Ecological effects of sediment deposition in Okura estuary

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INTRODUCTION

This report presents information on the potential threats to the ecosystems of Okura estuary that result from deposition of flood-borne sediments. It should be read in conjunction with the associated reports by Stroud et al ("Sediment runoff from the catchment of Okura estuary") and Green and Oldman ("Deposition of Flood-Borne Sediment in Okura estuary"). The report by Cooper et al ("Assessment of Sediment Impacts on Okura estuary Associated with Catchment Development") presents a synthesis of all three components of the Okura investigations.

The overall brief for the Okura investigations was to predict the risks of ecologically-damaging sediment events occurring in the estuary as a consequence of land disturbance associated with varying degrees of catchment development (rural intensification). This report and Green and Oldman (1999) address the estuarine components of the brief, with the latter determining factors controlling sediment deposition in the estuary. These estuary investigations have established the limits for event-based sediment inputs from the catchment, above which, impacts on the ecology of the various sub-environments in the estuary may be expected. Stroud et al. (1999) predict the risks of sediment input from the catchment exceeding these limit values for varying degrees of rural intensification.

Our objective was to present information on the potential threats to Okura's estuarine ecosystems that result from sediment deposition events. We designed a series of laboratory and field experiments to identify the immediate effects of smothering the natural sediment surface with fine sediments derived from the catchment. These experiments provide information that enables us to address three key questions:

- What is the critical depth of sediment that kills infauna?

- How long does the terrigenous sediment layer have to sit over the natural estuarine sediments to have this effect?

- How quickly do defaunated plots get recolonised and recover from this type of disturbance?

Addressing these questions enables us to link risks associated with sediment runoff from a catchment under various development scenarios to transport and dispersion of sediment in estuaries. Thus we are able to close the information loop and provide coherent predictions of risks to the ecology of the estuary.

In this report, we comment on the three sections of work required to provide an ecological assessment of potential effects: -

1. Mapping of habitats within the main body of the estuary and broad descriptions of benthic communities.

2. Laboratory experiments with selected species to estimate their ability to surface through different thickness of mud and/or survive short-term burial.

3. A field experiment corroborating the results of laboratory experiments and extending them to the resident macrobenthic communities in two habitats. The experiment was monitored to provide some indication of the potential for recovery of the macrobenthic community from a sedimentary event.

EXPERIMENTAL DESIGN

Selection of the specific details of the experimental designs (e.g., depth of added sediment, taxa tested and location of sites) needs to be based on the ecological characteristics of the estuarine ecosystem. Estuaries are physically complex; they contain a wide variety of habitats that are created by a number of interacting physical and biological processes. These processes, directly or indirectly, influence the distribution of plants and animals and create the settings for the ecological interactions amongst the biota. Therefore, we can broadly classify habitats within estuaries on the basis of physical conditions. Within this context, intertidal sandflats are often a spatially dominant feature.

A variety of direct effects can occur as a result of sudden increases in the rate of sedimentation (Table 1). As yet, we have insufficient information to assess the relative importance of each of these processes in producing changes in estuarine ecosystems, but it is likely that importance will depend on habitat type and size. As well as direct effects, we can also expect some indirect effects such as reduced habitat complexity/diversity, changes in the rates of predation, and other inter-species interactions, changes in structure and distribution of habitat forming organisms such as mangroves, seagrass, and beds of suspension feeding bivalves. Again, the relative importance of these processes will depend on habitat type and size.

Table 1: Direct effects of sudden increases in sedimentation on resident macrofauna

Smothering of sediment surface	• Turns underlying sediments anaerobic • Suffocates organisms that cannot climb through deposited layer, or have a restricted capacity for anaerobic metabolism. • Makes surface sediments unsuitable for recruitment. • Removes productivity by phytobenthos. • Changes conditions for epibenthic fish and other • near-bottom predators.
Changes in sediment particle-size	• Influences size and type of particles available for deposit feeders. • Changes sediment porosity and sediment stability thus influencing biogeochemical fluxes. • Changes suitability of surfaces for recruitment. • Influences rates of animal movement and bioturbation • Clogs feeding structures of suspension feeding animals.
Changes in water-column turbidity	• Limits light penetration affecting primary productivity of phytobenthos.
Changes in sediment food quality	• Depends on source and history of sediments. - But sub-surface sediments with a short transition time to the estuary will lower food quality.

