Auckland
Regional Council
TE RAUHITANGA TAIAO

Impacts of Terrigenous Material Deposition on Subtidal Benthic Communities

June 2003 Technical Publication 217

Auckland Regional Council
Technical Publication No. 217, June 2003
ISSN 1175-205X ISBN 1877353213

Printed on recycled paper

Impact of terrigenous material deposition on subtidal benthic communities

Andrew M. Lohrer
Judi E. Hewitt
Simon F. Thrush
Carolyn J. Lundquist
Pip E. Nicholls
Rick Liefting

Prepared for

Auckland Regional Council

ARC Technical Publication 217 (TP 217)
Auckland Regional Council

NIWA Client Report: ARC03205
National institute of Water & Atmospheric Research Ltd
Hamilton

June 2003

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Executive Summary

Changes in patterns of land-use associated with human population growth in the Auckland Region have altered the regime of terrigenous material export from catchments to rivers and subsequently to estuarine and marine communities. Because human population expansion is projected to continue and because terrigenous sediment is now widely recognised as a disturbance agent in estuarine and marine communities, NIWA was contracted to quantify effects on benthic communities at the seacoast and to correlate them with the amount of sediment added to the system. This report expands on previous investigations performed in intertidal estuarine flats and extends our knowledge base to deeper communities. Our summary conclusion is that terrigenous sediment deposition harms key species and alters macrobenthic community composition in subtidal soft-bottom habitats, though effect strengths are site-dependent. Communities in estuarine and coastal habitats are adapted to different baseline conditions, and this likely affects their tolerance of, and response to, terrigenous sediment disturbance.

Regarding the specific details of this study, NIWA was contracted to perform the following tasks.

- Deposit terrigenous sediment into replicate experimental plots at two subtidal sites, each of which was diverse enough to contain species that would respond in a meaningful way.

- Create three treatment levels (magnitudes of terrigenous material addition) to generate a range of responses.

- Track the persistence of the terrigenous deposits (i.e., event duration) as well as the interaction between event duration, terrigenous sediment resuspension, and hydrodynamics (near-bed current velocity, tidal and wave action).

- Sample macrobenthic communities at both sites to compare and contrast their response to varying levels of terrigenous material deposition.

- Assess effects on the dominant suspension feeders in the system (changes in feeding, growth, excretion).

After creating a well mixed slurry of terrigenous sediment and seawater, plots on the seafloor in Kawau Bay (Site MI) and Mahurangi Harbour (Site TK) were treated with 0 litres, 24 litres, or 56 litres of slurry to create terrigenous sediment deposits 0 mm, 3 mm, and 7 mm thick, respectively. Sites MI and TK differed both physically and biologically. Relative to Site TK, Site MI had coarser sediments, weaker tidal currents, and lower suspended sediment concentrations as well as greater species diversity, more individuals, and more taxa. While fewer individuals and taxa were present inside the harbour at TK, it was deemed sufficiently diverse to achieve meaningful results, and the

tidal hydrodynamics and the naturally elevated suspended sediment concentrations allowed us to make interesting comparisons between differing subtidal systems.

The experimental deposits of terrigenous sediment were remarkably persistent. The slurry of terrigenous soil and seawater that we applied was dense and cohesive, and rested on the seafloor as liquid layer shortly after application. The terrigenous deposits never fully de-watered in the subtidal environment, and thus the layers were thicker than anticipated. While depositional thickness decreased over time, terrigenous layers 1-2 cm thick were photographed in sediment cores on the final day of the experiment, buried by several mm of marine silt. Deposit thickness decreased slightly faster at TK, where tidal currents exceeded 25 cm/s and where effects of a storm event on Day 8 were more significant. Physical instruments were deployed to measure the resuspension of terrigenous sediment away from experimental plots, however none was observed. Clearly, a majority of the terrigenous material deposited in experimental plots remained on the seabed at both sites for the entirety of the experiment (30 days).

The macrobenthic communities at MI were apparently more sensitive to terrigenous materials than the communities inside the harbour at TK. Summarizing a variety of multivariate and univariate results, both the 3 and 7 mm treatments caused significant change at MI, whereas only the more severe 7 mm treatments caused significant change at TK. We suggest that naturally high suspended sediment loads and current-driven bedload transport have conditioned the animals in Mahurangi Harbour to cope with low level sedimentary disturbance to some extent. However, beyond a critical threshold, terrigenous sediment is a negative influence on the communities at this site as well.

Three types of suspension feeders were present in, or were transplanted to, the experimental deposits at MI and TK (horse mussels *Atrina zelandica*, sponges *Aaptos* spp., and ascidians *Styela plicata*). While none of these large, solitary animals were completely buried or killed by the thin depositional layers, there were significant effects on their condition and ability to feed when such variables were assessed in the laboratory three weeks later. *Atrina* at Site MI were more sensitive to terrigenous sediment than *Atrina* inside the harbour at TK, consistent with our results for benthic macrofauna and probably related to the greater suspended sediment concentrations in Mahurangi Harbour to which the *Atrina* had been adapted.

Previous studies suggest that the supply of terrigenous sediment to rivers and estuaries is pulsed and event driven, correlated with significant rainstorms that occur aperiodically. While rainstorms drive sediment supply, our physical data documents how storm-driven winds can keep such particles in suspension, thus increasing the likelihood of sediment transport offshore. Our biological studies have shown how diverse subtidal habitats will respond to the stress of terrigenous sediment input. Impacts to large, structure-forming and bioturbating species (i.e., key species such as *Atrina*, *Aaptos*, and *Echinocardium*) may eventually affect ecosystem structure and function, particularly if sediment loading increases in frequency or magnitude.

1. INTRODUCTION

Subtidal marine soft-sediment habitats cover a large proportion of the Auckland region's coastal environment. Such habitats can be rich and diverse, and often host key species that promote biodiversity and the proper functioning of ocean ecosystems (Gray 1997). Many commercially harvested species depend directly or indirectly on healthy soft-sediment systems for food and shelter, and sediments are important to nutrient budgets and the global carbon cycle (Thrush and Dayton 2002).

While marine sediments naturally contain particles of terrestrial origin, sudden deposits of terrigenous material can harm benthic communities (McKnight 1969, Ellis et al. 2000, Norkko et al. 2002, Cummings et al. 2003b, Hewitt et al. 2003, Thrush et al. in press). Patterns of sediment delivery from land to sea are dependent on many factors: climate, topography and land-use are among the most important. The Auckland region receives copious rainfall and has steep terrain in many of its coastal catchments. This creates short, fast rivers capable of moving sediments into estuaries and onward to the adjacent coastal shelf. Sediment delivery is typically pulsed and correlated to the magnitude and frequency of storm events (Hicks 1994, Stroud et al. 1999, Hicks et al. 2000). Terrigenous sedimentation events pre-date humans, but human land use practices have affected the regime of terrigenous sediment disturbance in many coastal systems. Species must cope with increased suspended sediment loads and increased accumulations of sediment per storm as well as the concomitant longer-term changes in habitats and the quality and quantity of suspended sediment. The significant broad scale threat is that critical thresholds for benthic species are probably exceeded with increased frequency, meaning less time for recovery between events and more chance for gradual degradations in benthic community structure and function.

