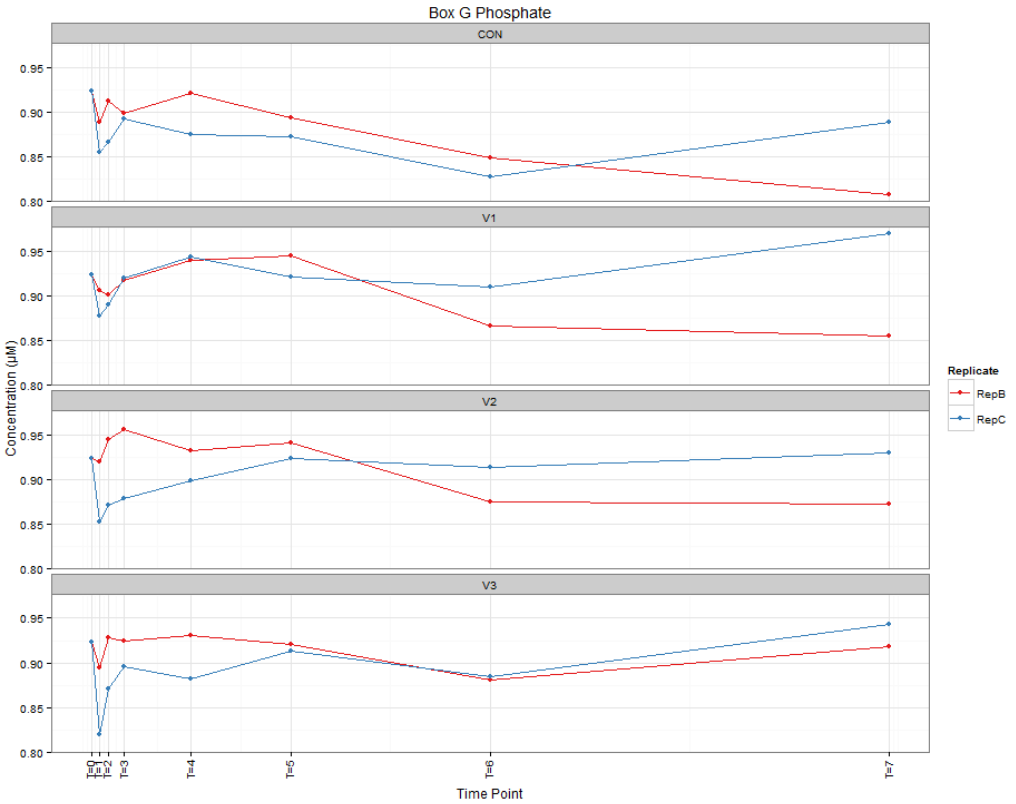



***Figure 2.36*** *Phosphate concentrations during resuspension of Box G (sand). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

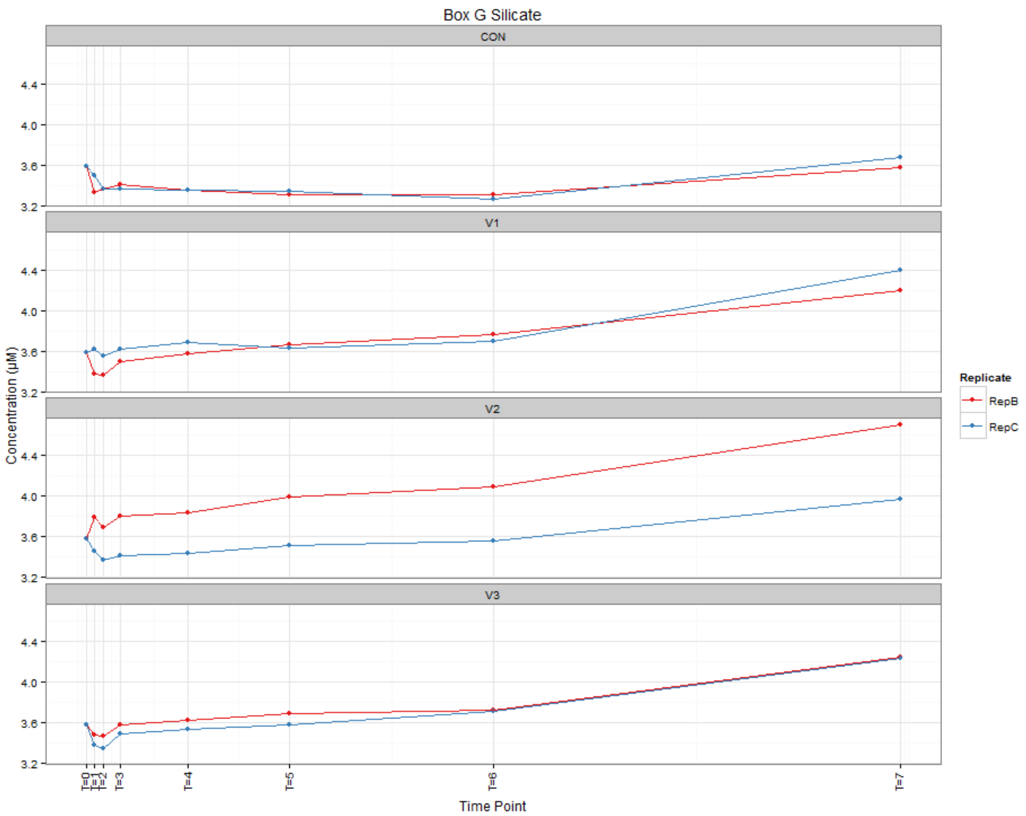



***Figure 2.37*** *Silicate concentrations during resuspension of Box G (sand). CON= control, V1 = 0-2cm, V2= 0-4 cm and V3=0-6cm.*

As can be seen from the above graphs, for ammonium, nitrate and nitrite, the background signal of nutrients from the bottom water sample do to some extend mask the nutrient release from the porewater and sediment particles. In contrast silicate shows a clear and sustained release pattern, particularly upon resuspension of the finer sediments at Box A (mud) and I (sandy mud). Here values increased by up to 100%, from ca. 3.8μM silicate to up to 7.5 μM over the 24h experiment. In the coarser sediments, the effect was less pronounced, but values still increased by up to 50 %, from a starting concentration of ca. 3.5μM to values up to 5μM. The shape of the release curves indicates a constant release from the resuspended particles, rather then an increase due to the porewater mixing. The other nutrient to show increasing values post sediment addition is phosphate. In this case the release is relatively fast, mostly within the first hour of the incubation.

## 2.4 Discussion

The experimental duration and approximate sediment concentrations (to allow realistic redox and chemical partitioning reactions) were informed by measured plume concentrations and longevity from the literature (O' Neil 2008 and 2012; Durrieu de Madrona et al., 2005) and early discussions (O'Neil, pers. Comm.). The nutrient chemistry of sediments changes significantly with depth in relation to sediment oxygenation and carbon breakdown reactions, which in terms are goverened by multiple factors such as supply from the overlying water-column and nature of the receiving sediment. As such, gears which penetrate differing depths are likely to result in differing chemical signatures and subsequent processing within trawl plumes.

The 4 main sites vary significantly in their sediment types, % fines, organic carbon and nitrogen levels and also redox layer depth as described by the oxygen profiles/OPD and aRPD from SPI.
Sites G is a sandy site with less than 5% silt in the upper 5cms at least. As the oxygen profile in **Figure 2.8** illustrates there is full equilibrium of porewater with the overlying water column down to ~4cms. As other work (Parker et al., 2012; Silburn et al., in prep) in the North Sea has shown, this low level of fines allows interstitial water flow to occur in the upper layers of sediments and allows full oxygenation to be maintained. Below this layer diffusion becomes dominant and the decrease in oxygen in pore-waters due to carbon respiration via other breakdown routes. Below the ~4cms depth we would therefore expect build-up of nutrients in the pore-water, though from the porewater profiles this only seems to be the case for silicate and to a lesser extend ammonium at significant depth. The other three sites (A, I and H) have increased fines and associated elevated organic carbon and nitrogen (OCN) levels as is expected from previous understanding of sediments in shelf seas (Parker et al 2012 and references therein). All the oxygen profiles are diffusive in nature and the oxygen penetration depth (OPD) is very shallow indicating strong oxygen respiration from within the sediment profile by bacterial processes. Below the OPD other carbon breakdown reactions (terminal electron acceptors nitrate, manganese, iron and sulphate) will drive the succession of pore-water chemistry with depth. In these muddy substrates it is likely that dissolved inorganic ammonium, phosphate and silicate will be readily available also in the upper few cms. The aRPD of the sites (ranging from 3.08 cm at Box H to 4.40 cm at Box H, with the muddiest/finest sediment from Box A averaging 3.69 cm) as linked to bioturbating fauna (Teal et al., 2010) will control mainly the nitrogen and phosphate cycles below the OPD and hence the availability of these two redox sensitive species upon resuspension, as well as overall OCN and labile carbon levels.

The profile data from each site (Figure 2.9) confirms their pre-resuspension status and potential availability of nutrients/OCN from the pore-water alone. From the values obtained, and given the approximately 400 fold dilution expected from suspending 10 ml of sediment (equivalent to approximately 5 ml of porewater) into 2000ml incubations, it is clear that no immediate measureable increase on the background values was to be expected, as the resulting values are not significantly above the measured bottom water concentrations.