1. Depth of added sediment.

Three depths of sediment were selected for testing. The largest (9 cm) has previously been observed in an estuary as a result of slip activity into a stream. The smallest (3 cm) was selected as it corresponded to the size of the largest bivalves found in the estuary. Critical depth is size/age dependent and is, for bivalves, related to their normal burial depth and length of their siphons. The smallest (3cm) treatment was therefore chosen as it was expected that it would give a mixed response in the animals tested. The intermediate depth (6cm) was selected as a mid point between the previous two.

2. Taxa for laboratory testing.

Bivalves normally live burrowed in the sediment. Siphons connect the animal to the sediment surface and transfer water (containing oxygen and food) across the gill membranes. The length of the siphon determines the maximum depth the bivalves can live at. Cockles (*Austrovenus*) have very short siphons and normally live near the surface; pipis (*Paphies*) live close to the sediment surface. However the deposit feeder, the wedge shell *Macomona*, is commonly found living deeper than 5 cm beneath the sediment surface. Bivalves that are subject to additional deposits of sediments have two ways of dealing with such a situation. They can either escape by repositioning themselves towards the sediment surface, or if this is difficult/impossible, by switching to anaerobic metabolic pathways and waiting for conditions to improve. Generally bivalves are tolerant, and can sometimes withstand several weeks of stress by utilising such anaerobic pathways. However, such a strategy is very energy-consuming, reduces their fitness and increases their susceptibility to other sources of mortality such as predation or disease.

Crabs, such as the mud crab *Helice crassa* are highly mobile and create burrows in the sediments. They are generally more numerous in muddy sediments and associated with mangroves. Because of their continuous digging activities associated with maintaining their burrows they have an important role in bioturbating the sediments they live in. Since mud crabs are adapted to muddy sediments they are expected to cope well with sedimentation events.

Glycerid polychaetes are large predatory worms common in sandy sediments. Orbinid polychaetes are deep burrowing deposit feeders common in sandy and muddy sand sediments. Both glycerids and orbinids are mobile free-living worms expected to cope well with sedimentation events.

3. Location of experimental sites

Our brief was to identify effects of sudden dumps of sediment that would smother areas of the estuary floor rather than identifying any potential longer-term changes. As we could not logically conduct experiments in all areas of the estuary, two areas representative of two habitat types were selected for experimentation. It is important to stress that this does not indicate that other areas/habitats in the estuary are unlikely to be influenced by sediment dumps. Rather, in trying to provide good information within the constraints of the contract, we have focused our attention on two areas, amenable to experimentation, and representing sensitive habitats likely to be subjected to sedimentation events. These two areas are in the middle to lower estuary. We did not locate experiments in the upper estuary mudflats and mangroves, although these habitats are more likely to undergo an event, for the following reasons. Sediment particle size changes would be slight, and the benthic communities in these habitats are less sensitive and diverse than those of the sandflats. Sandflats usually contain a far more diverse assemblage of organisms than muddier upper estuary habitats and, thus, exhibit a wider variety of sensitivity and responses to changing conditions. We also did not choose to locate experiments in the exposed wave swept sandflats at the mouth of the estuary. Although this habitat contains many sensitive species, the risk of sediment smothering the surface for sufficient time to kill sediment dwelling animals is very low.

METHODS

Habitat mapping

We constructed a habitat map based on aerial photographs, previously collected information and a survey of the intertidal areas. This map, together with information on a number of features, such as areas of wave disturbance, and areas of high macrofaunal diversity with sensitive suspension-feeding species, was used to identify ecologically sensitive areas. The map was also used to help us select appropriate species for the aquarium experiments and sites for the field experiments.

Laboratory- based aquarium experiments

A series of aquarium experiments were conducted to test the short-term behavioural responses of selected animals to deposition of terrestrial silts and clay.

The six species chosen for the experiments were three common bivalves (the deposit-feeding wedge shell *Macomona liliana* and the suspension-feeding cockle *Austrovenus stutchburyi* and pipi *Paphies australis*), the mud crab *Helice crassa*, and two common large polychaete worms (*Glycera americana* and *Orbinia papillosa*). The species selected were all commonly found on the intertidal sandflats of the Okura estuary, and are representative of different living-modes (e.g. different in terms of their feeding habits and their mobility) and expected responses to the deposition of sediment.

All animals and sediment used in the experiments were collected from Okura. Only recently collected animals in good condition were used in the experiments. All experiments were conducted at a constant temperature of 11ºC and with a 9:15 hour light:dark period. Each species was tested separately using the following protocol.

