CM 2000/Z:07 General Fisheries and Marine Ecology.

# The-impact of fishing disturbance on benthic nutrient regeneration and flux rate.

Philip Percival, and Chris Frid.

Philip Percival, Dove Marine Laboratory, Dept. Marine Sciences, University of Newcastle, Cullercoats, North Shields, NE30 4PZ, UK. [tel:+44 1912524850, fax+44 191 2521054, e-mail: philip.percival@ncl.ac.uk]. Chris Frid, Dove Marine Laboratory, Dept. Marine Sciences, University of Newcastle, Cullercoats, North Shields, NE30 4PZ, UK. [tel:+44 1912524850, fax+44 191 2521054, e-mail: c.l.j.frid@ncl.ac.uk ].

## Abstract.

Nitrogen products are often thought to be a major limiting factor for photosynthesis by marine primary producers, ultimately, therefore, fisheries yield is dependent on the amounts of new and regenerated nutrients within the system. It is generally held that greater than 90% of marine primary production is remineralised within the marine system. However, the contribution to this figure from sedimentary processes is less well understood. Little attention has, however, been paid to the potential change in nutrient regeneration dynamics and flux rates as a result of fishing disturbance of the seafloor. This study investigates benthic remineralisation and nutrient flux, including consideration of the role of benthic disturbance by fishing vessels. Two mesocosm systems containing sediment from an untrawled area of the North Sea were allowed to stabilise for two months prior to the study. One system was subjected to daily simulated trawl activity while the other system remained untrawled over a four day period. Flux chambers were used to gain data on concentration changes within the chambers for three hours following the disturbance. Results indicate that nutrient

concentration and flux are greatest immediately following a trawling event from sediments that have equilibrated. Nutrient concentrations and flux rates are reduced from sediments disturbed on successive days. Using these flux data, trawling within the ICES statistical sub-rectangle 39E8 is estimated to increase the annual flux by 1.4% for nitrite (NO;), 1.8% for ammonium (NH,'), 0.4% for nitrate (NO;) and 2.4% for phosphate $(PO_4^{3-})$.

## Introduction.

Nitrogen limitation is one of the main controlling factors for the photosynthesis of marine algae, and the basis of the pelagic ecosystem food web (Barnes and Owens 1998). Therefore fisheries yield is ultimately dependent on the quantity of new and regenerated nutrients within the system (McCaffey et at. 1980). In coastal waters the dominant source of nutrients for new production is via advection from estuaries and surface run off (Nielsen and Richardson 1996). In offshore areas the source is diffusion across the pycnocline and remineralisation within the mixed layer (Sathyendranath et al. 1995). As a result, any activity that stimulates nutrient regeneration and hence primary production in offshore waters, where terrestrial inputs of nitrogen are limited, may play an important role in determining ecological dynamics.

The availability of nitrogen products to the pelagic system is in part determined through sediment-water fluxes of nutrients. This, microbially mediated, benthic remineralisation of organic compounds is now recognised as a significant pathway by which inorganic nutrients are regenerated and released to the overlying waters (McCaffey et al. 1980). The magnitude of this recycling and release pathway can be a controlling factor for pelagic primary productivity, supplying a potentially significant proportion, up to 80%, of the nutrient requirements of primary producers (Nixon et al. 1976).

Studies have shown that where physical disruption to the sediment occurs, fluxes alter from those expected from gradient controlled molecular diffusion, the mechanism which occurs in undisturbed sediments (Duyl et al. 1993). Disturbance to the sediment by trawl gear can potentially alter the regeneration and flux of nutrients through three mechanisms, which may act in combination. Firstly nutrient cycling processes are reliant on specific oxidation boundaries within the sediment. The nature of marine sediments usually only allows for the uppermost layer of the sediment to exhibit oxidising conditions, underlain by a reduced sediment environment (Bagander and Niemisto 1978). However, alteration of the redox status by direct physical disruption by fishing gears effects the microbial activity within the sediments. Secondly tickler chains used for both otter and beam trawls are designed to scrape the surface layer of the sediment to increase the catch. Direct physical damage occurs to the benthic community from the contact of trawl gear and in areas of persistent trawl activity, can cause a shift in the assemblage of benthic organisms. Such a shift can potentially cause concomitant impacts to the nutrient dynamics of the system as the natural reworking of organic matter and release of nutrients through burrowing activity is altered. Thirdly, in areas of intensive fishing activity there is the addition of large amounts of labile organic matter, in the form of offal and discards. This organic input becomes the driving force behind the microbial activity as bacterial activity is governed by the supply of organic matter and is not dependent on the number of bacteria. Therefore fishing activity could actually be contributing to the source of inorganic nutrients for benthic remineralisation.

In this paper a study of sediment-water flux measurements is presented for trawled and untrawled sediments. Mesocosm systems were used to elucidate rates of inorganic nutrient release from North Sea sediments subject to trawling and left untrawled. While sediments were collected from an untrawled locality, the region is exposed to a high rate of trawl frequency, up to 12.9 times per year within the ICES statistical rectangle 39E8 (Frid and Clark 2000). The area is also subject to little surface run-off where anthropogenic sources of nutrients could be introduced into the system. This study aims to identify the flux changes between trawled and untrawled areas and uses these to derive the contribution to nutrient dynamics by trawl activity within the North Sea.

## Method.

### Field sites.

An untrawled area of the central-west North Sea was located using chart data and echo sounding equipment and consisted of a 'U' shape of shipwrecks and hydrographic features. The inner area between the wrecks was protected from fishing as the area was too small for the deployment of commercial fishing gear and the wrecks themselves comprised too many hangs for trawl activity to occur. The untrawled area, centred on (55°12.68'N 01°27.20'W) and covering an area approximately $100 m^2$, of the central-west North Sea was for used field sampling (Fig 1). The physical presence of the wrecks would have an impact on the benthic flow dynamics of the immediate vicinity but samples for this study were obtained from the centre of the area and so are unlikely to be greatly influenced by the presence of the structures (Hall et al. 1993).