With this in mind, the Auckland Regional Council has funded a series of studies designed to predict the effects of increased terrigenous sediment deposition (Norkko et al. 1999, Nicholls et al. 2000, Berkenbusch et al. 2001, Norkko et al. 2001b). First, catastrophic events were simulated in experimental plots that were covered with 10 cm of terrigenous sediment. The deposits smothered the underlying sediment and killed all macrofauna in the plots. Recolonisation and recovery was slow, and was mediated in part by crabs that could burrow into and break apart the terrigenous material. Subsequent experiments focused on deposits <1 cm thick (Berkenbusch et al. 2001). While the thinner layers did not completely defaunate the plots, significant alterations of community structure were apparent relative to controls. Multiple applications of thin depositional layers produced a gradual degradation of the macrobenthos over time.

Most of the investigations undertaken to date have focused on intertidal sand and mud flat communities that fringe estuaries. These locations were chosen because of their proximity to the source of terrigenous sediment, and due to the need to address site-specific questions in the Okura estuary and the Whitford embayment. However, terrigenous material deposits are not confined to intertidal areas alone; terrigenous sediment is regularly transported to adjacent subtidal habitats, outside estuaries, and to the continental shelf. Wheatcroft (2000) has documented sediment deposits of recent terrestrial origin across a spatially extensive portion of the Californian continental shelf (30 km x 8 km), and similar phenomena have been recorded off the East Coast of New Zealand (Foster and Carter 1997). We have observed highly turbid plumes of water, with an orange-brown colour characteristic of terrestrial sediment, engulfing Kawau Bay after heavy rain. The monitoring data collected from subtidal sites in Mahurangi Harbour also indicates temporal trends consistent with ecological change due to sediment loading (see Cummings et al. 2003a). Therefore, it is important to examine the behaviour of terrigenous deposits, and the responses of organisms to them, in subtidal soft-sediment habitats. While such investigations may be more logistically difficult than their intertidal equivalents, the results are applicable to a greater proportion of the Auckland Region and are likely to reveal important aspects of the threat posed by terrigenous sediment loading in the broader coastal environment.

As part of an ARC-funded study in the Whitford embayment, plots at a shallow subtidal site were exposed to thin layers of terrigenous material (Berkenbusch et al. 2001). There were a very limited range of subtidal habitats available in Whitford and the subtidal community we examined was relatively depauperate to begin with, possibly degraded by chronic sediment deposition prior to our experimental manipulations. Identification of anthropogenic effects is predicated on the availability of controls against which treatment effects can be contrasted, and these were probably lacking in the subtidal environment at Whitford. The response of the macrobenthic community was therefore difficult to assess and interpret. In addition, we were not completely satisfied that the terrigenous materials had been spread thinly and evenly across each subtidal plot, and methodological improvements were developed to test the effects of terrigenous sediment deposition more rigorously.

Here we report on studies of two subtidal communities, one in Kawau Bay and one in Mahurangi Harbour, which in our judgement better characterise the threat of terrigenous sediment deposition. The sites were deeper, more diverse, and much more suitable for informative and meaningful experiments than the subtidal habitat studied at Whitford. The locations were also known to receive sediment-laden runoff, resulting in highly turbid estuarine water. The sites contained an array of sessile and

mobile fauna, and supported ecologically and economically important species such as heart urchins, horse mussels, sponges, scallops, snappers, and shrimps.

The native horse mussel, *Atrina zelandica*, is a large filter-feeding bivalve that orients itself vertically in the sediment, with the tips of its shells extending 5-10 cm above the sediment-water interface. The shells of this species create physical structures and vertical relief in soft sediment habitats, providing points of attachment for bryozoans and soft-corals as well as refugia for small fish and invertebrates. Furthermore, infaunal diversity is increased in the immediate vicinity of *Atrina* because of sediment enrichment associated with horse mussel feeding and biodeposition (Norkko et al. 2001a). This species may suffer from the effects of terrigenous sediment, as increased suspended sediment loads at the seabed may interrupt feeding and respiration by clogging gill structures (Ellis et al. 2002). Sponges, another suspension feeding taxon, are also important structure formers and are thought to create biogenic habitat for juvenile fishes such as snappers. While bivalves can close their shells and isolate their tissues from environmental challenges, sponges may be more susceptible to the effects of sediment deposition.

Because large suspension feeders like horse mussels and sponges alter the densities and distributions of other taxa and are thought to be critical components of the ecosystem (Hewitt et al. 2002), a major focus of the present study was to quantify their response to terrigenous material inputs. Thin deposits may not smother and kill such large organisms; however, interruptions of feeding due to clogged filtration apparatus could affect their condition and scope for growth. Furthermore, the quantity and quality of the species' biodeposits could change with increased concentrations of inedible particles such as terrigenous sediment. Since biodeposition by *Atrina* is known to influence nearby macrofauna (Norkko et al. 2001a), such changes could ripple through the community.

With major field operations at two sites, we sought to achieve two broad objectives.

- First, we wanted to apply thin layers of terrigenous sediment, track their persistence over time, and quantify their effects on macrobenthic community structure. When submerged, the terrigenous sediment cannot de-water and dry as it can on intertidal flats, which may change its persistence and ecological effects. Therefore, we needed to determine if the deposits would remain on the seabed, eventually becoming incorporated into the fabric of the underlying marine sediment, or whether the materials would be resuspended and dispersed by currents and waves.

- Second, we wanted to assess the effects of terrigenous sediment on larger species not likely to be buried by the deposits. Specifically, we were interested in key species such as *Atrina zelandica* and other large suspension feeders.

To achieve the first objective, we collected sediment samples over time to quantify changes in sediment grain size and organic matter content, and we deployed instruments to measure current speeds, wave energy, and suspended sediment loads at the seabed. Macrofauna were also sampled following terrigenous sediment application in order to assess the immediate effects on benthic organisms and to gauge their recovery.

To achieve the second objective, we exposed several suspension-feeding taxa to terrigenous sediment deposits in situ, and later performed laboratory experiments to investigate changes in feeding behaviour and condition as well as respiration and excretion rates.

2. METHODS

2.1 Location and description of study sites

To assess the effects of terrigenous sediment on subtidal benthic communities, two sites with differing characteristics were chosen for study. The first site, MI, was located in a cove on the southwestern side of Motuketekete Island, at the mouth of Kawau Bay (Fig. 1). This site had sandy sediments, low suspended sediment loads (as judged by visibility under water), and moderately weak currents. The second site, TK, was located about 4 nautical miles to the southwest in Mahurangi Harbour, in the Te Kapa portion of this estuary (Fig. 1). Sediments were muddy, suspended sediment loads were high, and currents were strong at ebb and flood. While the hydrodynamic conditions, sediment properties, and general appearance of the seabed at the two sites differed greatly, we considered the biological communities at each site to be sufficiently diverse for the purposes of the study. That is, each was thought to contain species of various sensitivities at densities that would allow unbiased statistical tests and valid general conclusions.