A series of small aquaria were established that contain sandy sediments from Okura which had been sieved (0.5 mm mesh size) to remove macrofauna. Animals were placed on the sediment surface in individual aquaria and allowed to acclimatise for 24 h. In every test, all animals burrowed into the sediment within this time period. Individual aquaria (n=60) were submerged in larger waterbaths and oxygenated by air-pumps. A clay/silt slurry (water content 48%) from a sedimentation pond from Albany, close to the Okura catchment, was then added to each aquaria, except for those designated as controls. Sediment addition treatments consisted of a clay/silt layer either 3, 6 or 9 cm deep. Replicates of the different treatments were randomly dispersed amongst water baths. Separate replicates of each treatment were sampled after 1, 3, and 6 days (i.e. 24, 72 & 144 h), when the number of animals lying on the surface of the clay/silt layer, the position in the sediment of non-surfaced animals, and mortality were measured. For the bivalves, we also assessed how stressed the survivors were, by measuring their ability to re-bury themselves into clean sandy Okura sediments, as sub-lethally stressed animals remaining on the sediment surface are vulnerable prey to predators (Norkko & Bonsdorff 1996). Re-burial rates for all bivalves were measured over a 2 h period immediately after retrieval from the treatments.

It proved very difficult to collect large undamaged polychaetes from the estuary and only enough could be collected to carry out one experiment for each of the two species. These experiments were sampled after 6 days.

For each species tested, we used different numbers of test organisms (matching their corresponding densities in the field). For each replicate container of each treatment, we used 2 individual *Macomona* (120 total), and 3 individuals of both the *Paphies* and *Austrovenus* (a total of 180 for each species). We used 1 *Helice* in each container, totalling 15 individuals. Because only 4 undamaged glycerids were obtained, we used 1 worm in four replicates of one treatment (6 cm) without controls. For orbinids we used 1 orbinid per replicate container in two treatments (control and 3 cm).

Field experiment

Based on the habitat map and previous macrobenthic surveys of Okura (Hewitt et al. 1998), two intertidal locations were chosen for the experiment. The sites were on either side of the sandbar on the northern shore of the estuary (Fig. 1), and both represent areas of high macrofaunal diversity, although they contain different macrobenthic communities. The benthic community at the inner site, Site 1, is dominated by bivalves (*Austrovenus* and *Macomona*) and several species of polychaetes. The seaward site, Site 2, contained more bivalves (especially *Paphies*) and fewer polychaetes. Site 1 is more sheltered and less exposed to wind-waves as compared to the seaward site. Sediment characteristics at the two sites were also different with Site 1 being predominantly muddy sand and Site 2 medium to fine sand with shells. At each site we measured wave climate at intervals over the duration of the experiment using a DOBIE wave gauge. This data was used to supplement wave models described in the companion report by Green & Oldman (1999).

The experiment consisted of 4 treatments replicated 3 times at both sites. Sediment depths used for the treatments were those used in the laboratory experiments (i.e., 0 cm, 3 cm, 6 cm and 9 cm). Based on the laboratory experiments and our observations of sediment events elsewhere, we anticipated that this range would provide a good indication of ecological risk to the macrofaunal communities.

On October 31, 1998, sediment was obtained from a sediment retention pond in the Okura catchment. Sediment from the pond was mixed into a slurry (determined by analysis as being 46% fresh water content) and transported to the estuary by helicopter. At the sites, the sediment was deposited into 2-m radius experimental plots. Distance between plots was 15 m, with replicates of the different treatments distributed using a Latin square design.

Macrofauna in the plots were sampled prior to sediment dumping and in a time series following this event (Table 2). Two 10 cm diameter cores penetrating 15cm into the original sediment were taken for macrofaunal analysis. The cores were sectioned in layers separating the clay/silt, the top 2 cm and the remaining 2-15 cm section of the original sediment. The respective sections from the two cores were then pooled for later analysis.

We also sampled the sediment surface for cohesiveness, and depth of the deposited clay (Table 2), at five random positions within each plot. A shear vane (47 mm diam) was inserted 5 mm into the sediment surface and the force required to move the sediment measured. A penetrometer with a 25 mm diam base was used to measure the force required to push the the base 5 mm into the sediment surface. Although the measurements from these instruments can be converted into kg/cm^2, in this report the numbers are used for relative comparisons only. Five replicate measurements were also made on the depth of the clay/silt sediment to test for erosion of the clay/silt layer.