The nutrient data from the experimental sediment resuspension show a complex picture, with limited nutrient release above control values for ammonium, nitrate and nitrite. As the bottom waters were not filtered, there is evidence of significant activity in the controls as well as in the resuspension samples. The nutrient that shows the strongest consistent pattern of release particularly from the finer, organic matter rich sediments is silicate. Interestingly there was little difference observed between the different resuspension depths. Values continue to increase throughout the resuspension experiment indicating a slow dissolution process rather than a pulse release upon initial mixing. This corresponds well with the sustained increase in chlorophyll and phaepigment (Figures 2.16 and 2.17), as dissolution of silicate containing cell walls from phytodetritus is a likely mechanism for the observed silicate release into the water. The observed release of phosphate, again stronger in the finer sediments, in contrast is dominated by a faster initial release rate, mostly plateauing after the first hour of incubation.

Further work calculating differential release rate over differing time steps for both phosphate and silicate, should provide useful progress towards the development of an experimental/statistical model for release signatures for these key nutrients resulting from sediment resuspension (by gears or other disturbances) relating to depth of impact and substrate type.

The experimental work has illustrated the importance of considering the nature of the sediment on which the disturbance acts and also the highlighted how the duration of the perturbation has an effect on the magnitude of the nutrient release triggered, which is different depending on the nutrient under observation and the mechanism for its transfer into the watercolumn.

## 2.5 Conclusions

The experimental work described above used sediment quantities and resuspension depth informed by the related observational work investigating impacts of fishing gears. The observed effects of sediment resuspension in bottom waters did not result in measurable oxygen drawdown or significant increases in ammonium, nitrate and nitrite, but silicate levels rose and continued to increase for the duration of the experiments (24h) while phosphate levels increased significantly during the first hour post resuspension. The level of silicate release in particular corresponded strongly with sediment type, with the fine sediments resulting in approximately twice the concentration increase compared to the sandy site. The nature of the gradual silicate release is commensurate with dissolution from particles, and its overall scale will be influenced by the longevity of the plume.

While fuller exploration of the wealth of experimental data collected is recommended, it is clear that the type of data produced is novel and significant. Findings from these investigations could provide the basis for improvements in future modelling efforts. For example, when comparing the impacts of fleet gear distributions regionally and their potential role in mediating or changing sediment–water column fluxes in nutrients and oxygen. As highlighted in Dounas et al. (2007) and Coughlan et al. (2012) these could have more significant effects on water column productivity in the shelf seas overall by altering large-scale nutrient fluxes and ratios. In due course this work could improve the assumptions underpinning future attempts at estimating scales of impacts and respective sensitivities of different sediment types to trawling induced resuspension.

Valuable lessons have already been learned, also in terms of experimental design, and it is expected that continuing work both on the emerging data from this section and collaborative interpretation building on the new insights gained in other parts of the overall Benthis programme will lead to a much improved understanding of the likely scale of fishing gear-induced resuspension impacts on biogeochemical processes.

# Section 3 Estimates of nutrient fluxes due to trawling relative to background

## 3.1 Introduction

A simple assessment of the significance of the nutrient flux due to direct trawling impacts is made for ammonium and nitrate. The relative impact is assessed by comparing with observed values of background benthic-pelagic nutrient fluxes. When supplemented by trawling intensity data and information on background fluxes the approach described here can form the basis for assessing the regional relevance of trawling to nutrient recycling. Because of the dependence of particle adsorption on redox conditions, calculation of the trawling flux for phosphorous was deemed to be too uncertain to estimate (see discussion later).

Work presented in section 1 (see also O'Neill & Ivanovic, 2015) has given a detailed idea of the processes by which trawling gears may cause sediment disturbance and potential nutrient release. Following O'Neill & Ivanovic (2015) two modes of bed disturbance were considered:

1) "Geotechnical" disturbance, occurring when parts of the fishing gear physically impact the seabed producing furrows or other features (down to some assumed penetration depth) that can be observed in video or sonar images.

2) "Hydrodynamic" disturbance of the bed due to the turbulent wake generated by the fishing gear that will resuspend surface sediments including deeper layers exposed by geotechnical disturbance.

For the purposes of nutrient release, the turbulent wake effect can be divided into: i) a resuspension flux whereby nutrients contained in the suspended pore water and those bound to the suspended particulates may be released into the water, and ii) a release of pore water and associated nutrients from deeper layers due to the pressure drop above the bed as the gear moves over it.

An attempt is made to quantify the relative importance of the trawling flux compared to the natural background for process 1 and 2(i) above. The physical basis on which to assess 2(ii) was felt not sufficiently well understood to make a detailed estimate at this time. We mainly consider the initial 'acute' impact of a trawl. It is possible that post trawl the background flux is perturbed. This may increase due to higher concentration pore water/sediment being exposed or decrease due to possible disruption of the biogeochemical processes governing remineralisation.

## 3.2 Methods

An order of magnitude calculation is carried out to gauge the importance of trawling compared with natural background flux. This is based on observational data collected in Shelf Seas (Lohse et al 1993) for a range of sediment types. This dataset was chosen as one the few published data sets that contained all the information required for the assessment (fluxes, pore and bottom water concentrations for both ammonium and nitrate).

The physical aspects of trawl impact is based on the gear type (**Figure 3.1**) and data presented in O'Neill & Summerbell (2011). A key quantity for nutrient release is the depth of the resuspended sediment layer $d_s$ (m). This was estimated for three sediment types (sand, muddy sand 2 and sandy mud 1) reported in O'Neill & Summerbell ( 2011) by matching the resuspended sediment weight m (kg $m^{-2}$ ) given in their table 4, using the relationship

$$d_s = m / [(1 - \varphi)\ \rho_s] \qquad 1)$$

where sediment density was taken as $\rho_s$=2650 kg $m^{-3}$ and porosities were estimated as $\varphi$ = 0.4, 0.45 and 0.66 for the sand site (S1), muddy sand site (MS2) and sandy mud (SM1) respectively.

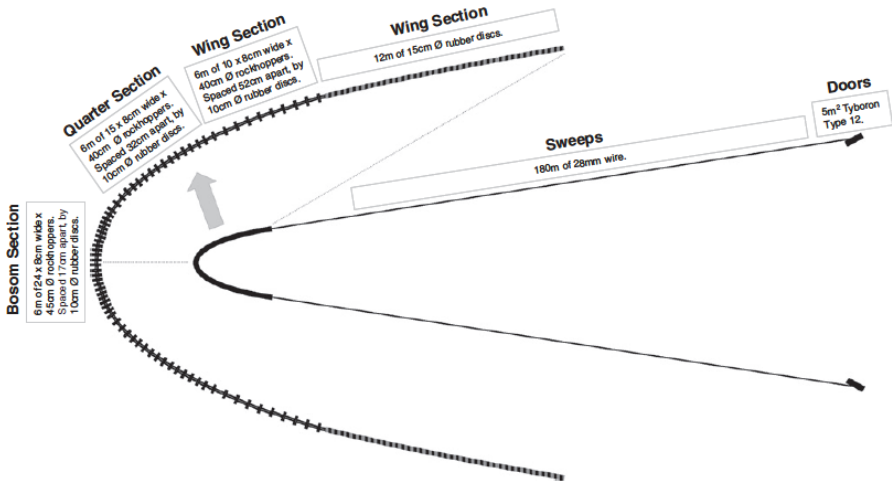



***Figure 3.1:*** *Gear type that physical impacts are calculated from in this section.*

In terms of the different gear comprising a trawl, all gear types are amalgamated into an average value apart from the doors which were treated separately because they generally have significantly larger penetration depth. To calculate the desorption of nutrient from suspended sediments, an estimate of the water column of the suspended material is required. This was done by assuming a plume height of h=1m. Particle volume concentration c ($m^3$ $m^{-3}$) is then calculated from

$$c = (d_s / h)\ (1 - \varphi)$$

Estimation of the trawling fluxes relative to the natural background flux required measurements of: 1) pore water nutrient profiles (mmol $m^{-3}$); 2) bottom water nutrient concentration (mmol $m^{-3}$); 3) background sediment water nutrient fluxes (mmol $m^{-2}$ $day^{-1}$). The observations at three of the sites reported in Lohse et al. (1993) were used. The three sites were matched on the basis of sediment type to one of the sand, muddy sand or sandy mud sites (S1, MS2, MS1) of the O'Neill & Summerbell (2011) experiments and the corresponding estimate of trawl resuspension depth.

The conceptual model of trawl impact is of a penetration by a gear component leading to exposure of deeper sediment, followed by resuspension of this new exposed sediment plus surrounding surficial sediment by the gear generated turbulence. A key value is a pore water concentration associated with the resuspension depth. This was assigned by visual inspection of the pore water profiles of the three chosen sites from Lohse et al (1993) adjusted to account approximately for an assumption that half the sediment suspended is the original surficial sediments exposed and half is that newly exposed down to the gear penetration depth. Given the approximate estimate sought and the complexity of the detailed interaction with the bed, this approach was considered accurate enough to obtain a reasonable value for the pore water concentration.