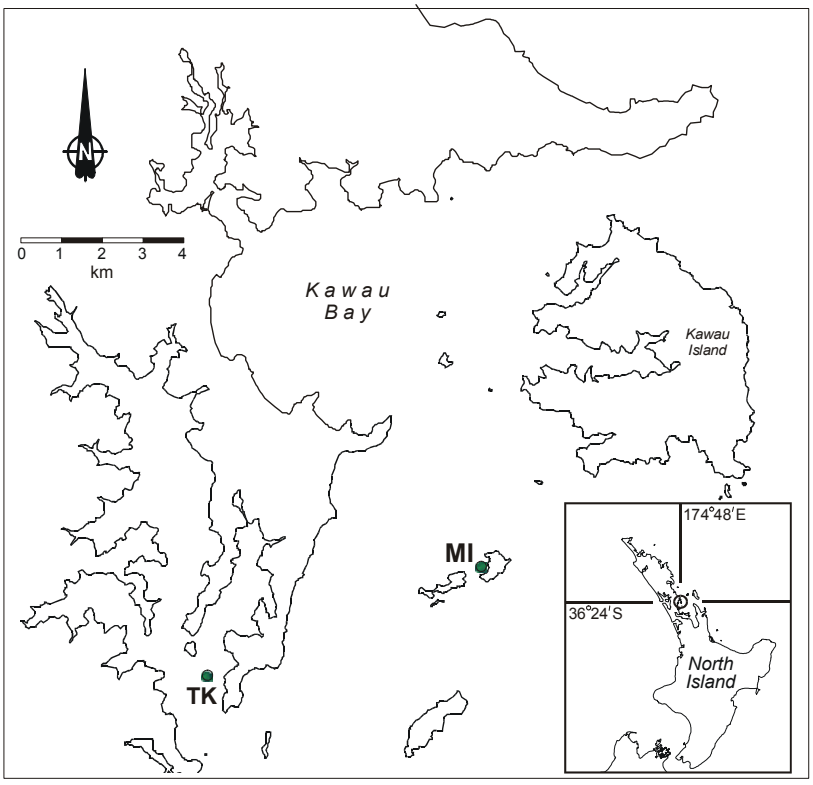


Figure 1: Map of study sites. Site MI is next to Motuketekete Island in Kawau Bay. Site TK is at the mouth of the Te Kapa sub-estuary in Mahurangi Harbour.

There were several large suspension-feeding taxa present at each study site and horse mussels, *Atrina zelandica*, were common at both. The horse mussels at TK were often covered with soft coral colonies (*Alcyonium aurantiacum*), whereas horse mussels at MI were generally free of large epibionts. The other large suspension feeders observed during this study included tunicates (e.g., *Styela plicata*), sponges (e.g., *Aaptos globosum, Aaptos rosacea*) and scallops (*Pecten novaezelandiae*). The tunicates, sponges, and scallops were slightly more common at the MI site, but each was rare overall (<1 individual/10 m^2).

2.2 Characteristics of Terrigenous sediment used

The ARC identified a source of terrigenous material and arranged our collection of approximately one cubic metre from a paddock in the Warkworth area. The dry soil was broken apart and then mixed with seawater in concrete mixers. After thorough stirring and mixing, it was passed through a 1-2 cm mesh sieve and stored in a large vat. About 675 litres of sediment-seawater slurry were prepared, at a ratio of dry soil to seawater of approximately 1:3.

Sediment-seawater mixtures can be acidic (Berkenbusch et al. 2001) and the slurry described here had an initial pH of 2.9. To buffer the slurry, 2 kg of sodium hydroxide (NaOH) was dissolved in seawater and added to the vat. The pH of the solution was neutral after NaOH addition and vigorous stirring, but the ions continued to react for several days. The pH of the sediment slurry was 5.6 when the final measurements were taken, about 3 hours prior to the start of the experiment.

2.3 Design and Deployment of Experimental Arrays

At both sites, experimental arrays were arranged according to the plans shown in Fig. 2. A mooring for the boat was established at each site, becoming the centre of a system of labelled ground lines leading to experimental plots and equipment. Arms 1 and 3 were laid parallel to the predominant current direction during flooding tides, whereas Arms 2 and 4 were laid perpendicular to it. The mooring system and ground lines remained in place for the entirety of the experiment. Divers used the area immediately surrounding the central mooring as a staging area, where materials and

equipment could be placed. Other areas were kept free of operational disturbance, and an MSA surface marker was used.