### Mesocosm systems.

Six replicate Haps-cores were collected in May 2000 from a site at the centre on the untrawled region (Fig. 1). The cores were immediately placed, with minimal disturbance to the sediment, into mesocosms (approximately $0.03\ m^3$) and three sub-samples (approximately 30g) were removed from each system for sediment characterisation. Sediment depth in each tank was approximately 25cm. A regulatedcontinuous flow water column of filtered seawater overlay each sediment system. The water flow was maintained at a rate of approximately 45 $l hr^{-1}$. Water circulation velocity and aeration was achieved through a 45 degree splash plate positioned approximately 5cm above the water surface and directly under the continuous water flow. This allowed flow and oxygen to be introduced into the system and was kept at a rate just below that of visible surface resuspension of the sediment. Ambient light and temperature were maintained for both trawled and non-trawled systems. Following a stabilisation period of two months, flux and nutrient concentration chemistry were measured.

### Sediment characterisation.

The three replicated sub-samples taken from the grab samples were analysed for sediment particle size, percentage organic matter and porosity. Particle size analysis was determined by wet sieving (62ym mesh aperture) a known dry weight (approximately 25g) sub-sample from each site to measure the silt-clay fraction (Buchanan 1984). The remaining sand fraction was then further divided by dry sieving through a series of graded mesh apertures (2mm, 500µm, 250µm, 125µm, and 62µm) using electric agitation for 15min. To account for a possibility of the presence of mineral carbon (coal) organic matter was determined by wet digestion method. Approximately 10g of oven dried sediment was digested by heating with a 6% hydrogen peroxide solution until the reaction ceased. The remaining material was then dried to a constant value and the percentage organic matter determined by loss of mass. Porosity measurements were derived by weight loss from a known amount of sediment oven dried at $80^{\circ}C$ to a constant value.

Sediment-water fluxes.

The mesocosm systems were allowed a two month period to stabilise, in order for the chemical and biological systems to reach equilibrium prior to experimental trials. For the trials one mesocosm system was designated the trawled system and the other remained undisturbed. In the trawled system, prior to sampling, a chain positioned on the sediment was dragged across the surface, penetrating to a depth approximately 3cm, to mimic trawl activity.

Immediately after this flux chambers were placed over the sediment. Sediment-water exchange measurements were made using flux chambers. Flux chambers consisted of cylindrical glass tubes fitted with a flexible membrane top. Immediately following the trawl simulation, the flux chamber was introduced and the $t_0$ sample taken. Once emplaced these chambers trapped approximately 0.8 $dm^3$ of seawater over $0.0045m^2$ of sediment. Chambers in the untrawled system were placed with care to avoid disturbance to the surface layer. Nutrient concentrations within the chambers were determined by sampling each chamber at 30-minute intervals over a three-hour period and after 24-hours, just prior to the trawl impact being repeated. This method enabled data to be gained on concentration and flux changes to an untrawled and trawled system.

Samples were obtained through the membrane using acid cleaned, over lying water flushed, 20ml plastic syringes. The chamber membrane collapsed slightly as samples were withdrawn. Water volumes within the chambers were calculated from depth graduations (cm) on the side of the glass tube. Filtration using 45µm filters ensured removal of any particulate matter before nutrient analysis. All samples were transferred to gas tight polypropylene bottles and refrigerated at 4°C immediately after collection and were analysed within four hours of collection. Flux measurements were calculated from nutrient concentration change over time, controlling for the volume and surface area of the chambers. Experimental trawling procedures were repeated on successive days to elucidate data for changes following equilibration and repeated disturbance (experimental time period 24 hours).

Nutrient analysis.

Sample nutrient concentrations were determined with an automated nutrient analyser, SKALAR San $^{Plus}$, for dissolved nitrates ($NO_2^-$ and $NO_3^-$), ammonium (NH,‘) and phosphate ($PO_4^{3-}$). The detection limits of the nutrient analyser used were 0.1 µm and 0.05 pm for nitrates and phosphate respectively. Methods used were the standard air segmented flow colourimetric analysis for nitrate, nitrite (diazonium ion) (Brewer and Riley 1965), phosphate (phospho-molybdenum blue complex) (Kirkwood 1989) and ammonium (indophenol blue) (Mantoura and Woodard 1963). All presented pm concentrations are in µm $l^{-1}$. Benthic fluxes (µmol $m^{-2}$ $hr^{-1}$) were calculated. Mann Whitney statistical tests were performed on percentage organic matter, porosity data and nutrient concentrations from trawled and untrawled sediment. Logarithmic transformation was applied to particle size analysis. Nutrient concentrations (pm l-‘) are presented graphically.

## Results.

### Sediment characteristics.

Trawled and untrawled mesocosm sediments did not vary in sediment characteristics. The results for particle size analysis showed the mean particle size to be 3.5 phi for both systems. Porosity showed no significant difference (n=3, W=6, p=0.081) between mesocosm systems. Percentage organic removal exhibited no significant difference (n=3, W=6, p=0.081)

### Mesocosm nutrient concentrations.

#### Nitrite, ( NO;).

The $NO_2^-$ concentration in the equilibrated untrawled system maintained, within a concentration range of 0.1 pm, a steady state for all sampling times at approximately 1.2 to 1.3 pm (Fig. 2a). The first simulated trawl event to the equilibrated sediment caused a large efflux of $NO_2^-$ to the overlying water, significantly changing the concentration (W=73, p=0.011) compared to control, between 0.5 to one-hour after the trawling. From one-hour after trawling, the concentration exhibited a steady decline towards equilibrium. The chamber concentration three hours following trawling, had still not returned to the initial concentration (Fig. 2a). After 24-hours from the trawl event $NO_2^-$ concentrations were below that of the baseline observed in the equilibrated system (Fig. 2b). Subsequent daily trawling did not cause concentration to significantly diverge (p=1.000, W=53) from that in the untrawled system, both maintaining a concentration range within 0.2 pm (Figure 2b).