To calculate partitioning between dissolved and particle bound (adsorbed) nutrient phases an assumption of instantaneous equilibrium was made with dissolved *W* (mmol m-3) and particulate *P* (mmol $kg^{-1}$ sediment) concentrations related by a partition coefficient $K^*$ ($m^3\,kg^{-1}$)

$$P = K^* \; W \qquad 2)$$

Observed dissolved-particulate partition coefficients for ammonium are given in Mackin and Aller (1984). Nitrate exists in the dissolved phase only.

Let

$d_s$ =depth of resuspension by fishing gear (m)

$d_g$ =penetration depth of fishing gear (m)

$C_p$ = average pore water nutrient concentration in the resuspended layer (mmol $m^{-3}$)

$C_w$ = nutrient concentration just above the seabed (mmol $m^{-3}$)

$\varphi$ = sediment porosity

c = particle volume concentration in suspension ($m^3\,m^{-3}$)

K* = dissolved particulate partition coefficients (mmol $kg^{-1}$ sediment)

h = assumed height of turbulent wake (m)

$\rho_s$= sediment density of with a value of 2650 (kg $m^{-3}$)

The net amount released from the pore water (mmol $m^{-2}$) by resuspension is

$$D = ( d_s + 0.5\, d_g )\, \varphi \; (C_p - C_w)$$

where it is assumed that the area of actual penetration of the bed by the gear is about half the area resuspended by the trailing wake.

From the pore water concentration the particulate concentration per (bulk) volume can be calculated using equation 2) as $(1 - \varphi)\, \rho_s K^* C_p$ (mmol $m^{-3}$) so the amount resuspended (mmol $m^{-2}$) is

$$B = d_s\, (1 - \varphi)\, \rho_s K^* C_p$$

To estimate the amount desorbed from the resuspended particulates consider the unknown dissolved concentration W' (mmol $m^{-3}$) and suspended particulate concentration P' (mmol $kg^{-1}$) in the water column after re-equilibration. Neglecting the existing dissolved background and the new pore water release, P' and W' satisfy

$$(1-c)\, W' + c\, \rho_s P' = B/h \qquad 3)$$

where c ($m^3$ $m^{-3}$) is the particle volume concentration in suspension. The required estimate of the total amount of dissolved nutrient released by desorption from the suspended sediment is F = h W' (mmol $m^{-2}$). Substituting from equation 2) yields for this quantity

$$F = B /[(1-c) + c\, \rho_s K^*]$$

The above is a simplified treatment ignoring the background nutrition water concentration but will overestimate the desorption flux. It is reasonable providing the water concentrations are much smaller than the pore water concentrations. It is also likely to be an overestimate as some re-adsorption of nutrient might be expected as sediment settles. We assume it is sufficient for the order of magnitude estimates made here.

The approach described above was used to calculate ammonium and nitrate trawl fluxes. Unfortunately, phosphorous adsorption depends strongly on redox condition. In oxygenated sediments phosphate is highly particle reactive; in anoxic conditions much less so. Depending on sediment type the transition between the regimes is likely to occur within a few centimetres of the sediment surface and generally within the depth range that trawling will impact. This makes a theoretical or modelling based calculation very difficult as trawling will mix sediment from differing redox states. When resuspended sediments originating from the oxygenated layer are likely to release phosphorous while sediments potentially exposed by gear penetration from anoxic region will tend to remove dissolved phosphorous. The net effect is likely to be highly dependent on specific bed and trawl conditions that are hard to predict.

## 3.3 Results

### 3.3.1 Flux estimates

The results of the resuspension depth calibration estimates are shown in table 3.1. The resuspension depths are calibrated to obtain the values in the second from last row. An assumption about the proportion of trawl width each gear type occupies yields values for the width between door average suspension mass density (last row) that is close to those estimated in O'Neil & Summerbell (2011).

**Table 3.1:** Resuspension depths. S1, MS2, SM1 refer to the experimental sites of O'Neil & Summerbell (2011).

| | Sand (S1) | | Muddy sand MS2 | | Silt/sandy mud SM1 | |
|---|---|---|---|---|---|---|
| | Door | Rest | Door | Rest | Door | Rest |
| %Proportion of active width occupied by gear type | 4 | 30 | 4 | 30 | 4 | 30 |
| Porosity | 0.4 | 0.4 | 0.45 | 0.45 | 0.66 | 0.66 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Assumed gear penetration depth (m) | 0.03 | 0.01 | 0.05 | 0.02 | 0.1 | 0.04 |
| Resuspension depth (m) | 0.005 | 0.0004 | 0.015 | 0.002 | 0.05 | 0.005 |
| Plume height | 1 | 1 | 1 | 1 | 1 | 1 |
| SPM concentration ($m^3$ $m^{-3}$) | 0.003 | 0.00024 | 0.00825 | 0.0011 | 0.017 | 0.0017 |
| Calibrated resuspension mass (kg $m^{-3}$) | **8.0** | **0.64** | **21.9** | **2.9** | **45.1** | **4.5** |
| Resuspension mass density O'Neil & Summerbell (2011) value (kg $m^{-3}$) | **9.9** | **0.6** | **22** | **2.5** | **48** | **5** |
| Weighted to trawl width between doors (see O'Neil & Summerbell, 2011) | | 0.51 | | 1.75 | | 3.15 |

*Ammonium*

Data from Lohse 1993 were used to obtain pore water and background flux values for ammonium (table 3.2). The partition coefficient for ammonium was taken as K* = 0.003 ($m^3$ $kg^{-1}$) which is at the upper end of measured values (Mackin and Aller, 1984). This will tend to give upper bounds for the estimates of ammonium release.

The resulting estimates of trawling ammonium flux are shown in table 3.3. The results indicate that the nutrient released from a single trawl is of the same order of as the daily background flux. Thus even for a relatively heavily trawled region (area trawled once per year) the trawling ammonium flux when converted to an annual value is less than %1 of the annual background flux.

This outcome is explored by considering a sample calculation in more detail. Consider first the pore water release. For site 12 in the German Bight of Lohse (1993), a pore water concentration of Cp = 20.0 mmol N $m^{-3}$ in the top 5cm of the bed is a typical average (table 3.2). Assuming a porosity $\varphi = 0.4$ and a resuspension depth of $d_s$=0.02 m, the calculated release is

$$D = d_s \ \varphi \ (C_p - C_w)$$

yielding a value (neglecting the water column correction $C_w$)

$$D = 0.16 \text{ mmol N m}^{-2}$$

The measured daily ammonium flux is 0.18 mmol $m^{-2}$ $day^{-1}$ so that the trawled pore water release is of the order of the natural daily release[1]. On an annual basis for an area trawled 1-2 times a year the trawl release appears relatively small.

Considering ammonium adsorbed onto the particulates; the observed partition coefficient K* = 0.003 $m^3$ $kg^{-1}$ with typical porosity values implies the ammonium per unit volume of the seabed in the particulate phase is 3-5 times that of the dissolved phase. For the same resuspension depth and assuming all the adsorbed ammonium goes into dissolved form in the water column (reasonable based on the results in table Y3) this still yields a value for a single trawl that is only comparable to the daily background flux.

*Nitrate*

Data from Lohse (1993) were used to obtain pore water and background flux values for nitrate (table 3.4). Nitrate does not adsorb to sediment so the dynamics only involve pore water. The resulting estimates of trawling nitrate flux are shown in table 3.5. Note that for the muddy sand/silt site 13 the average background flux is from the water into the sediment based on averaging observations in February and August. The calculated trawling flux in this case is also negative because the pore water concentrations (again based on averaging the two annual data points) are less than water column values. The trawl flux for this case is about twice the daily flux. The calculated fluxes for the other two sites appear to be much less than daily fluxes.

[1] An alternative way of looking at this is to consider the flushing time for pore water. A flux of 0.18 mmol $m^{-2}$ $day^{-1}$ acting on bed concentration of 20.0 mmol N $m^{-3}$ in the top d=5 cm gives a flushing time $T_{flush} = d\ \phi\ C_p =$ 0.05 x 0.4 x 20.0/ 0.18 ≈2 days . Thus roughly speaking the top 5 cm of the sediment is exchanged on the order of 2 days by the ambient flux , compared with a similar magnitude release only once a year for a assumed trawling intensity based on assuming each region of the bed is trawled once a year

**Table 3.2:** Lohse 1993 ammonium data at 3 sites. Values obtained by visual inspection of pore water profiles. Fluxes positive from sediment to water.

| | | German Bight 12 | SE of Dogger bank 6 | German Bight 13 |
|---|---|---|---|---|
| D50 (mm) | | 0.18 | 0.09 | 0.03 |
| Porosity | | 0.4 | 0.45 | 0.66 |
| Class | | Fine sand | v. fine sand | Silt |
| Water column (mmol $m^{-3}$) | Winter | 2 | 1 | 6 |
| | Summer | 3.5 | 3 | 3 |
| PW average 0-2cm (mmol $m^{-3}$) | Winter | 15 | 10 | 100 |
| | Summer | 30 | 20 | 250 |
| | Average | 22.5 | 15 | 175 |
| PW average 2-5cm (mmol $m^{-3}$) | Winter | 20 | 25 | 300 |
| | Summer | 60 | 40 | 750 |
| | Average | 40 | 32.5 | 525 |
| PW average 5-10cm (mmol $m^{-3}$) | Winter | 90 | 25 | 700 |
| | Summer | 130 | 40 | 2000 |
| | Average | 110 | 32.5 | 1350 |
| Background Flux (mmol $m^{-2}$ $d^{-1}$) | Winter | 0.04 | 0.04 | 0.18 |
| | Summer | 0.31 | 0.34 | 12.00 |
| | Average | 0.18 | 0.19 | 6.1 |