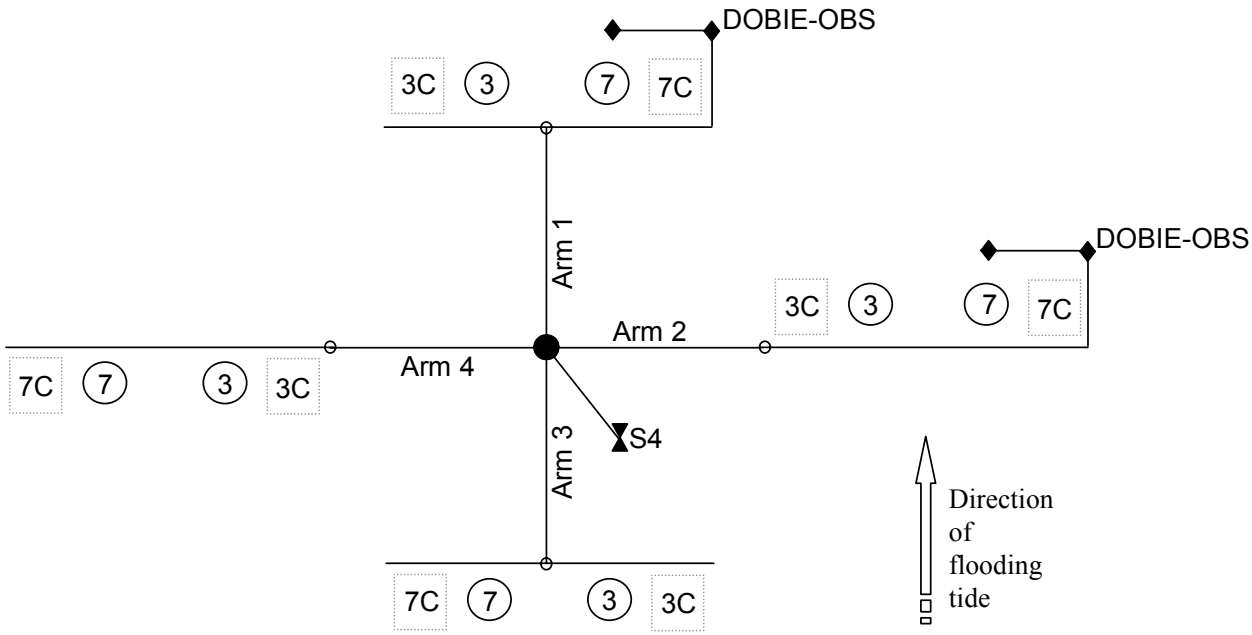
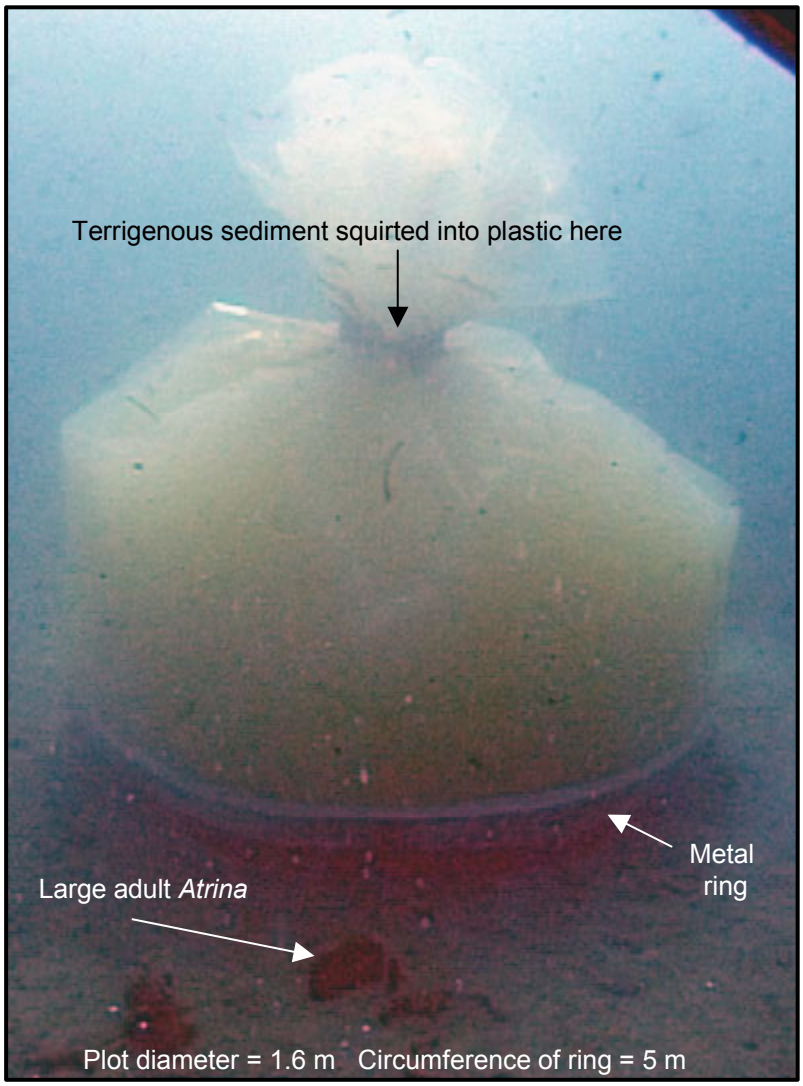


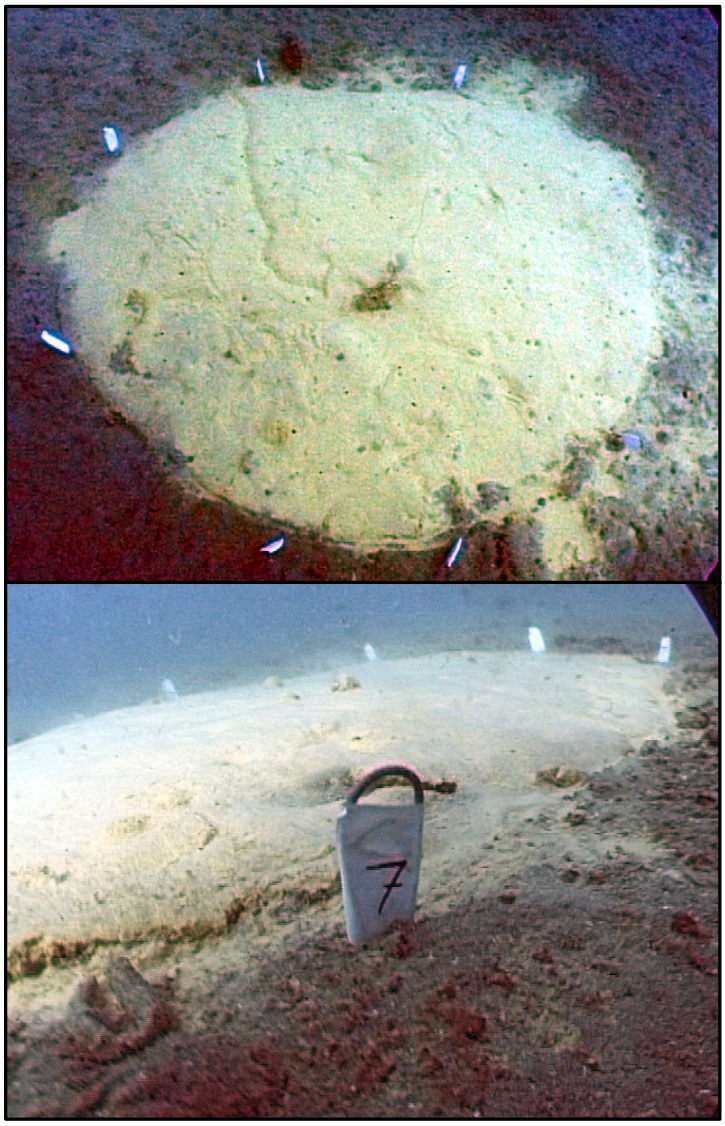
Figure 2: Plan view of the experimental array established at each subtidal site (i.e., Site MI in Kawau Bay, and Site TK in Mahurangi Harbour). Grounds lines extended outward from a central mooring in 4 directions, and these lines (Arms 1-4) each spanned 10 m. Additional line was laid at the end of each arm so that we could locate all plots and physical sensors on each visit to the site. Four wave gauges with optical backscatter sensors (DOBIE-OBS's, indicated with diamonds) were placed at each site, as was one electromagnetic current meter (an S4). The terrigenous sediment was deposited into circular plots at the terminus of each arm. The circular deposits were either 3 or 7 mm thick (indicated as circles with 3 or 7 written inside), covering an area of seafloor 2 m^2. Each circular plot that received terrigenous sediment (3 or 7 mm) was paired with a control area (indicated as squares with 3C or 7C written inside). There were four replicates of each treatment (i.e., 3, 3C, 7, 7C) per site.