#### Ammonium (NH,‘)

The $NH_4^+$ concentration in the overlying water, of the untrawled control system, in both equilibrated and repeatedly trawled mesocosms remained constant throughout the duration of the experiment, within a concentration range of 5 μm (Fig. 3a &3b). Following trawl activity chamber concentrations exhibited a significant difference compared to the control both for the initial trawling of the equilibrated sediment (W=77, p=0.002) and the repeated trawlling (W=77, p=0.002). Following trawl activity to the stabilised sediment a large initial concentration change was apparent (approximately 15 to 40 pm) (Fig. 3a). This elevated concentration was maintained over the remaining time of the first day’s experiment. This pattern was also observed in the trawled system on subsequent days (Fig. 3b). The initial NH,’ concentration in the overlying water was approximately the same as the initial concentration in the equilibrated system of day one (Fig. 3b). The change in concentration over the three hour period however, was reduced (approximately 15 to 25 µm) (Fig. 3b).

### Nitrate (NO,).

The concentration of NO; in the untrawled system remained at a constant level, approximately 8.5 µm, throughout the experiment (Fig. 4a). However, the initial concentration in the trawled system was approximately 1µm greater. Over the course of the first 3 hours of the experiment there was a significant difference (W=75, p=0.005) in NO,‘ concentration between trawled and untrawled sediments. However, the initial differences in $NO_3$ concentration mean it is impossible to accurately quantify the change due to the trawling treatment. Immediately following trawling disturbance to the previously stabilised system it exhibited an increased from approximately 10 µm to 11 µm (Fig. 4a). One-hour after trawling the $NO_3^-$ concentration declined to less than that detected initially (approximately 9 µm) and continued to move towards the situation in the undisturbed system (Fig. 4a). The concentration of $NO_3^-$ overlying the untrawled sediment on subsequent days remained relatively constant at approximately 11.5 µm. The NO,‘ concentration from the repeatedly disturbed sediment initially increased, from approximately the same level as the equilibrated system (approximately 11.5 µm), before declining below the initial concentration (to approximately 11 µm) after one-hour thirty minutes (Fig. 4b). However, the concentration increased above the initial level to approximately 12 pm for samples, two to two and a half-hours after trawling (Fig. 4b). Compared to untrawled, over the subsequent days there was no significant difference (W=60, p=3.71) in the chamber $NO_3^-$ concentration.

### Phosphate (PO,“)

The PO,” concentration in the chamber overlying the untrawled sediment remained relatively constant (within 1µm) for the duration of the experiment (Fig. 5a). Comparison of $PO_4^{3-}$ from trawled and untrawled sediments showed significant difference in concentration (W=70, p=0.030) from the stabilised tank. Trawling of the equilibrated sediment $PO_4^{3-}$ concentration caused a large concentration increase from approximately 4.5 µm to 11.5 µm (Fig. 5a). Following disturbance $PO_4^{3-}$ concentrations were maintained at the increased level for the remaining samples on the first day (Fig. 5a). A similar pattern of concentration increase immediately following trawling was also observed in the repeatedly disturbed system (Fig. 5b), with a significant difference (W-77, p=0.002) compared to untrawled. The untrawled $PO_4^{3-}$ concentration remained within a range of approximately 0.2 µm throughout the experiment (Pig. 5b). However, the measured concentration was lower than that of the stabilised mesocosm (approximately 1 µm to 1.4 µm) for the untrawled system and repeatedly trawl events (Fig. 5b).

### Benthic fluxes.

The derived flux rates were based on the measured nutrient concentrations. Therefore, only differences in the magnitude of the flux change are highlighted, as the overall pattern is the same as the one exhibited by concentration. For nutrients; $NH_4^+$, $NO_3^-$ and $PO_4^{3-}$, following a trawl event to equilibrated sediment large effluxes from the sediment occur (Table 1). The flux rate for nitrite displayed an initial influx following trawling before a relatively large efflux one-hour after the trawl event. The flux rate then declined over the remaining sample times. The rate for untrawled sediments was however, lower than that of the trawled sediment (Table 1). For the repeatedly disturbed sediment, the overall flux rates were reduced, although there was the same pattern of an influx before an efflux for nitrite (Table 1 & 2). There was also the same pattern of an initial high flux followed by reduced flux rates observed for; NH,‘, $NO_3^-$ and $PO_4^{3-}$, (Table 2). Comparison of the total flux rates between the repeatedly trawled and the previously stabilised sediments showed the overall flux rate for each nutrient to be less for those sediments that were trawled without time for full recovery to occur (Table 1 & 2).

### Percentage flux change.

The results show that the percentage flux change of ammonia and phosphate one hour following a trawl event, for sediment that is in equilibrium, can be up to approximately 2300 % and 6500% increase respectively (Table 3). The percentage change for each nutrient species reduced over a three hour period (Table 3). Percentage change of benthic fluxes, within those sediments that were repeatedly disturbed, decreased with time from the trawl event (Table 4). In all cases the magnitude of the initial and subsequent flux changes were reduced from changes observed from stabilised sediments (Tables 3 & 4).