**Table 3.3**: Ammonium calculations. Fluxes positive from sediment to water.

| | Site 12 German Bight (Sand - matched S1) | | Site 6 SE of Dogger Bank ( Muddy sand - matched to MS2) | | Site 13 German Bight (silt/sandy mud - matched to SM1) | |
|---|---|---|---|---|---|---|
| Gear type | Door | Other gear | Door | Other gear | Door | Other gear |
| %Proportion of active width occupied by gear type | 4 | 96 | 4 | 96 | 4 | 96 |
| Porosity | 0.4 | 0.4 | 0.45 | 0.45 | 0.66 | 0.66 |
| Erosion depth (m) | 0.005 | 0.0004 | 0.01 | 0.002 | 0.05 | 0.005 |
| Adjusted PW concentration over depth (mmol $m^{-3}$ pw) | 20 | 15 | 25 | 15 | 700 | 300 |
| Above bed annual average concentration (mmol $m^{-3}$) | 3.0 | 3.0 | 2.0 | 2.0 | 3.0 | 3.0 |
| Particulate volume concentration in bed (mmol $m^{-3}$ bulk) | 95.4 | 71.6 | 109.3 | 65.6 | 1892.1 | 810.9 |
| Pore water release per area swept by gear component (mmol $m^{-2}$) | 0.3 | 0.1 | 0.8 | 0.2 | 69.7 | 7.4 |
| Particulate resuspension per area swept by gear component (mmol $m^{-2}$) | 0.5 | 0.029 | 1.1 | 0.13 | 94.6 | 4.1 |
| Desorbed release per area swept by gear (mmol $m^{-2}$) | 0.5 | 0.029 | 1.0 | 0.13 | 83.3 | 4.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Pore water release integrated (mmol $m^{-2}$ total area swept) | | 0.076 | | 0.18 | | 9.92 |
| Desorbed release integrated (mmol $m^{-2}$ total area swept) | | 0.05 | | 0.17 | | 7.17 |
| Total trawl flux (PW+adsorbed) (mmol $m^{-2}$ area swept) | | 0.12 | | 0.35 | | 17.09 |
| Background Flux (mmol $m^{-2}$ $d^{-1}$) | | 0.30 | | 0.20 | | 6.2 |
| % annual relative flux trawled / background assuming area is trawled once per year. | | 0.111 | | 0.48 | | 0.76 |

**Table 3.4:** Lohse 1993 nitrate data at 3 sites. Values obtained by visual inspection of pore water profiles. Fluxes positive from sediment to water.

| | | German Bight 12 | SE of Dogger bank 6 | German Bight 13 |
|---|---|---|---|---|
| D50 (mm) | | 0.18 | 0.09 | 0.03 |
| Porosity | | 0.39 | 0.45 | 0.66 |
| Class | | Fine sand | v. fine sand | Silt |
| Water column (mmol $m^{-3}$) | Winter | 20 | 4 | 42 |
| | Summer | 2 | 1 | 4 |
| PW average 0-2cm (mmol $m^{-3}$) | Winter | 30 | 10 | 25 |
| | Summer | 3 | 3 | 1 |
| | Average | 16.5 | 6.5 | 13 |
| PW average 2-5cm (mmol $m^{-3}$) | Winter | 15 | 2 | 1 |

| | | | | |
|---|---|---|---|---|
| | Summer | 3 | 4 | 1 |
| | Average | 9 | 3 | 1 |
| PW average 5-10cm (mmol $m^{-3}$) | Winter | 3 | 2 | 1 |
| | Summer | 4 | 4 | 1 |
| | Average | 3.5 | 3 | 1 |
| Background Flux (mmol $m^{-2}$ $d^{-1}$) | Winter | 0.12 | 0.05 | -0.05 |
| | Summer | 0.29 | 0.26 | -0.07 |
| | Average | 0.20 | 0.16 | -0.1 |

**Table 3.5:** Nitrate calculations. Fluxes positive from sediment to water.

| | Site 12 German Bight (Sand - matched S1) | | Site 6 SE of Dogger Bank ( Muddy sand - matched to MS2) | | Site 13 German Bight (silt/sandy mud - matched to SM1) | |
|---|---|---|---|---|---|---|
| Gear type | Door | Other gear | Door | Other gear | Door | Other gear |
| %Proportion of active width occupied by gear type | 4 | 96 | 4 | 96 | 4 | 96 |
| Porosity | 0.4 | 0.4 | 0.45 | 0.45 | 0.66 | 0.66 |
| Erosion depth (m) | 0.005 | 0.0004 | 0.01 | 0.002 | 0.05 | 0.005 |
| Adjusted PW concentration over depth (mmol $m^{-3}$ pw) | 8 | 4 | 5 | 6 | 1 | 5 |
| Above bed annual average concentration (mmol $m^{-3}$) | 2.0 | 2.0 | 2.5 | 2.5 | 23.0 | 23.0 |
| Particulate volume concentration in bed (mmol $m^{-3}$ bulk) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Pore water release per area swept by gear component (mmol $m^{-2}$) | 0.120 | 0.011 | 0.088 | 0.042 | -2.2 | -0.45 |
| Particulate resuspension per area swept by gear component (mmol $m^{-2}$) | 0.0 | 0.000 | 0.0 | 0.00 | 0.0 | 0.0 |
| Desorbed release per area swept by gear (mmol $m^{-2}$) | 0.0 | 0.000 | 0.0 | 0.00 | 0.0 | 0.0 |
| Pore water release integrated (mmol $m^{-2}$ total area swept) | | 0.015 | | 0.044 | | -0.52 |
| Desorbed release integrated (mmol $m^{-2}$ total area swept) | | 0.00 | | 0.00 | | 0.00 |
| Total trawl flux (PW+adsorbed) (mmol $m^{-2}$ area swept) | | 0.015 | | 0.044 | | -0.52 |
| Background Flux (mmol $m^{-2}$ | | 0.20 | | 0.16 | | -0.06 |

| | | | | | | |
|---|---|---|---|---|---|---|
| d$^{-1}$) | | | | | | |
| % annual relative flux trawled / background assuming area is trawled once per year. | | 0.021 | | 0.08 | | 2.37 |

### 3.3.2 ERSEM model outputs

To illustrate the seasonal variation that might be expected in background fluxes model output is shown. Time series of modelled PO4, NO3 and NH4 fluxes (figure 3.2) show a clear seasonal variation generally reaching a peak in spring or summer. Also of interest is the relative proportion and variation in the total (pore water and particulate) nutrient content of the surface sediment layer. This shows that the quantity of phosphorous is highest per unit area.

Because of the scarcity of observational data with all the required measurements, for a regional assessment it is attractive to consider use of a model that, in principle, can give all the required values.

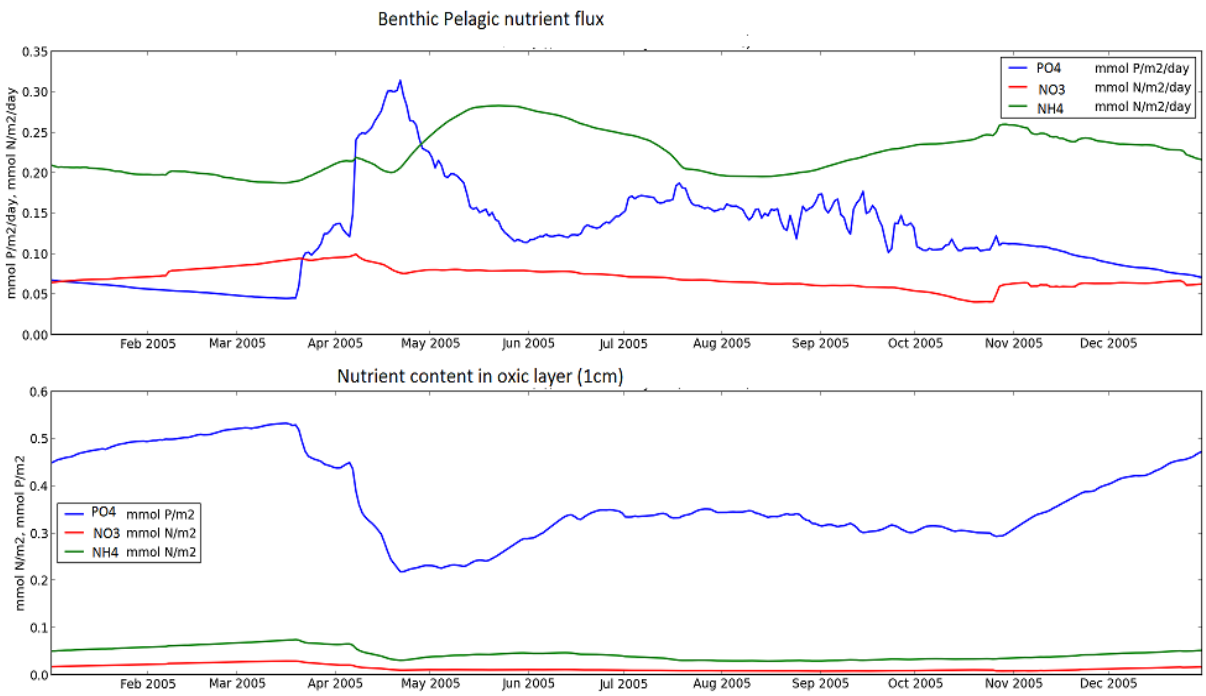



*Figure3.2: Example ERSEM model benthic-pelagic nutrient fluxes and bed nutrient content in the oxygenated layer.*

## 3.4 Discussion

Although the interaction of a trawl with the seabed and effect on the biogeochemistry is complex, some order of magnitude estimates can be made for potential trawl induced nutrient fluxes for nitrate and ammonium. The work of O'Neil and Summerbell (2011) and O'Neil and Ivanovic (2015) provides an excellent basis for estimating the physical resuspension and bed disturbance aspects needed for assessing the biogeochemical impacts. A parameterisation of the thickness of the turbulent wake and height of sediment resuspension behind a trawl was the main physical element that was absent. However, it is likely that other existing studies could provide this information.