Two circular plots (diameter 1.6 m) were established at the terminus of each arm. The circumference of each plot was delineated by a weighted metal strip, pushed firmly into the sediment. Attached to the 5 m metal strip was plastic sheeting (2 m wide along its entire length). The unattached side of the plastic sheeting was gathered together to form the point of a cone. Thus, with the metal ring embedded into the sediment, a cone of water above 2 m^2 of seafloor was sealed inside plastic (Picture 1). The sediment slurry preparation could then be introduced through the hole at the cone's point, allowing the terrigenous material to settle out in a confined location.



Picture 1: View of metal ring and attached plastic sheeting. The plastic contained the terrigenous sediment slurry for approximately 2 hours until the material settled onto the portion of seabed enclosed by the ring.

One plot per arm was scheduled to receive 3 mm of terrigenous sediment, and the other plot was to receive 7 mm. The sediment slurry was measured out into plastic bags in 4 litre quantities. The negatively buoyant bags were brought underwater, opened, and squirted into the plastic cones. The 3 mm plots received 6 bags of slurry, and the 7 mm plots received 14 bags of slurry. The mixture dispersed rapidly and settled evenly over the area of sediment intended for treatment.



Picture 2: Upper panel is a view from above a 7 mm plot at MI just hours after terrigenous sediment application. Notice the relatively well-defined edges of the plot. Lower panel is a side view of the same plot, with a labelling peg indicating the thickness of the treatment.

The cones and rings were left in place for a period > 2 hours to allow the terrigenous particles to settle out. Divers lifted the cones vertically and slowly, and circular patches of yellow-orange terrigenous material were left in place (Picture 2). In some cases, there were rivulets of the fluid sediment pouring over the boundaries of the plots and/or dusty coats of terrigenous sediment adjacent to plots. However, the sediment slurry was dense and viscous, and largely remained in place as a liquid layer several cm thick.

According to our calculations, we introduced the proper amount of slurry to produce 3 and 7 mm layers of dry, de-watered soil (similar to the thin layers we deposited previously in intertidal habitats). Here in the subtidal, however, the sediment-slurry remained in a fluid state and was much thicker than anticipated. Nevertheless, two distinct sediment treatment levels were achieved and applied at both experimental sites.

Control areas (no sediment added) were also recognized, and separate controls were maintained for each type of treated plot (i.e., 3 and 3C; 7 and 7C)(Fig. 2). There were no rings or definite boundaries for the control areas; samples were collected haphazardly from areas several meters away from the nearest treated plot. Since current direction was incorporated into the experimental design, control areas were not likely affected by terrigenous sediment moving laterally out of treated plots nearby. There were four replicates of each treatment type per site (Fig. 2).

2.4 Sampling methodologies

Digital Video Recordings

One day prior to terrigenous sediment application (Day 0), four video transects (10 m long x 50 cm wide) were recorded in order to estimate the density of *Atrina zelandica* and other notable features and organisms. The transects extended outward from the centre of the array at each site (the central arms of Fig. 2). Divers also counted the number of *Atrina* and other suspension feeders inside the treated plots, and their presence and status (living/dead) was recorded on each visit until the experiment was terminated on Day 30. Furthermore, video was used to document the initial response of large mobile organisms (e.g., hermit crabs, shrimps, heart urchins, starfish, and scallops) and to record temporal changes in the physical appearance of the plots from Day 1 to Day 30.

Physical data collection.

An electromagnetic current meter (InterOcean S4a) was deployed to each site to measure current speed and direction. Both machines were set up to record a 1-minute burst of data (frequency of 2 Hz) every 5 minutes for 30 days. These current meters logged data from a position 50 cm above the seabed, and integrated over a water volume of approximately 1 m^3. During analysis, values from each 1-minute burst were averaged, providing 20 current speed and direction estimates per hour for the entirety of the experiment. Unfortunately, the current meter at Site MI did not function properly. It logged data, but the data were obviously corrupted, perhaps by magnetic fields associated with the volcanic island. The current meter worked well at Site TK, and allowed us to characterize the currents at the site where tidal flows were relatively strong.

In addition, four DOBIE wave gauges with optical backscatter sensors (OBS) were placed on the seabed at each site to quantify significant wave height (H_{sig}) and the penetration of wave energy to the seabed (orbital bed velocity, U_{sigb}). Seven-minute data bursts (5 Hz) were recorded every 20 minutes, and data from bursts were averaged during analysis. In addition to wave information, DOBIE's record water depth, thus providing time-stamped tide information, and the OBS yields suspended sediment concentrations (SSC). Calibrations of each OBS with sediments collected from the site of deployment allowed us to translate the electrical voltages into suspended sediment concentrations (mg of sediment per litre of seawater). To quantify resuspension of terrigenous sediment from the experimental plots, we placed DOBIE-OBS's downcurrent of treated and control areas (Fig. 2).

Depth of the terrigenous sediment deposits.

Because of the fluid characteristics of the deposits and the microtopography of the underlying sediment, the thickness of the terrigenous layers was quite variable. Nevertheless, attempts were made to quantify the thickness of the deposits using sediment cores. On days 3, 7, 14, and 30, one core per plot (2.4 cm diameter, 8 cm deep) was collected, placed vertically into a rack, and brought back to the boat. The sediment was extracted from the core cylinder while the water above the sediment surface was carefully drained away. The depth of the terrigenous layer was measured while wet. Additionally, one large core per plot (5 cm diameter, 12 cm deep) was collected on Day 30 and frozen. Each frozen core was split, and the depth of the terrigenous layer was measured. By Day 30, marine silt was present on top of

each terrigenous sediment deposit, and the thickness of the silt layer was recorded as well.

Sediment grain size, organic matter content, and chorophyll *a* concentration.

To characterize how the sedimentary environment changed at each site following the application of terrigenous material, sediment samples were collected at five intervals during the experimental period. Two plastic vials of surficial sediment (to a depth of 2 cm) were collected from each treated plot and adjacent control on Days 1, 3, 7, 14, and 30. Day 1 samples were collected < 1 hour after the plastic application cones were lifted away from the treated plots. All samples were frozen and kept in the dark until analysis.

To determine sediment organic matter content, one vial per plot was thawed, stirred, and several grams of sediment were placed in an aluminium dish. Organic matter content was calculated from loss on ignition (LOI, i.e., by the change in the mass of the sediment after drying at 60°C for 48 h and combusting in a muffle furnace for 5.5 h at 400°C).

A 6% solution of hydrogen peroxide was added to the vials of sediment slated for particle size analysis, a digestion process that removed organic matter. After 48 h, the percent volumes for 11 different grain size categories were determined with a Galai particle analyser (Galai Cis - 100; Galai Productions Ltd., Midgal Haemek, Israel).

Macrobenthic infauna.