## Discussion.

The magnitude of nitrification that can occur in marine sediments is dependant on the extent of the oxidised layer (Nedwell et al. 1983). Following the trawl disturbance to the equilibrated system additional oxygen would be introduced to the sediment through the physical mixing with the aerated overlying water. This, in effect, temporally increases the surface area of the oxidised layer of sediment. Within the equilibrated system, while the concentration of ammonia immediately increases, there is a one-hour lag before a nitrite peak occurs (Fig 2a & 3a). The chemical transformation of ammonium to nitrite and subsequently to nitrate (nitrification) would account for this. A corresponding peak from the effects of nitrification is not carried into nitrate concentration during the experimental time, but may be due to the process of denitrification. This is demonstrated by a corresponding peak in nitrite 30-minutes after the highest nitrate concentration (Fig. 3a & 4a). The combined effects of nitrification and denitrification appear to be reduced during repeatedly trawled events (Fig. 2b, 3b & 4b).

Many previous studies have shown the release of regenerated nutrients to ultimately depend on the remineralisation of organic matter in creating steep vertical concentrations of pore water constituents (Rowe et al. 1975; Rasmussen and Joergensen 1992; Duyl et al. 1993). Diffusion based on chemical gradients however does not adequately describe the release of benthic inorganic nutrients to the overlying water observed in this study. The results of this study indicate that in areas where equilibrium is achieved, the role of trawl activity can act to enhance benthic flux rates by up to 6641% for phosphate and 2389% for ammonium. The increased nutrient flux immediately following trawling, observed for all nutrients in the equilibrated system, in the field would be transported horizontally by currents and could serve to supply a proportion of the nutrient requirements of planktonic organisms. Such an increase in the supply to planktonic organisms has crucial, long and short term, consequences to ecosystem dynamics (Nielsen and Richardson 1996). Those sediments that are subjected to a high frequency of trawl disturbance however, exhibit a reduced initial flux with (observed in nitrate) an net influx from the overlying water. If the rate of disturbance is greater than that of the regeneration needed, not only to reach equilibrium but to create steeper chemical gradients for an efflux, the sediment will become a nutrient sink.

In situ sediments would receive additional organic input through the settling of detrital debris and the introduction of offal and discards from fishing activity. The results of this study are therefore, likely to be conservative estimates due to the loss of organic matter during transformation in the stabilisation period as substitute sources were not introduced.

Extrapolation of flux data enabled the percentage increase in nutrient flux from trawl events compared to the annual untrawled sediment flux rates within the ICES statistical sub-rectangle 39E8 to be estimated. The percentage increase in nutrient flux attributable to trawling activity with the 39E8 region was 1.4% for $NO_2^-$, 1.8% for $NH_4^+$, 0.4% for NO,- and 2.4% for PO,*, of the total annual untrawled flux rate. These estimates were based on the flux rate 0.5 hours following trawl disturbance being maintained for 30 minutes after each trawl event followed by a return to background rates.

Future work needs to establish chemical recovery rates following trawling and the time interval needed between trawl events to maximise benthic release and regeneration of inorganic nutrients.

# Bibliography.

Bagander, L. E. and L. Niemisto (1978). "An Evaluation of the Use of Redox Measurements for Charaterizing Recent Sediments." tnarine. Coastal and Marine Science 6: 127- 134.

Barnes, J. and N. J. P. Owens (1998). "denitrification and Nitrous Oxide Concentrations in the Humber Estuary, UK, and Adjacent Coastal Zones." Marine Pollution Bull& 37(3-7): 247-260.

Brewer and Riley (1965). "The automated determination of nitrate in sea water. (modified to increase sensitivity, by decreasing the ammonium chloride concentration." Deep Sea Research 12: 765-772.

Buchanan, J. B. (1984). Sediment Analysis. Methods for the study of marine benthos. N. A. Hohne and A. D. McIntyre. London, Blackwell Scientific Publications: 41-65.

Duyl, F. C. V., W. V. Raaphorst, et al. (1993). "Benthic bacterialproduction and nutrient sediment-water exchange in sandy North Sea sediments." Marine Ecology Series 100: 85-95.

Frid, C. L. J. and R. A. Clark (2000). Long-term changes in North Sea benthos: discerning the role of fishing. Effects of fishing on non-target species and habitats. M. J. Kaiser and S. J. deGroot. London, Blackwell Science: 198-2 16.

Hall, S. J., M. R. Robertson, et al. (1993). "The Possible Effects of Fishing Disturbance in the Northern North-Sea • an Analysis of Spatial Patterns in Community Structure Around a Wreck." Netherlands Journal of Sea Research 31: 201-208.

Kirkwood, D. S. (1989). Simultaneous determination of selected nutrients in sea water. ICES CM 1989/C: 29.

Mantoura, R. F. C. and E. M. S. Woodard (1983). "Optimization of the indophenol blue method for the automated determination of ammonia in estuarine waters." Estuarine. Coastal and Shelf Science 17: 219-224.

McCaffey, R. J., A. C. Myers, et al. (1980). "The relationship between pore water chemistry and benthic fluxes of nutrients and manganese in Narragansett Bay, Rhode Island." Limnology and Oceanography 25( 1): 3 1-44.

Nedwell, D. B., S. E. Hall, et al. (1983). "Seasonal changes in the distribution and exchange of inorganic nitrogen between sediment and water in the Northern Baltic (Gulf of Bothnia)." Estuarine, Coastal and Shelf Science 17: 169-179.

Nielsen, E. and K. Richardson (1996). "can changes in the fisheries yield in the Kattegat ( 1950- 1992) be linked to changes in primary production?' ICES Journal of Marine Science 53: 988-994.