The results based on data from sites considered here suggest trawling nutrient fluxes are relatively small when considered on an annual basis. The study of Couceiro et al. (2013) looked at the effect of resuspending a 0.7cm layer of sediment which is consistent with the resuspension depth values assumed for gear types other than doors in in table 3.1. They compared the simulated trawl release relative to the background values finding that trawl release was typically equivalent to 2-4 days of background flux. These values appear consistent with the order of magnitude estimates we obtain for the muddiest site. Dounas et al (2007) measure excess nitrogen concentrations after trawling for deep muddy site off Crete. The values they obtain for nitrogen ~ 500 µM $m^{-2}$ (sic) seem to be the same order of magnitude as some of the estimates obtained here if their stated µM is Interpreted as meaning µmol. Unfortunately, they do not measure background fluxes to compare against the trawled values.

With regard to the effect of the pressure drop in the turbulent wake and the possible effect on drawing out pore water from deeper in the sediments, although no attempt has been made to quantify this effect, it seems unlikely that it would lead to a flux significantly larger than those already accounted for. Tentatively it is suggested that this source could at most enhance the estimated fluxes by a factor of two to three.

Given the potentially large amount of phosphorous in the oxygenated layers it is important to try and assess the potential effect of trawling on this nutrient. As discussed it was not possible to do this here because of the combination of the redox chemistry of this nutrient and the effect of trawling in potentially mixing, exposing and then resuspending a mixture of anoxic and oxygenated sediments. The experiments carried out in this work package, where bed sediments were artificially suspended, provide a starting point for disentangling these interactions. However, they are not at this stage sufficient to allow a theoretical/modelling estimate to be made with any confidence. It may be the case that the net behaviour is highly site, time and fishing gear dependent making predictive calculation unfeasible. In this case field experiments may be the only way of evaluating the sediment flux due to trawling. Dounas et al. (2007) for example show a positive flux from sediment to water column for phosphorous but with a magnitude that is an order of magnitude smaller than for nitrogen.

In general the top surface layers appear to be relatively rapidly exchanged if the measured fluxes of nutrients are accepted. It is suggested that any additional release due to the direct impact of trawling appears to be minor. Post trawl effects such as changes to the background flux were not considered although they might in principle be addressed by experiments or by modelling.

# Conclusion

The report presented here covers three separately conducted significant areas of investigation: observed and modelled physical changes resulting from trawling across different types of sediments (section 1), experimentally constrained associated changes in biogeochemical parameters, such as oxygenation, pigment content, organic and inorganic nutrient concentrations and associated fluxes between the benthic and the pelagic system (section 2), and a theoretical comparison derived from observations and models on likely magnitude of resuspension impact compared to natural background processes (section 3).

The work on the physical impacts of gear components emphasises the hydrodynamic nature of sediment mobilisation and the relationship found between the amount of sediment put into the water column and the hydrodynamic drag confirms the findings of O'Neill and Summerbell (2011). It is also demonstrated that the weight (and presumably the penetration) of a component does not influence the amount of sediment mobilised. This is especially interesting as it is often assumed that the amount of sediment put into the water column behind a gear component is directly related to the size of the trench/furrow/scour that it makes on the seabed.

The experimental work undertaken on resuspending sediment aliquots from four different sites across a gradient from mud to sand, show contrasting behaviours of different nutrients and the influence of the site characterists on the nutrient releases into the watercolumn that the resuspension affected. Strongest increases in watercolumn concentrations were observed for silicate and phosphate, while nitrate, nitrate and ammonium releases were less pronounced. The dynamics of the silicate and phosphate releases differed in that phosphate was released relatively quickly, largely within the first hour post resuspension, wheras silicate concentrations increased throughout the incubation (i.e. up to 24 hours) consistent with slow dissolution from a phytodetritus source. Comparing different sediment types, it was apparent that resuspending the fine, organic matter rich sediments with shallow oxygen penetration depth and increased porewater nutrient concentrations, had higher impacts on subsequent watercolumn chemistry. While this finding is not unexpected, the experimental observations strengthen the case for differentiating how trawling impacts are assessed in light of underlying sediment biogeochemistry.

Early indications from the calculations estimating nutrient fluxes due to trawling induced resuspension relative to natural background flux values, are that the effect is less pronounced for the two chemical species investigated (nitrate and ammonium) than suggested in earlier studies. Further investigations of other parameters, such as phosphate and silicate, might have different finding though, as the above experimental results certainly suggest more significant effects than observed in the nitrogen containing species.

It is further of note that the presented estimates were based solely on physical resuspension and associated change in chemical concentrations, and not on coupled biologically mediated processes which could accompany trawling pressure, i.e. changes in rates of sediment nutrient processing and resulting benthic-pelagic fluxes post resuspension and resettling of the disturbed bed. Effects of the physical impact and the instant change in oxygenation status and chemical environment experienced by the sediment biota (macro-, meio- and microbenthos) during a gear pass, might longer term be additionally significant in shifting cycles of nutrients, carbon and oxygen, than the instantaneous changes in concentrations and nutrient availability alone. So while the expected resuspension related chemical fluxes for nitrate and ammonium might only be of a comparable order of magnitude to the natural flows, the effect on the system might be significantly different, as organisms adapted to anaerobic conditions or a strongly reducing environment are suddenly exposed to completely different conditions as found in the water-column. And post re-settling of the suspended sediment, new gradients will establish with potentially altered chemical fluxes. Differentiating between acute effects and longer-term consequences of the short term disruption of the established chemical gradients will require further work. Links across to other efforts, such as the work on chronic effects of fishing, will be essential in enabling a more coherent evaluation of the various levels of systematic change experienced.

# References

Brown, L., Bresnan, E., Summerbell K. and O'Neill F.G. 2013. The influence of demersal trawl fishing gears on the resuspension of dinoflagellate cysts. Marine Pollution Bulletin, 66, 17 – 24.

Churchill, J., 1989. The effect of commercial trawling on sediment resuspension and transport over the Middle Atlantic Bight continental shelf. Cont. Shelf Res. 9, 841–864.

Couceiro, F., Fones, G.R., Thompson, C.E.L., Statham, P.J., Sivyer, D.B., Parker, R., Kelly-Gerreyn, B.A., Amos, C.L. (2013) Impact of resuspension of cohesive sediments at the Oyster Grounds (North Sea) on nutrient exchange across the sediment-water interface. Biogeochemistry, 113: 37-52.

Coughlan, C., van der Molen, J., Aldridge, J., Parker, R., & Stephens, D. (2011). Marine Ecosystem Connections: essential indicators of healthy, productive and biologically diverse seas (contract ME3205). Report: impacts of climate variability and trawling on ecosystem dynamics: GIS and ERSEM model analysis. Milestone Report 5a, ME3205, 11.

Diesing, M., Stephens, D., and Aldridge, J. (2013). A proposed method for assessing the extent of the seabed significantly affected by demersal fishing in the Greater North Sea. ICES Journal of Marine Science, 70: 1085–1096.

Dounas, C. G. (2006). A new apparatus for the direct measurement of the effects of otter trawling on benthic nutrient releases. Journal of Experimental Marine Biology and Ecology, 339: 251 –259.

Dounas, C., Davies, I., Triantafyllou, G., Koulouri, P., Petihakis, G., Arvanitis, C., Sourlatzis, G., and Eleftheriou, A. (2007) Large scale impacts of bottom trawling on shelf primary productivity. Continental Shelf Research 27: 2198–2210.

Drillet, G., Hay, S., Hansen, B. W., O'Neill F.G., 2014. Effects of demersal otter trawls on the re-suspension of copepod resting eggs and its potential effects on recruitment. Journal of Fisheries and Livestock Production, 2:1. http://dx.doi.org/10.4172/2332-2608.1000114

Durrieu de Madrona*, X., Ferréa, B., Le Correb, G., Grenzc , C., Conand , P., Pujo-Payd , M., Buscaila, R. and Bodiot, PO. 2005 Trawling-induced resuspension and dispersal of muddy sediments and dissolved elements in the Gulf of Lion (NW Mediterranean). Continental Shelf Research 25(19-20): 2387-2409.