To assess macrobenthic community structure in treated and control plots, 2 large sediment cores (8 cm diameter, 15 cm deep) were taken on each of three dates, from every plot, at each site. Cores on Day 7 were collected to assess the effect of terrigenous sediment deposition, whereas cores on Days 14 and 30 were taken to assess the trajectory of recovery following the initial impacts. Different sectors of the circular plots were sampled on each date to avoid undesired re-sampling effects. We also avoided edge effects by collecting samples in the interior of the plots (i.e., >30 cm from plot boundaries).

Macrofaunal samples were sieved on 0.5 mm mesh, preserved in 70% isopropyl alcohol, and stained with 0.2% Rose Bengal. Macrofauna were sorted and identified to the lowest taxonomic level practicable. Because of the difficulty of identifying and enumerating such a large number of diverse samples, we report results from one core per plot on Days 7 and 30 only. The remaining samples are sorted, and will be identified, analysed, and summarised with supplementary support from FRST.

2.5 Statistical analysis

A variety of univariate and multivariate statistical techniques were used to characterise the response of macrofauna to the experimental addition of terrigenous sediment. The percent similarity among samples in various treatments was computed using PRIMER 5.0 (Clark and Gorley 2001). Bray-Curtis similarity matrices were created from untransformed macrofaunal community datasets, and the significance of differences in macrofaunal community structure was assessed visually using an ordination procedure (multi-dimensional scaling, MDS plots) and mathematically using an analysis of similarities procedure (ANOSIM). We also used a non-parametric multivariate analysis of variance program (NP-MANOVA, Anderson 2001) when investigating macrobenthic community recovery between sampling dates. Following an initial impact (i.e., significant differences between treatments and controls), subsequent increases in the similarity of treated and control communities would be indicative of recovery. Differences in the magnitude of effect related to the day of sampling would tend to result in significant treatment *day interactions. The NP-MANOVA program generates probabilities for main effects and interaction terms, while ANOSIM (in the PRIMER package) only produces probabilities for main effects. Therefore, NP-MANOVA allowed us to evaluate recovery between Days 7 and 30 by estimating the significance of treatment *day interactions.

Differences with respect to site, date, and treatment were assessed with analysis of variance (ANOVA) for variables such as the total number of individuals and taxa per sample, and Shannon-Wiener diversity index. The densities of several common species from each site were also analysed. However, because the physical and biological attributes of each site differed greatly, and because the two sites had few macrofaunal species in common, an a priori decision was made to analyse data from the two sites separately. Furthermore, we used Wilcoxon two-sample tests on the treatment-control pairs shown in Fig. 2. Since the Wilcoxon tests were based on the

differences between samples collected just a few metres apart[1], there was less spatial variability to countermand treatment effects. Furthermore, the non-parametric test is based on rank scores, and can be more powerful when assumptions of normality and homogeneity of variance cannot be satisfied (which was the case for most of the individual species analyses).

2.6 Suspension feeding experiments

The effect of terrigenous sediment on three suspension-feeding epifaunal species was assessed using field and laboratory experiments. Because such epifauna were encircled and exposed to terrigenous sediment at both sites, it was possible to relate changes in physiological condition to the magnitude of terrigenous sediment deposition (i.e., 0 mm vs. 3 mm vs. 7 mm). Horse mussels (*Atrina zelandica*) were common at both MI and TK and thus we tested the effects of terrigenous sediment on *Atrina* collected from both sites. Golf ball sponges (*Aaptos* spp.) were present in low densities at MI, but were common inside Kawau Bay at Iris Shoal. Thus, 4-5 sponges were transplanted from Iris Shoal into experimental plots at MI at the time of sediment deposition. Sponges were also transplanted to control areas at Site MI so that the effects of transplantation itself could be tested. Finally, we experimented with the solitary ascidian *Styela plicata*, as a few of these animals were found inside and outside plots at MI and TK.

To assess the impact of terrigenous sediment on these suspension feeders, we measured condition, feeding rate, oxygen consumption rate, and ammonium excretion rate. All measurements were made in a laboratory setting using animals collected from our field sites. The time of collection was three weeks after terrigenous sediment application. All tests involving live animals were started within 2-24 hours of collection.

Condition. The dry flesh weight of animals was measured after 72 hrs in an oven at 60°C. For *Atrina* and *Aaptos*, three animals per treatment were measured. For *Styela*, 1 – 3 animals per treatment were pooled and measured, depending on the number recovered from the experimental plots. Condition was then calculated as dry flesh weight corrected for animal size by dividing by

[1] H_0: control-treatment differences are less than or equal to zero. H_A: control-treatment differences are significantly greater than zero. Tests were one-tailed with $\alpha = 0.05$. We deemed $P < 0.10$ to be marginally significant, given the relatively low number of replicates used ($n = 4$). The value of P is defined as the probability of getting data at least as large as were obtained if the tested hypothesis is true. Also note, a one-tailed test with $\alpha = 0.05$ is comparable to a two-tailed test with $\alpha = 0.025$.

dry shell weight (*Atrina*), wet body diameter (*Aaptos*), or wet displacement volume (*Styela*).

Feeding rate. Three replicate animals were placed into plastic containers filled with seawater, freshly collected from Kawau Bay. The seawater had ambient concentrations of phytoplankton and other solids, but we did not add anything else to it. Total suspended solid (TSS) concentrations were measured at the beginning of the experiment and 1 hr later by filtering the seawater onto pre-weighed GFC filters and re-weighing the filters after 48 hrs in an oven at 60°C. The difference in TSS concentration at the beginning and end of the experiment yielded clearance rates (*CR*, ml min^{-1}), which were calculated in the following way.

$$CR = \frac{\left(TSS_{beginning} - TSS_{end}\right)V}{TSS_{beginning}\ T}$$

Where V = volume of water in ml, and T = time in minutes.

Clearance rate is thus the volume of water cleared by an animal per unit time. *Atrina* from each type of plot (control, 3 mm, 7 mm) at each site were used in these experiments. *Aaptos* from each of the experimental plots at MI were also used. Rates for *Styela* were not assessed, due to low numbers. The volume of water cleared was standardized for each species (to a 9 g dry weight *Atrina* and to an 11.8 g dry weight *Aaptos*) by dividing the clearance rate by the dry flesh weight of the individual and multiplying by the standard weight.

Recall that we transplanted sponges to MI from a donor site at Iris Shoal. To better understand the speed of response, and to characterise the effects of the transplantation process itself, we performed one additional filtration experiment using naïve sponges from Iris Shoal. As previously, the animals were collected and placed into containers with seawater from Kawau Bay. The containers were then dosed with 3 mm or 7 mm of terrigenous sediment (from the same batch of sediment that was deposited in the field). Controls of seawater only (0 mm dose) were run as well. The volumes of seawater cleared by the animals were again calculated.