Nixon, S. W., C. A. Oviatt, et al. (1976). "Diel metabolism and nutrient dynamics in a salt marsh embayment." Ecology 57: 740-750.

Rasmussen, H. and B. B. Joergensen (1992). "Microelectrode of seasonal oxygen uptake in a coastal sediment: Role of molecular diffusion." Marine Ecology Progress Series 81: 289-303.

Rowe, G. T., C. H. Clifford, et al. (1975). "Benthic nutrient regeneration and its coupling to primary productivity in coastal waters." Nature 255: 2 15-2 17.

Sathyendranath, S., A. Longhurst, et al. (1995). "Regionally and seasonally differentiated primary production in the North Atlantic." Deep-Sea Research 42( 10): 1773-I 802.

Table 1. Calculated nutrient flux rates at each sample time and the total flux over a three-hour period for trawled and untrawled sediments that were previously left to stabilise. (+ ve numbers denote a flux out of the sediment into the overlying water, - ve numbers denote a flux into the sediment).

| | Nitrite µmol $m^{-2}$ $h^{-1}$ | | Ammonia µmol $m^{-2}$ $h^{-1}$ | | Nitrate µmol $m^{-2}$ $h^{-1}$ | | Phosphate µmol $m^{-2}$ $h^{-1}$ | |
|---|---|---|---|---|---|---|---|---|
| Sample Time | Trawled | Untrawled | Trawled | Untrawled | Trawled | Untrawled | Trawled | Untrawled |
| 00:30 | -13.1 | +1.0 | +10237.2 | +1076.7 | +381.4 | -255.2 | +2925.7 | +160.0 |
| 01:00 | +79.1 | -3.2 | +288.9 | -17.7 | -298.3 | +118.7 | +85.3 | +34.6 |
| 01:30 | -14.7 | -6.9 | +105.7 | +79.6 | -141.8 | -61.4 | +20.6 | +53.2 |
| 02:00 | -9.9 | +0.7 | +56.3 | +137.8 | -14.1 | -13.0 | +14.1 | +19.1 |
| 02:30 | +3.5 | -6.0 | +60.8 | +290.2 | -32.0 | -3.9 | NA | +8.8 |
| 03:00 | -7.4 | +2.0 | +83.2 | -244.8 | +12.2 | +2.7 | +276.4 | -2.3 |
| Total flux | +37.5 | -12.4 | +10832.1 | +13.21.8 | -92.6 | -212.1 | +3322.1 | +273.4 |

Table 2. Calculated nutrient flux rates at each sample time and the total flux over a three-hour period for trawled and untrawled 'sediments that underwent repeated intermediate. trawl disturbance. (+ ve numbers denote a flux out of the sediment into the overlying water, - ve numbers denote a flux into the sediment).

| | Nitrite µmol $m^{-2}$ $h^{-1}$ | | Ammonia µmol $m^{-2}$ $h^{-1}$ | | Nitrate µmol $m^{-2}$ $h^{-1}$ | | Phosphate µmol $m^{-2}$ $h^{-1}$ | |
|---|---|---|---|---|---|---|---|---|
| Sample Time | Trawled | Untrawled | Trawled | Untrawled | Trawled | Untrawled | Trawled | Untrawled |
| 00:30 | -4.0 | -14.1 | +3530.6 | +699.8 | +691.2 | +143.8 | +70.9 | -42.0 |
| 01:00 | +0.3 | - 4.9 | -545.0 | -126.5 | -242.5 | -102.1 | -13.6 | -7.1 |
| 01:30 | +1.8 | +1.2 | +44.9 | +190.4 | -184.7 | -56.0 | -1.2 | +4.0 |
| 02:00 | -3.7 | -1.1 | -68.0 | -247.9 | +161.2 | -72.3 | -3.0 | -9.6 |
| 02:30 | +1.1 | +2.6 | +22.0 | +104.5 | +7.1 | +139.3 | -0.3 | +7.9 |
| 03:00 | -0.8 | +0.5 | +6.0 | +75.7 | -85.3 | -121.1 | -2.4 | -0.9 |
| Total flux | -5.3 | -5.8 | +2990.5 | +696.0 | +347.0 | -68.4 | +50.4 | -47.7 |

Table 3. Percentage change in benthic fluxes following a trawl disturbance to a previously stabilised system. (+ ve numbers denote an efflux from the sediment; - ve numbers denote an influx to the sediment).

| | % change of product from trawled sediment. | | | |
|---|---|---|---|---|
| Chemical recovery time. | Nitrite | Ammonia | Nitrate | Phosphate |
| One hour | +392.54 | +2389.04 | +483.32 | +6641.41 |
| Three hour | +74.27 | +819.50 | -179.61 | +2931.10 |

Table 4. Percentage change in benthic fluxes following a trawl disturbance to an intermediately disturbed system. (+ ve numbers denote an efflux from the sediment; - ve numbers denote an influx to the sediment).

| | % change of product from trawled sediment. | | | |
|---|---|---|---|---|
| Chemical recovery time. | Nitrite | Ammonia | Nitrate | Phosphate |
| One hour | -114.14 | +1286.98 | -528.88 | -2478.98 |
| Three hour | -52.92 | +429.69 | -136.32 | -725.79 |

Figure 1. Map of the of the central-west North Sea. Centre of sample site illustrated by (1).

Figure 2a. Concentration of nitrite (µm l“) from an equilibrated system for trawled and untrawled sediments.

Figure 2b. Concentration of nitrite (pm $l^{-1}$) from a repeatedly trawled sediments and an untrawled system.