Gilkinson K., Paulin M., Hurley S., Schwinghamer P., 1998, Impacts of trawl door scouring on infaunal bivalves: results of a physical trawl door model/dense sand interaction, Journal of Experimental Marine Biology and Ecology, vol. 224, pp. 291-312.

HMSO (1983) The Determination of Chlorophyll in Aquatic Environments 1980. Methods for the Examination of Waters and Associated Materials. 26pp ISBN 0 11 751674 0

Hoerner, S.F., 1965. Fluid-dynamic drag. Published by the author.

Jones, J.B. (1992) Environmental impact of trawling on the seabed: A review. N Z J Mar Freshwater Res, 26: 59–67.

Kirkwood DS (1996) Nutrients: practical notes on their determination in seawater. Techniques in marine environmental science no. 17. ICES, Copenhagen.

Kaiser, MJ, Clarke, KR, Hinz, H, Austen, MC, Somerfield, PI, Karakassis, I. 2006. Global analysis of response and recovery of benthic biota to fishing. Marine Ecology Progress Series 311, 1-1

Lohse, L., Malschaert, J.F.P., Slomp, C.P., Helder, W., Vanraaphorst, W. (1993) Nitrogen cycling in North Sea sediments - Interaction of denitrification and nitrification in offshore and coastal areas. Marine Ecology Progress Series Volume 101, Issue 3, 1993, Pages 283-296.

Mackin, J. E. , Aller, R. C. (1984) Ammonium adsorption in marine sediments, Limnology and Oceanography. 29(2) 1939-5590

Mason, C. (2011) Particle Size Analysis (PSA) for Supporting Biological Analysis. NMBAQC's Best Practice Guidance.

O'Neill F.G. and Ivanovic, A. (2015) The physical impact of towed demersal fishing gears on soft sediments. ICES Journal of Marine Science. DOI:10.1093/icesjms/fsv125.

O'Neill F.G., Robertson, M., Summerbell K., Breen M. and Robinson, L.A. (2013). The mobilisation of sediment and benthic infauna by scallop dredges. Marine Environmental Research, 90: 104 – 112.

O'Neill F.G., Simmons S.M., Parsons D.R., Best J.L., Copland P.J., Armstrong F., Breen M. and Summerbell K. (2013b). Monitoring the generation and evolution of the sediment plume behind towed fishing gears using a multibeam echosounder. ICES Journal of Marine Science, 70 (4): 892 – 903.

O'Neill F.G. and Summerbell K. (2011). The mobilisation of sediment by demersal otter trawls. Marine Pollution Bulletin, 62: 1088 – 1097.

Palanques, A., Guillén, J. and Puig, P. (2001) Impact of bottom trawling on water turbidity and muddy sediment of an unfished continental shelf. Limnol Oceanog 46: 1100–1110.

Palanques, A., Puig, P., Guillén, J., Demenstre, M., and Martin, J. (2014) Effects of bottom trawling on the Ebro continental shelf sedimentary system (NW Mediterranean). Continental Shelf Research, 72: 83-98.

Parker, R., Barry, J., Bolam, S., Eggleton, J., Powell, C., Weston, K. and Coggan, R. (2012) Objective 4: Assessing the sensitivity of sediment habitats. Defra Contract report (ME5301).

Parker, R., Weston, K., Barry, J., Powell, C. (2012) Deliverable 2.6 Recommended biogeochemical targets and indicators for MSFD monitoring and management of the UK seabed. Defra milestone report (ME5301).

Percival, P. (2004) Impacts of trawl fisheries on marine benthic biogeochemistry. PhD Thesis Newcastle University pp 174.

Pilskalin, C.H., Churchill, J.H. and Mayer, L.M. (1998) Resuspension of Sediment by Bottom Trawling in the Gulf of Maine and Potential Geochemical Consequences. Conservation biology 12(6):1223 – 1229.

Pusceddu, A., Fiordelmondo, C., Polymenakou, P., Polychronaki, T., Tselepides, A. and Danovaro, R (2005) Effects of bottom trawling on the quantity and biochemical composition of organic matter in coastal marine sediments (Thermaikos Gulf, Northwestern Aegean Sea). Continental Shelf Research 25: 2491–2505.

Rabouille, C., Denis, L., Dedieu, K., Stora, G., Lansard, B. and Grenz, C (2003) Oxygen demand in coastal marine sediments: comparing in situ microelectrodes and laboratory core incubations. Journal of Experimental Marine Biology and Ecology, 285/286: 49-69

Silburn, B., Parker, E.R., Mason, C. and Parker, W.R. (in prep) 'Rapid fines assessment: A quantifiable volumetric method to assess fines content in marine soft sediments'.

Sivyer, D. B. (1999). Nitrogen cycling in intertidal sediments of the Wash, UK MSc by Research, University of East Anglia.

Stephens, D. and Diesing M (2015). Towards quantitative spatial models of seabed sediment composition. PLoS One, 10(11): e0142502.

Teal, L.R., Parker, E.R. and Solan, M (2010) Sediment mixing layer as a proxy for benthic ecosystem process and function. Marine Ecology Progress Series, 414, 27-40.

Tengberg, A., Almroth, E. and Hall, P. (2003) Resuspension and its effect on organic carbon recycling and nutrient exchange in coastal sediments: in situ measurements using new experimental technology. Journal of Experimental Marine Biology and Ecology, 285-286: 119-142.

Tett, P.(1987) Plankton. In, Baker, J.M. and Wolff, W.J. (eds), Biological surveys of estuaries and coasts. Estuarine and brackish water sciences association handbook. Cambridge University Press, Cambridge, U.K., pp. 280-341.

Thompson, C.E.L., Statham, P.J., Sivyer, D.B., Parker, R., Kelly-Gerreyn, B.A., Amos, C.L. (2013) Impact of resuspension of cohesive sediments at the Oyster Grounds (North Sea) on nutrient exchange across the sediment-water interface. Biogeochemistry, 113: 37-52.

Trimmer, M., Nedwell, D.B., Sivyer, D.B., Malcolm, S. (1998) Nitrogen fluxes through the lower estuary of the river Great Ouse, England: The role of the bottom sediments. Marine Ecology Progress Series 163:109-124.

Trimmer, M., Petersen, J., Sivyer, D.B., Mills, C., Young, E. and Parker, E. R. (2005). "Impact of Long-Term Benthic Trawl Disturbance on Sediment Sorting and Biogeochemistry in the Southern North Sea." Marine Ecology Progress Series 298 (August): 79–94.

Verardo, D.J., Froelich, P.N., McIntyre, A. (1990) Determination of organic carbon and nitrogen in marine sediments using the Carlo Erba NA-1500 analyzer. Deep-Sea Res 37: 157–165.

# Annex I Plots of suspended particulate matter for each station.

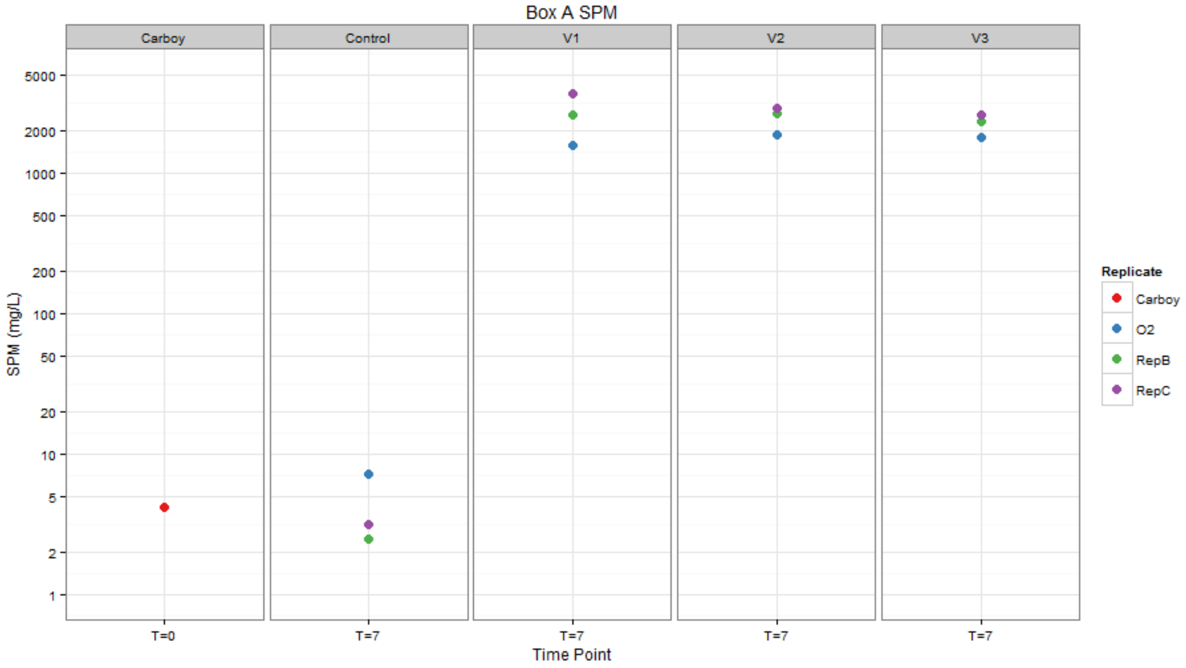



Figure AI 1: Suspended particulate matter concentration during resuspension experiment of Box A Mud