Oxygen consumption and ammonium excretion. To measure oxygen consumption and ammonium excretion rates, the suspension-feeders were placed individually into sealed, stirred respiration chambers. The chambers were filled with unfiltered seawater from the field sites and maintained at 21°C in darkness. Again, animals exposed to each of the field treatments (controls, 3 mm, 7 mm) were used in the trials. Water samples were collected at timed intervals in order to measure dissolved

oxygen and ammoniacal nitrogen concentrations. Decreasing oxygen consumption signals physiological stress, as it indicates reduced activity during an environmental challenge (i.e., the animals try to isolate their tissues from the stressor and wait until the challenge ends). Ammonium excretion may decrease with decreased food processing, or may increase concomitantly with greater faeces and pseudofaeces production during periods of high suspended sediment concentration.

Tests for experimental effects were done using one-way ANOVAs or Kruskal-Wallis tests for each site separately. When overall significance was detected ($P < 0.05$), post hoc comparisons (paired tests with a Bonferroni adjustment) were used to determine the significance of differences between treatments.

3. RESULTS

3.1 Diver and video observations

Day 0

The video transects revealed that horse mussels were indeed more abundant inside the harbour at TK than they were at the island site, MI (Fig. 3). In general, TK had more sessile suspension feeding fauna such as horse mussels, ascidians, and sponges, whereas MI had more of the large mobile taxa (e.g., hermit crabs, echinoderms, gastropods; Fig. 4).

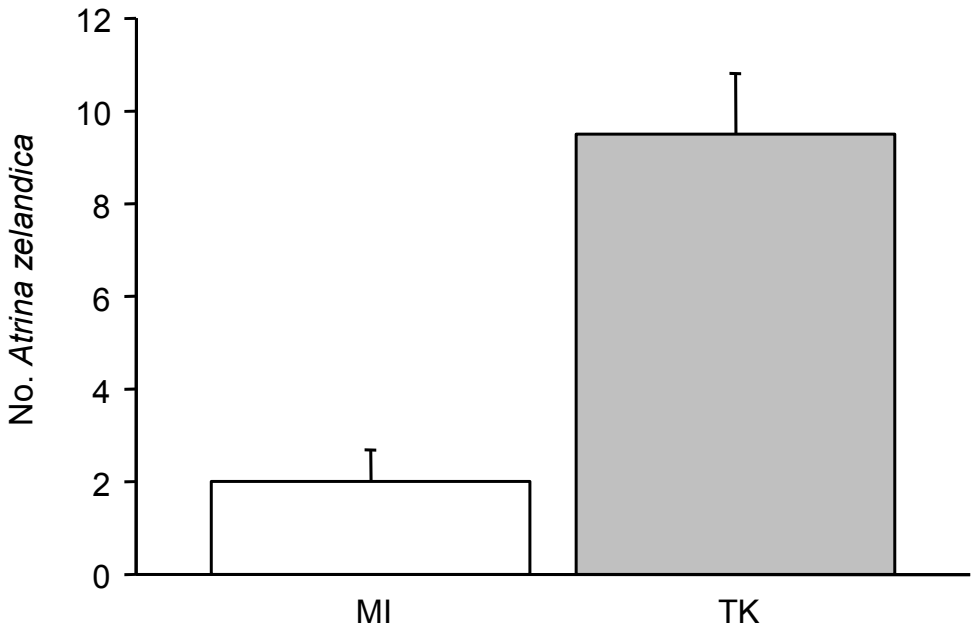


Figure 3: Number of *Atrina zelandica* per transect (10 m length x 50 cm width) on Day 0. Results for the two experimental sites, MI and TK, are given as mean + 1 *SE* (*n* = 4 transects per site). The number of *Atrina* differed significantly by site (*t*-test, *P* = 0.0124).

Day 1

The application of terrigenous sediment was successful at both sites. We were able to confine the material to well-defined plots on the seafloor and also produce even layers of sediment across the entirety of each plot. The terrigenous material that did

escape to the seafloor (only substantial in 2 of 16 plots) remained close to the plot boundaries and did not diminish the integrity of the control areas.

Less than 1 hour following application, the soil-seawater slurry rested lightly on the seabed as cohesive liquid deposits. The terrigenous sediment mixture was obviously denser than seawater alone. Some large mobile organisms escaped from the plots, while others could not (Picture 3). The tracks from hermit crabs and sea stars were not well defined; small bow waves preceded these animals as they moved and the slurry was too fluid to stay in place after displacement (Picture 4). A sizeable shrimp was observed at the surface of an MI plot, outside its burrow, mired in the deposit (Picture 5). A juvenile scallop (*Pecten novaezelandiae*) and another small free-swimming bivalve (Limidae?) were also observed at the surface of MI plots.

There were numerous observations of burrow clearing, as plumes of terrigenous sediment were seen being ejected from hole and burrow structures in the seafloor. These structures were probably occupied by fan worms, crabs, shrimps, and/or infaunal bivalves. The burrow clearing seemed effective, as even 1 hour post-application, there were numerous circular holes extending down from the surface of the deposits (Picture 6).

Terrigenous sediment was stuck to the *Atrina* present inside the plots. However, nearly all of the *Atrina* had their valves open and were apparently feeding/respiring (Picture 7). The solitary ascidians (*Styela plicata*) were also alive with siphons open (Picture 8). The condition of sponges was difficult to assess visually, but all sponges (transplanted and naturally occurring) survived the initial deposition event and until collection 21 days later (Picture 9).

Day 3

There was a clear interface between the deposits and the overlying water by Day 3 of the experiment. The material was still soft and relatively thick at both sites (see Terrigenous sediment depth section below), but was less fluid and more confined to the seabed than it had been just hours after deposition.

Some of the Day 3 observations suggested immediate negative impacts from terrigenous material deposition. The most noteworthy finding was the presence of 17 heart urchins (*Echinocardium australe*) at the surface of the experimental deposits at the MI site. All of the urchins were dead, and nearly all had large holes indicative of predation (Picture 10). Heart urchins are slow moving, infaunal burrowers that respire

through small ventilation shafts created in the sediment column. We suspect that the terrigenous deposit interfered with the construction of these shafts and drove them to the surface for oxygen. Once exposed, opportunistic predators probably attacked them. Sea stars and snappers are known to eat *Echinocardium*, and both were observed in and around the plots at MI. The density of gastropods was high at MI on Day 3 as well (Fig. 4), and most of these were scavenging the tissues of dead *Echinocardium* and the occasional bivalve.

Other observations from Day 3 suggested the beginnings of recovery. Many of the holes and burrows were surrounded by small cones of dark marine sediment (Picture 11), where the inhabitants had obviously re-excavated and cleaned the terrigenous sediment from their burrows. In addition to the reworking of sediment from within plots, ambient marine silt from beyond plot boundaries was beginning to collect on top of the deposits by Day 3. Over time, plots at both sites became covered with marine sediment, though it seemed more rapid and extensive at TK. Nevertheless, at least some yellow terrigenous sediment was visible in every plot at the end of the experiment on Day 30 (Picture 12).