Figure 3a. Concentration of ammonia (pm $l^{-1}$) from an equilibrated system for trawled and untrawled sediments.

Figure 3b. Concentration of ammonia (µm $l^{-1}$) from a repeatedly trawled sediments and an untrawled system.

Figure 4a. Concentration of nitrate (µm $l^{-1}$) from an equilibrated system for trawled and untrawled sediments.

Figure 4b. Concentration of nitrate (µm $l^{-1}$) from a repeatedly trawled sediments and an untrawled system.

Figure 5a. Concentration of phosphate (µm $l^{-1}$) from an equilibrated system for trawled and untrawled sediments.

Figure 5b. Concentration of phosphate (µm $l^{-1}$) from a repeatedly trawled sediments and an untrawled system.

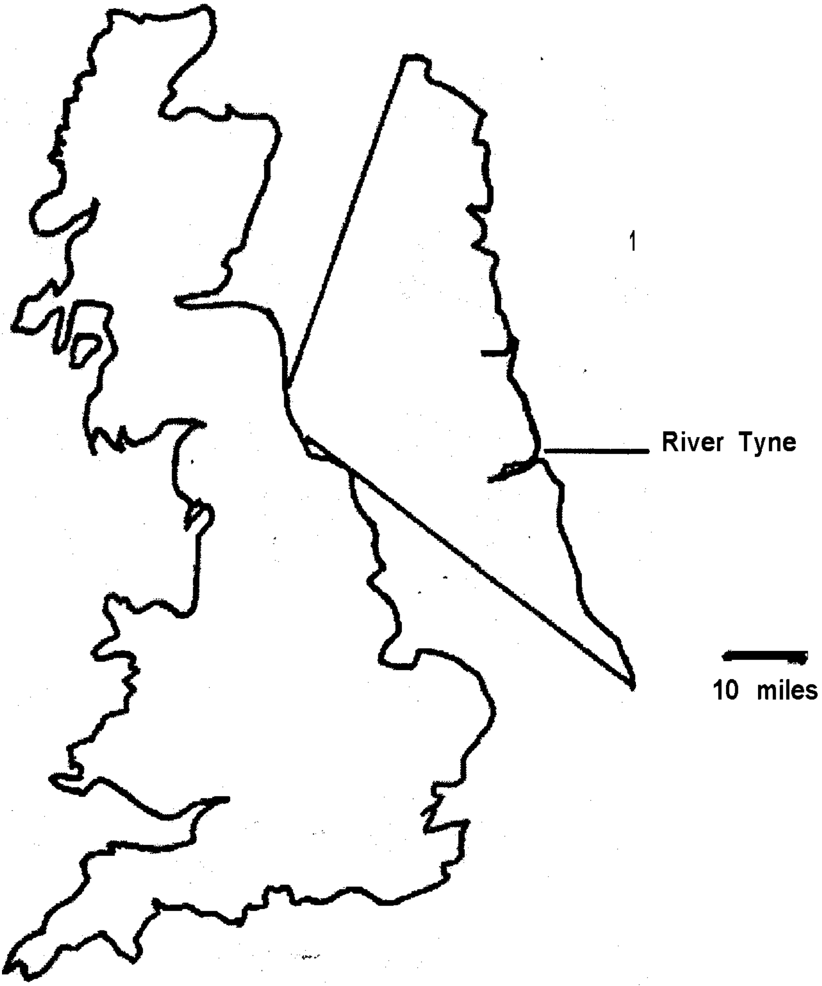

Figure 1.

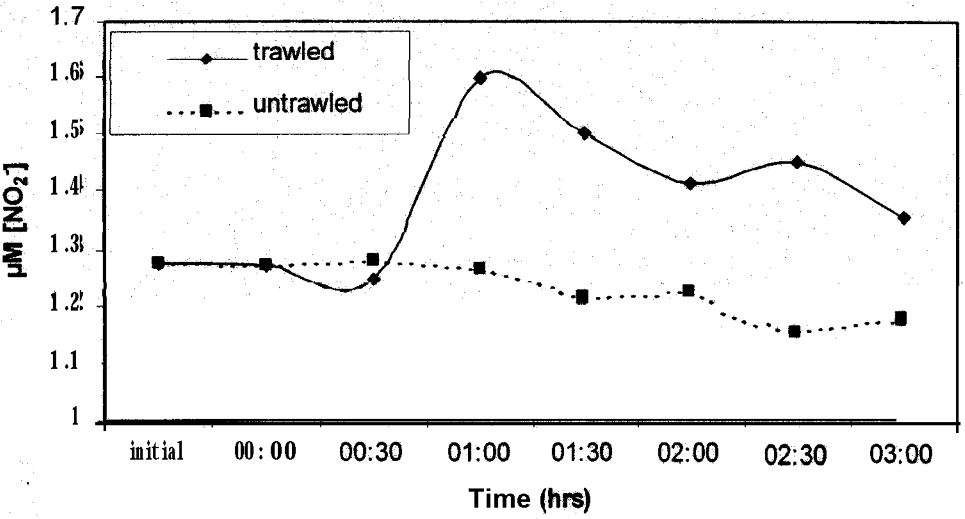

Figure 2a.