Table 2: Sampling frequencies and parameters measured at Site 1 & 2 during the course of the field experiment. S1 = Site 1; S2=Site 2. Chl.*a* = Chlorophyll *a* of the surface sediment; LOI = loss on ignition (440 ºC).

Date	**Day**	**Macrofauna**	**Chl. *a*, LOI**	**Geotechnical measurements**	**Depth of clay/ silt-layer**
30/10/98	-1	Baseline samples			
31/10/98				Start of experiment	
1/11/98	1		S1 & S2	S1 & S2	S1 & S2
2/11/98	2				S1 & S2
3/11/98	3	S1 & S2	S1 & S2		S1 & S2
10/11/98	10	S1 & S2	S1 & S2	S1 & S2	S1 & S2
2/12/98	31	S1 & S2	S1 & S2	S1 & S2	S1
6/1/99	66	S2	S1 & S2	S1 & S2	S1
31/1/99	91	S2	S2	S2	
8/2/99	99	S1	S1	S1	S1

Smaller core samples (2 cm diam, 1.5 cm deep) were obtained from each plot for the measurements of sediment chlorophyll *a*, sediment water content, organic matter, and sediment particle size. Photographs were taken from the plots in order to document visual sediment characteristics and possible colonisation of crabs and other large macrofauna.

The macrofauna samples were sieved on both a 0.5 and 1.0 mm mesh, preserved in 70% IPA and stained with 0.2% Rose Bengal. Animals in the samples were sorted and identified to the lowest level practicable.

As a measure of food supply to the benthic animals, chlorophyll *a* was determined. Chlorophyll *a* was extracted from sediments by boiling in 95% ethanol, and measured spectrophotometrically. An acidification step was used to separate degradation products from chlorophyll *a* (Sartory 1982). Samples to be analysed for sediment particle size were digested in 6% hydrogen peroxide for 48 h to remove organic matter. A Galai particle analyzer (Galai Cis - 100; Galai productions L^{td}, Migdal Haemek, Israel) was used to measure particle size (% volume at 1 phi intervals from -1 to 10 phi). Cumulative % volumes were calculated for the medium sand, fine sand, silt and clay fractions. Organic content of the sediment was measured as loss on ignition in 12 h at 440^{0}C, after drying the samples at 40^{0}C for 6 h.

The photographs from each plot were examined for distinct biological features, such as burrows.

Statistical analyses

None of the bivalves used in the laboratory experiments managed to move up to the top of the sediment surface. Thus responses to the different clay/silt treatments were assessed using Chi-square goodness-of-fit tests on the reburial of animals. These tests treated the results from the controls as the expected model, and compared the results of the other treatments as observed deviations. For the polychaete and crab taxa investigated, responses were so obvious that no statistical test was needed to interpret the results.

In the field experiment, macrobenthic community responses over time were examined using non-metric multidimensional scaling (PRIMER, Clarke & Warwick 1994) on Bray-Curtis similarities based on raw data. This ordination method produces a 2 dimensional plot showing how the communities change over time. The closer together points are in the plot the more similar the communities are. Conversely, the larger the area taken up by points representing a single treatment over time, the more the communities in that treatment are changing over time. The responses of total numbers of individuals, numbers of taxa and numbers of individuals of dominant taxa found were examined graphically.

RESULTS

Habitat mapping

A mosaic of sedimentary habitats can be identified in the Okura estuary. In general, however, there is a gradient of increasing sandiness moving from the inner towards the outer reaches of the estuary. Muddy sediments dominate the intertidal flats at the inner parts of the estuary, upstream from the Okura township. Muddy sediments also occur in and along the tidal channel, at the small embayments, and on the rocky platforms on the southern shores of the estuary (Fig. 1). Extensive sandflats dominate the northern shores from the mouth of the estuary stretching to the sandbar opposite Okura township. There is also a substantial pocket of sandy sediments on the inner side of the sandbar. The wave-exposed areas in the outer reaches are dominated by sand-ripples, illustrating the dynamic nature of these sediments (Fig. 1).