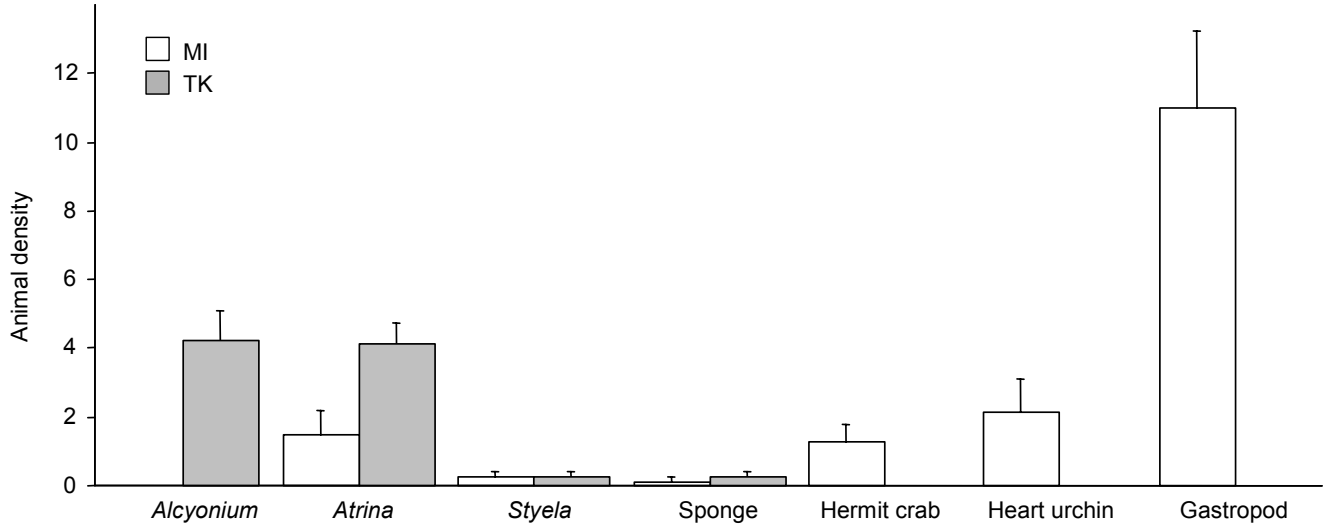
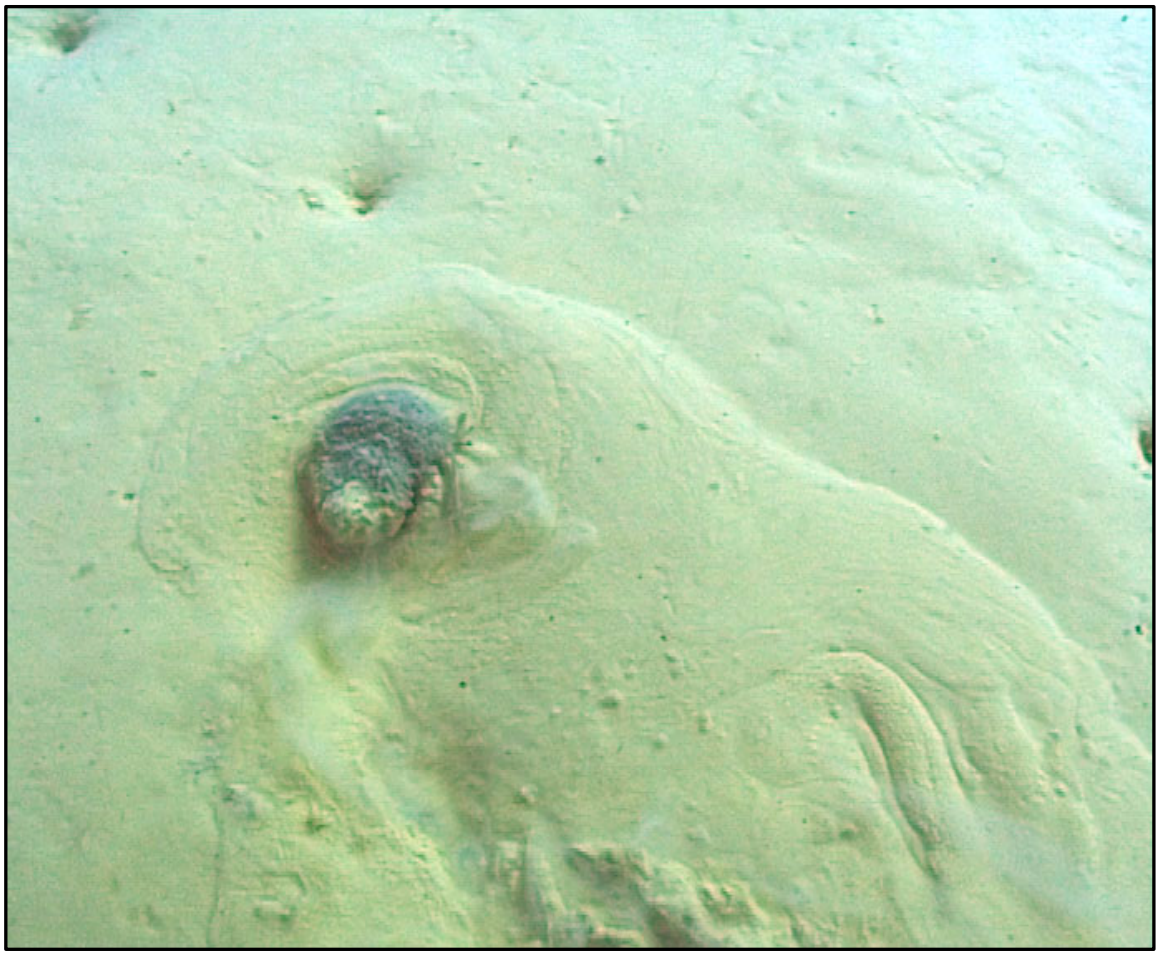


Figure 4: Large fauna observed inside the plots on Day 3. Results are given as mean density per plot (+ 1 *SE*); $n = 8$ treated plots per site. The area of each plot was 2 m^2.

Picture 3: Upper panel: the seastar *Astropecten polyacanthus* inside an experimental plot at MI. This animal may have been feeding at the time of terrigenous sediment deposition (see bulge at central disk). Lower panel: a different individual from the same species, covered with terrigenous sediment, photographed after exiting an experimental deposit at Site MI.



Picture 4: Hermit crab in a terrigenous sediment deposit approximately 2 hours following application at Site MI. A bow wake preceded the animal and no clear footprints were visible behind it, demonstrating the fluid nature of the deposits in the subtidal zone on Day 1. Puffs of resuspended sediment can be seen in the photograph as well.

Picture 5: An unidentified shrimp in a terrigenous sediment deposit 1-2 hours following application at Site MI. The shrimp was struggling vigorously in the watery deposit.