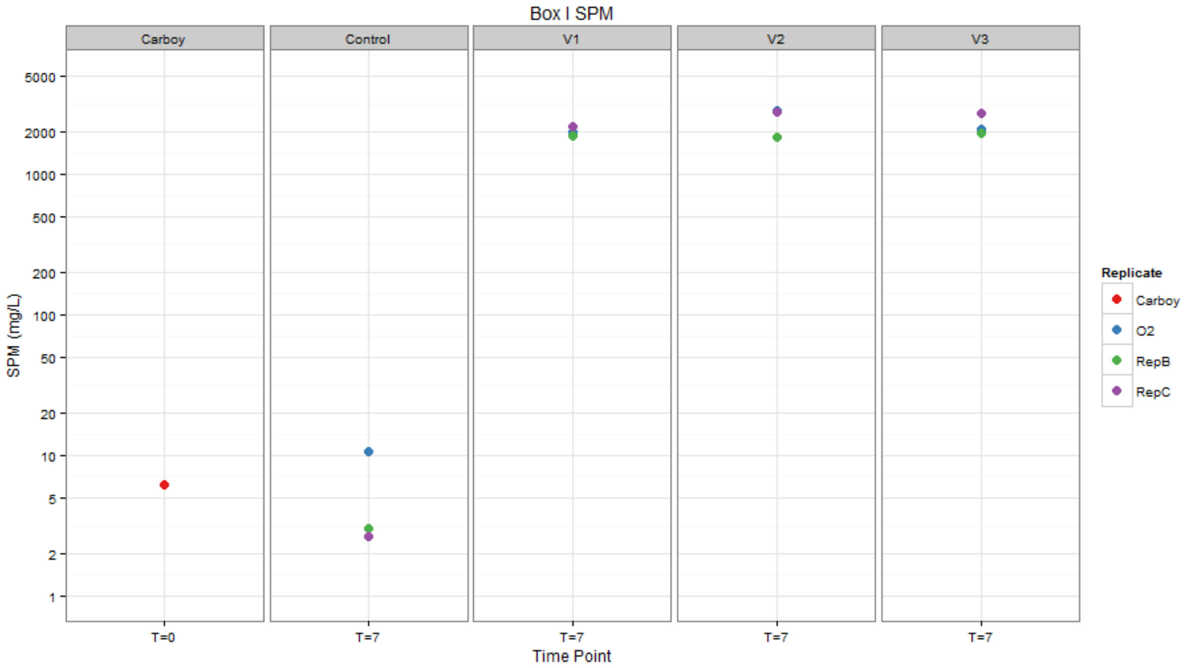



**Figure AI 2:** Suspended particulate matter concentration during resuspension experiment of Box I Sandy Mud

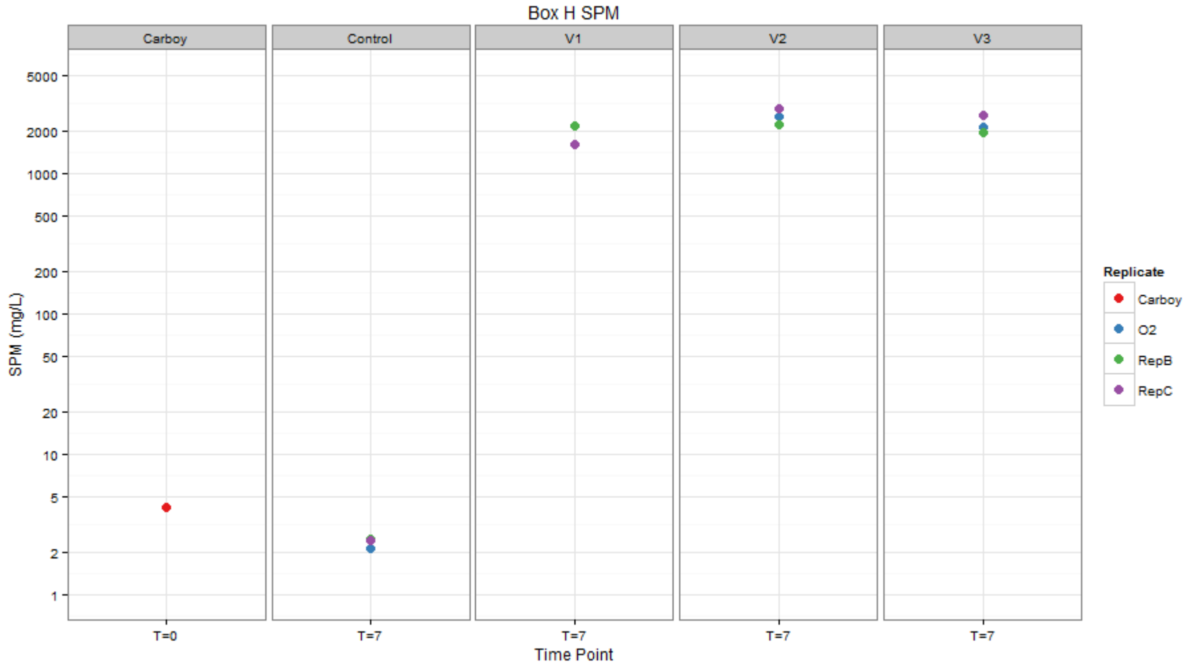



**Figure AI 3**: Suspended particulate matter concentration during resuspension experiment of Box H Muddy Sand

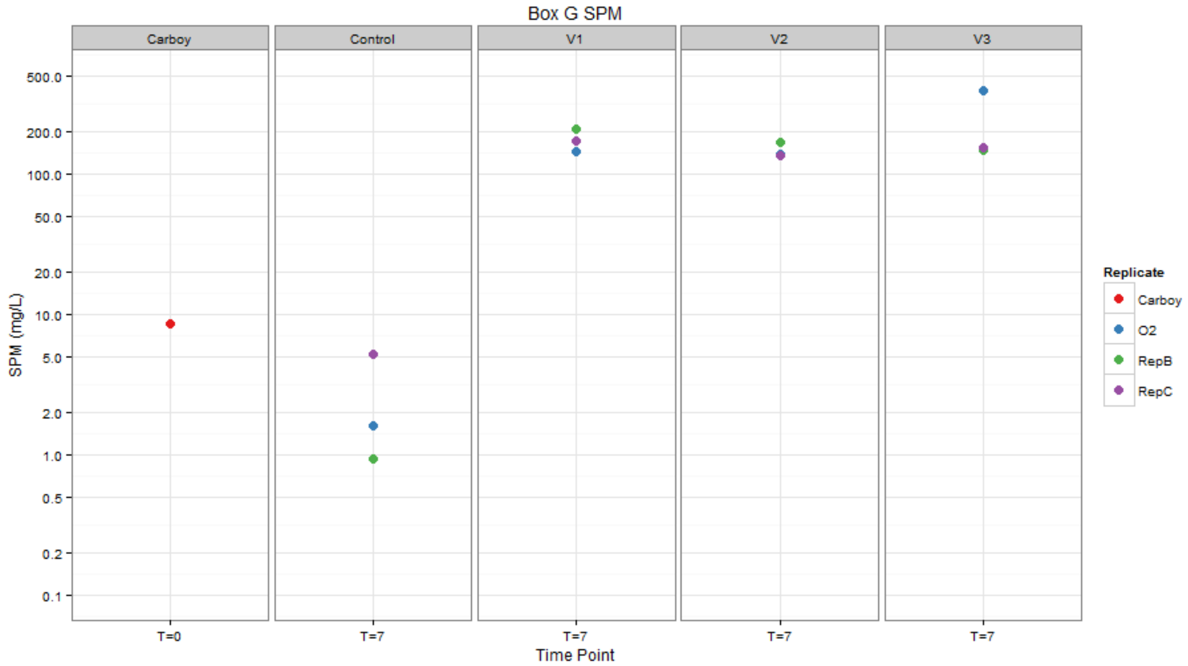



**Figure AI 4:** Suspended particulate matter concentration during resuspension experiment of Box G Sand

# Annex II Correlations between SPM values and pigments (Chlorophyll and Pheaopigment indicative of labile carbon sources)