The gradient in sedimentary habitats is reflected in the distribution of the benthic communities present in the estuary. The macrofaunal communities along the estuarine gradient have been investigated previously for the ARC (Hewitt et al. 1998). Despite some seasonal variability, numbers of taxa are fairly consistent throughout the estuary, ranging between 15 and 30 per core (Fig. 2). The highest number of taxa are found in the sedimentary transition-zone in the middle reaches of the estuary. This is also true for number of individuals found, with the highest abundances occurring in this area. This transition-zone represents a mixture of taxa from both the outer and inner parts of the estuary, thereby forming an area of comparatively high diversity bordering two different communities. It is important to remember that other ecological communities in the estuary also are vulnerable to deposition of fine sediment.

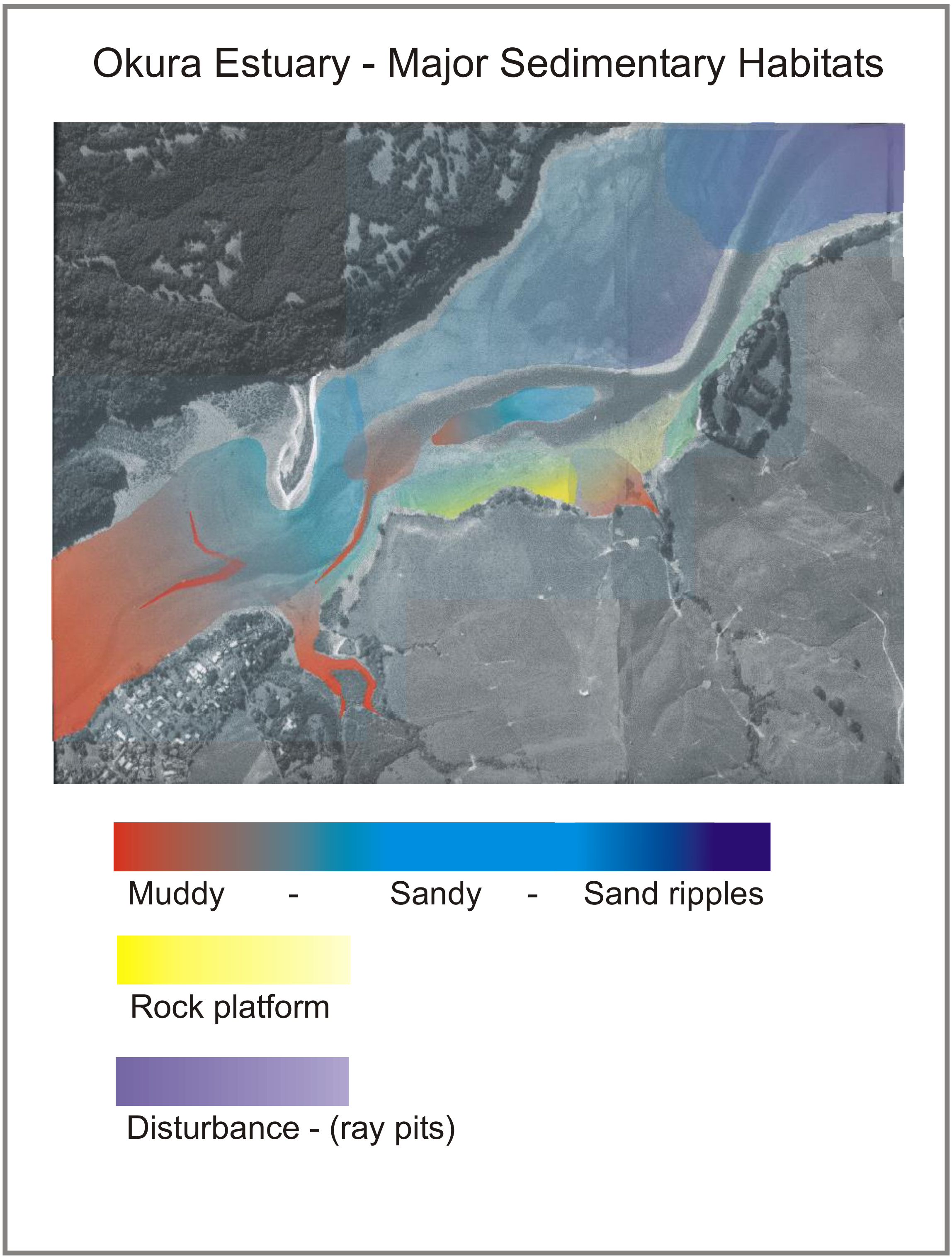


Figure 1: Major sedimentary habitats in the Okura estuary.