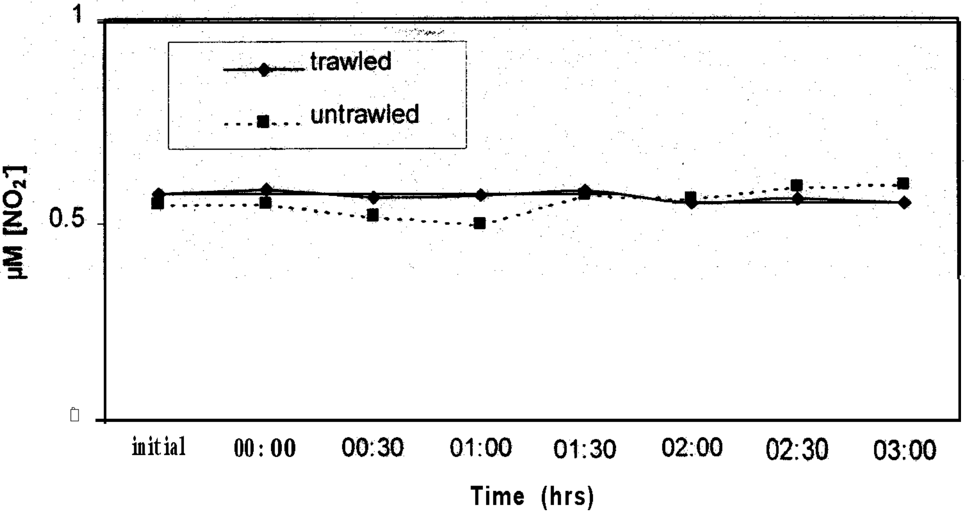

Figure 2b.

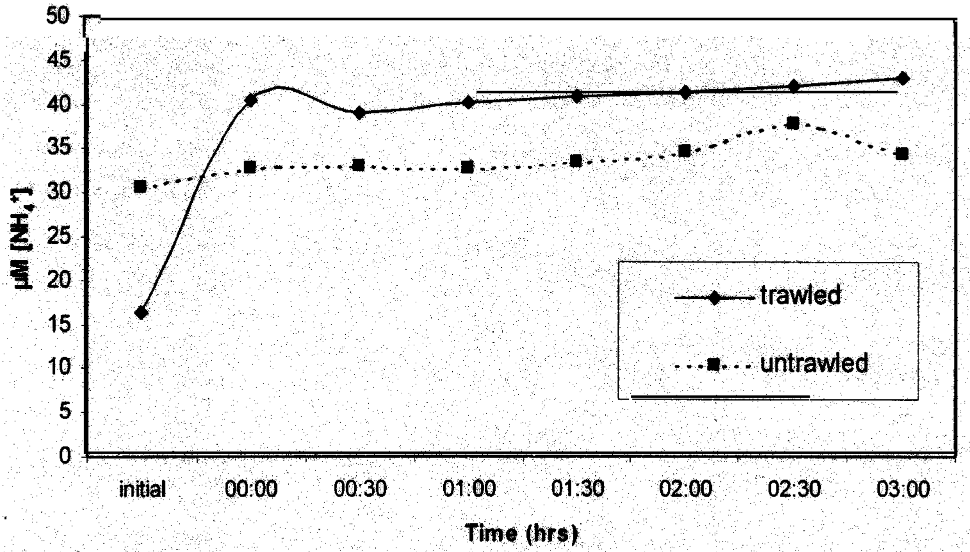

Figure 3a.

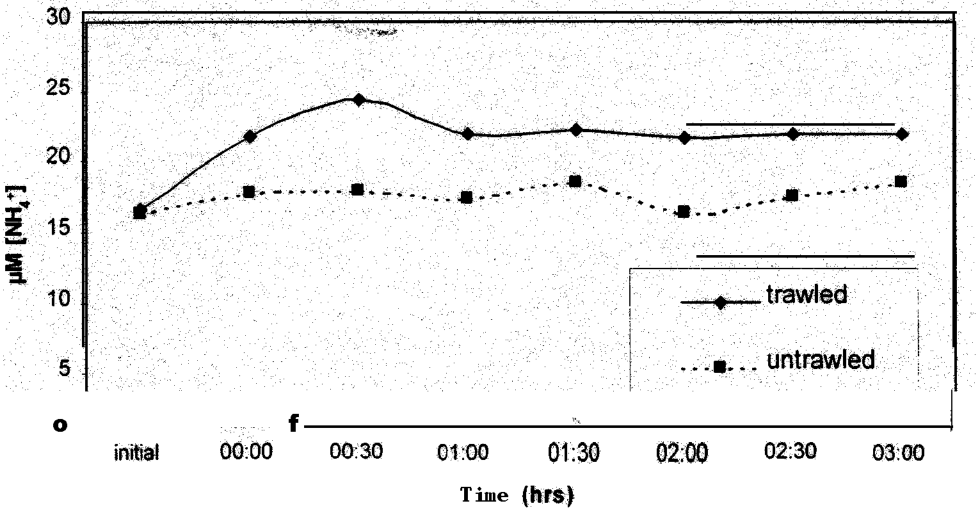

Figure 3h.

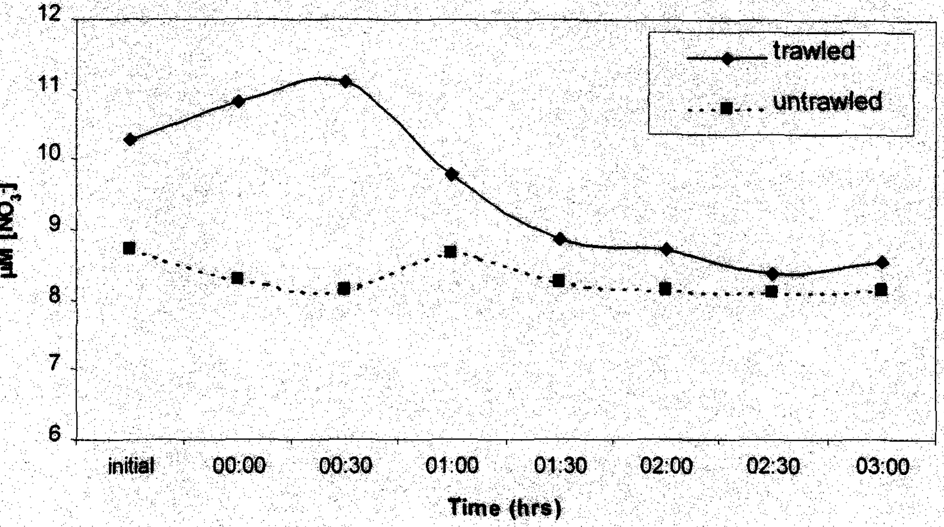

Figure 4a.