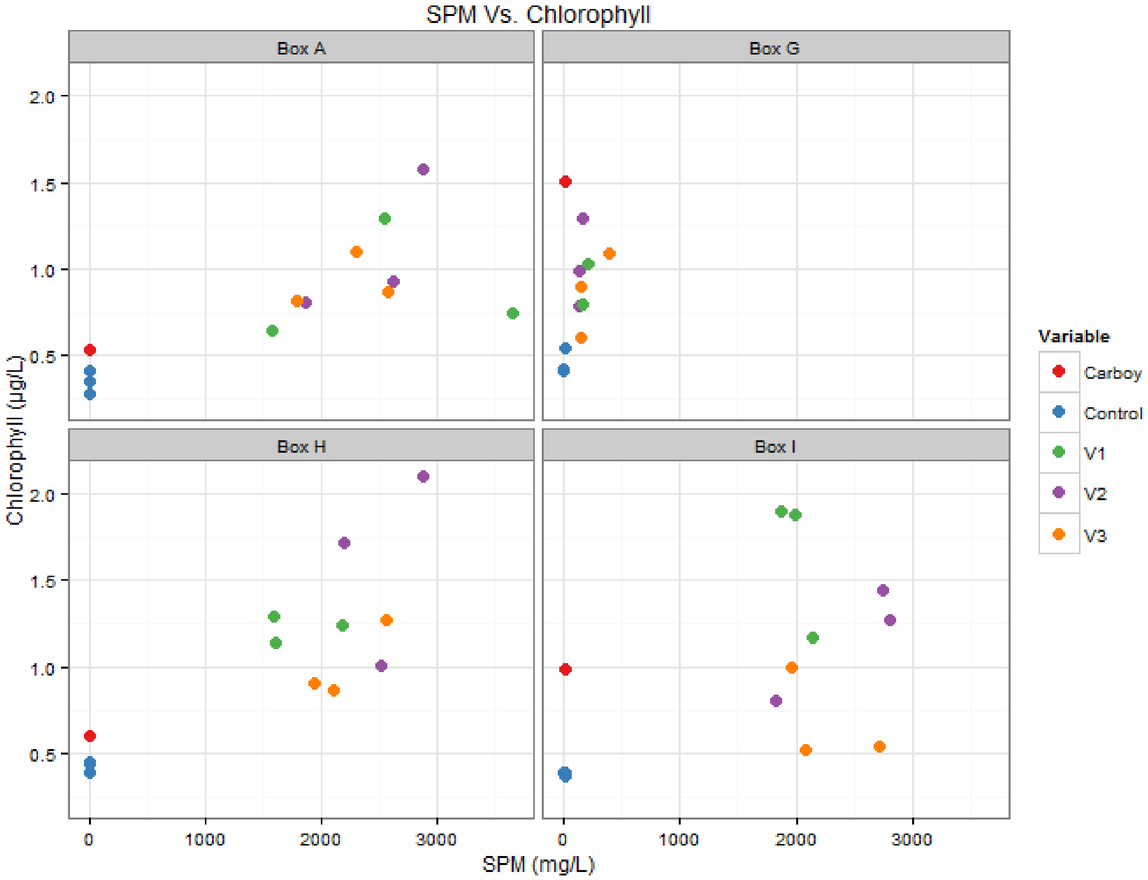



**Figure AII 1** Scatter plot showing individual relationship between chlorophyll and suspended particulate matter for all four sediment types (Box A Mud, H Muddy Sand, I Sandy mud and G Sand) and resuspension depth (V1= 0-2 cm, V2 = 0-4 cm, V3= 0-6 cm).

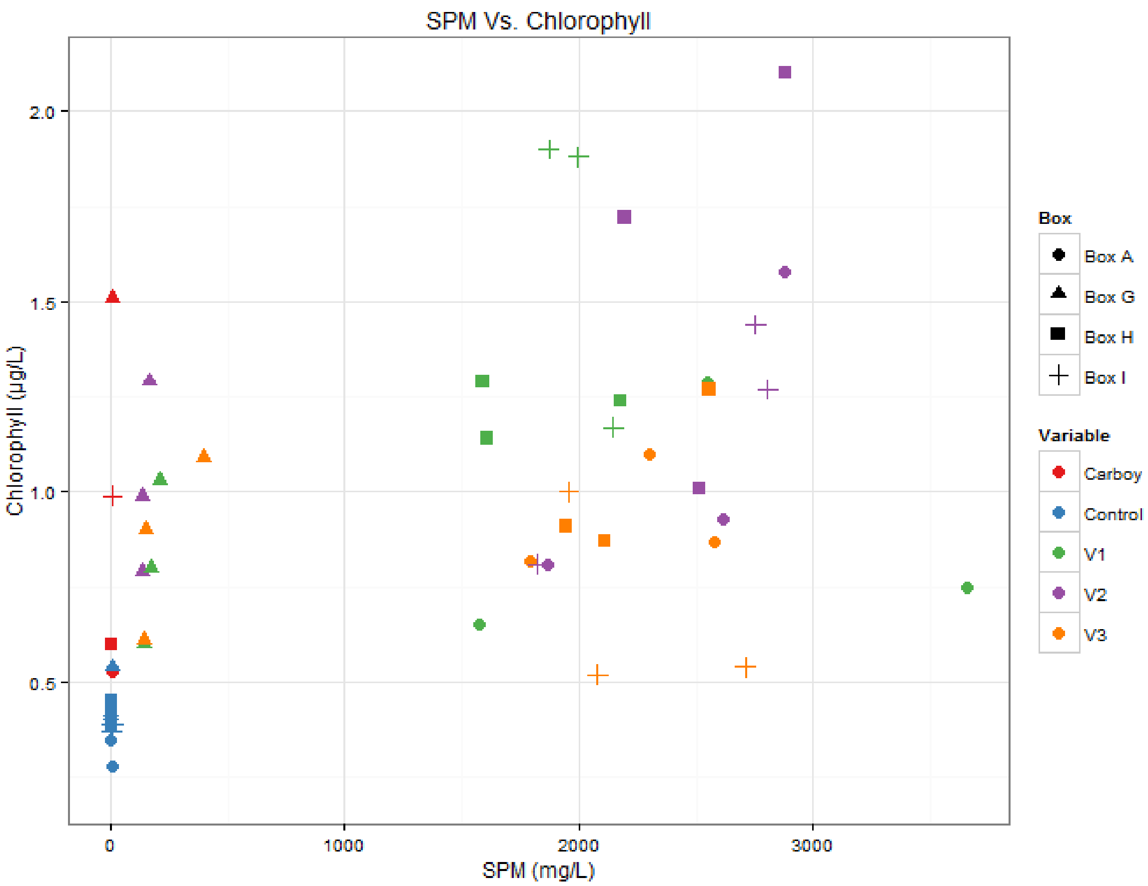



**Figure AII 2** Scatter plot showing correlation between chlorophyll and suspended particulate matter for all four sediment types (Box A Mud, H Muddy Sand, I Sandy mud and G Sand) and resuspension depth ((V1= 0-2 cm, V2 = 0-4 cm, V3= 0-6 cm) combined

# Annex III Observations regarding the experimental set-up/ Specific experimental constraints and lessons learned

Detailed below are some constraints that affect the experimental incubations, which are recorded in detail in order to enable improvements to be considered for any future studies:

1. Limited space in the CT lab on board the RRS Discovery meant that the experiment had to be performed in an incubation tank. This resulted in difficulties in accessing the individual bottles for sampling and retrieving them out of the tank interrupted the sediment resuspension by the stirrers. The submersion of the bottle in the tank also made it difficult to see if the stirrers were spinning throughout the experiment. It would be considered advantageous for future studies to conduct the experiments in a CT room and increase the spacing between vessels.

2. Two factors contributed to sub-optimal resuspension of the sediment: in spite of significant effort being directed at sourcing entirely flat-bottomed incubation vessels, the received plastic bottles did have some welding lines and therefore the stirrers did not spin as smoothly as expected. Secondly, the individual magnetic stirrers used could not be set to a sufficiently high speed to keep heavier particles in suspension, because at higher speeds the magnetic fields of the individual stirrers started to interfere with each other. This limited the degree to which the larger sediment particles stayed in suspension and thus particularly affected the sandy site.

3. The added sediment volume was not identical across the three different depth, as syringes that sampled the required depths while maintaining the same sample volume of sediment could not be sourced.

4. The OxyDot optical cables did not stay consistently in position against the Oxydot spots. Blu Tack™ was used to secure the cable, but occasionally handling of the adjacent bottles resulted in disturbance of the set-up and subsequently the signal was briefly lost/interrupted (as apparent in noise/spikes observed in the continuous recordings). This could be overcome in future through the wider spacing between bottles suggested above and/or bespoke cable guides.

5. Only when sampling the bottles at the end of the experiment (T=7) were they removed from the tank, tumbled and the required sample amount measured out into a cylinder. This resulted in more sediment in the sample as compared to sampling *in situ* from the tank through the tubing, the method applied at the previous times steps. As already stated above, the stirrers were not keeping the heavier sediment particles fully in suspension and the sub-sampled water was less turbid as would otherwise be expected from the added sediment load.

6. Sample filtration of samples with such high sediment loads (particularly at T7, where manual tumbling ensured best mixing) resulted in unusually long filtration times (3-4 hours) when preparing filtrates for subsequent analysis (i.e. nutrients, chlorophyll). This might have implications in terms of sample degradation.

7. Subsampling from Rep 2 and Rep 3 resulted in the introduction of air to the sample bottles, potentially affecting oxygenation levels in these replicates compared to the sealed Rep 1. Compensation through the addition of bottom water to keep the sample vessels filled was considered but would have resulted in a change in concentration of dissolved parameters such as nutrients so was not done.

8. The relatively high concentration of suspended particles in solution will have added to cell disruption and subsequently chlorophyll degradation not only while in suspension but also during sample filtration, a source of additional phaeopigment formation not necessarily representative of degradation in plume conditions.