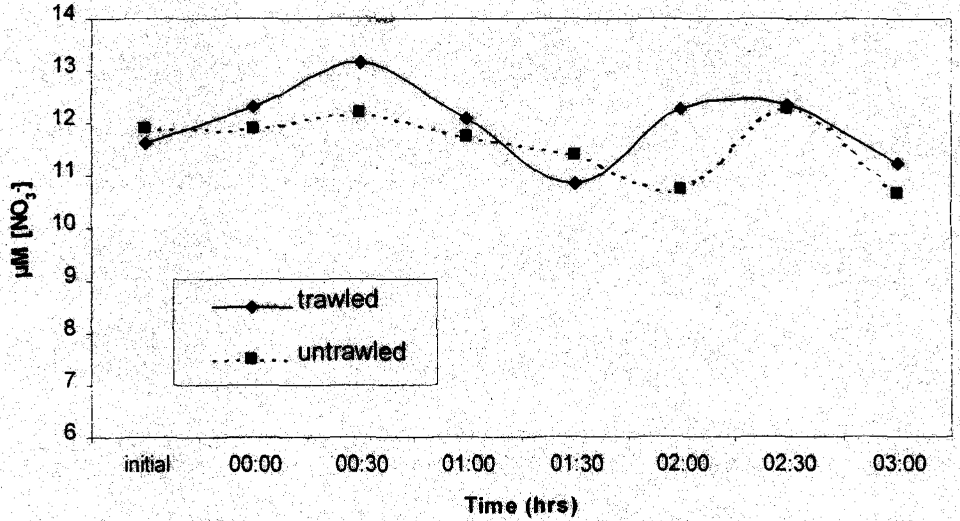

Figure 4b.

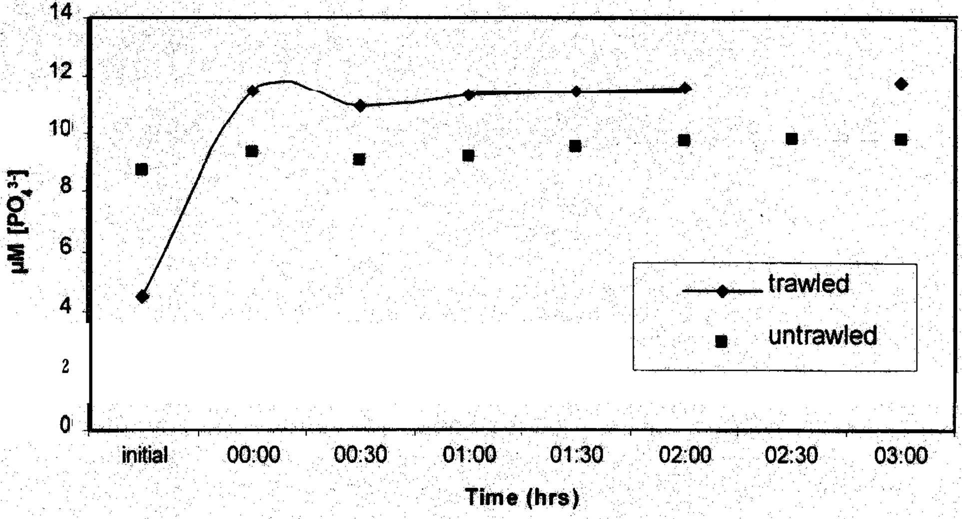

Figure 5a.

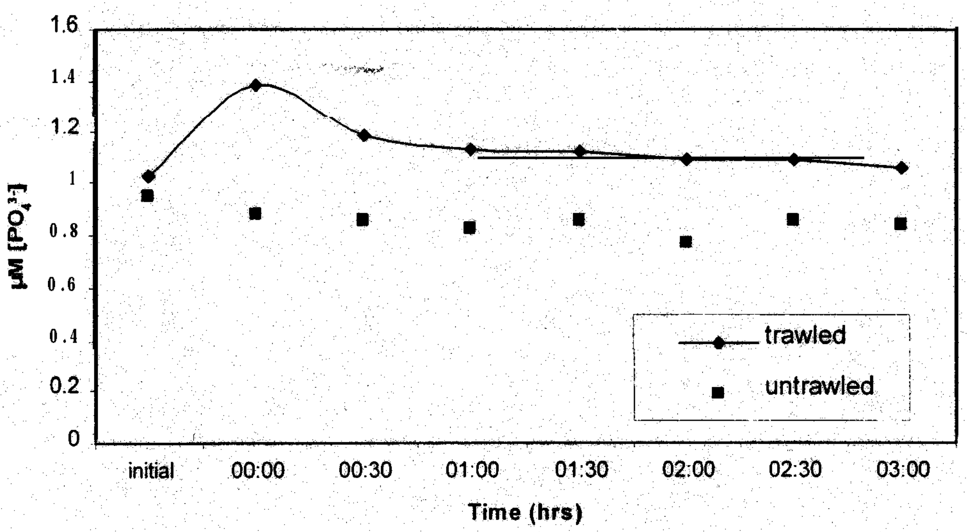

Figure 5b.