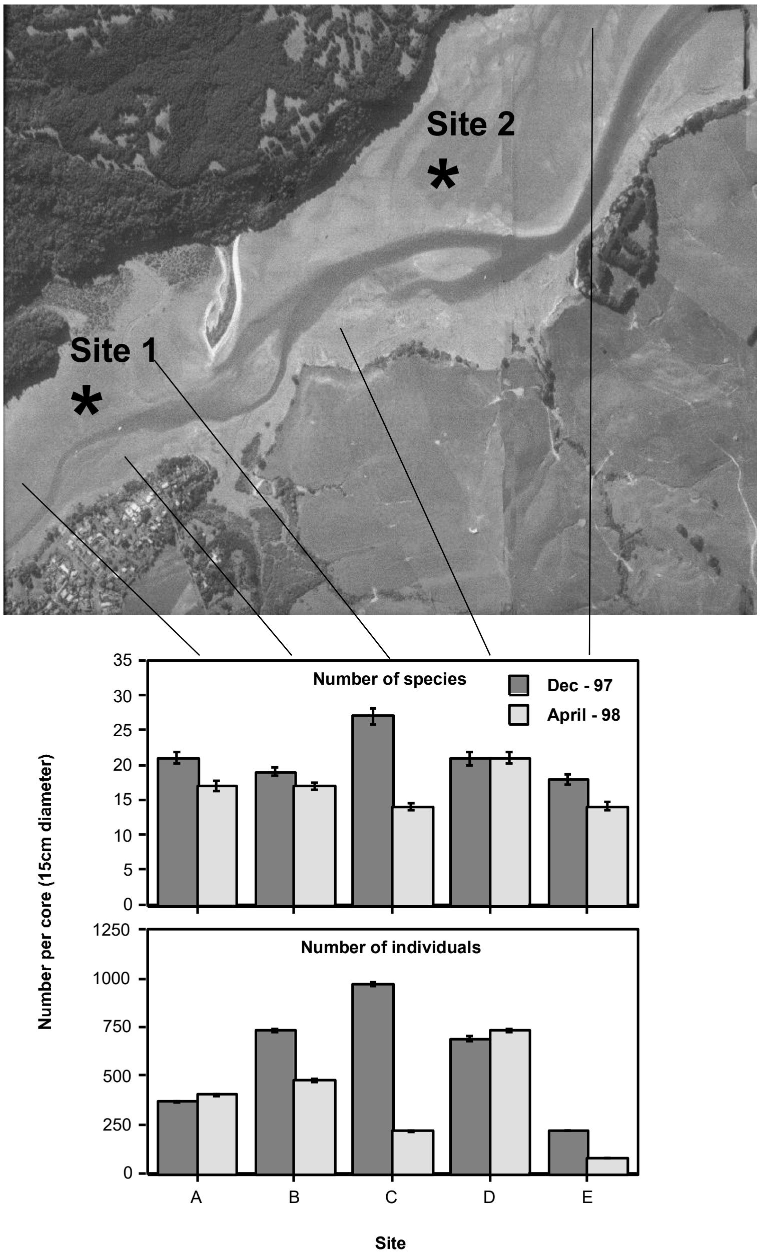


Figure 2: Mean number of taxa and individuals found in a core (15cm diameter) in different areas of the estuary. The field experiment sites (Site 1 & 2) are indicated with asterisks.

Along the estuarine gradient there is gradual change in the benthic communities matching the changes in sedimentary habitats (Fig. 3). The exposed sandy areas in the outer reaches of the estuary are dominated by medium to fine sands worked into sand ripples (about 2 cm high) with occasional patches of shell hash. The macrobenthic communities are dominated by the bivalve *Paphies australis* (pipi), with *Austrovenus stutchburyi* (cockles) and *Macomona liliana* (wedge shell) also being common. Few polychaetes are found and those that are mainly Orbinids (Fig. 3). Moving up the estuary, *Austrovenus* replaces *Paphies* as the dominant bivalve with slight changes in the relative dominance of the other taxa present (Fig. 3). Polychaetes become more abundant. The major differences in the benthic communities occurring in the middle reaches of the estuary may be found in the overall number of taxa and abundances of animals present (Fig. 2). Dominants are composed of a similar suite of taxa (Fig. 3), although *Macomona* (especially as adults) decrease in abundance. In the muddier parts of the estuary capitellid polychaetes increase in importance, and in the muddiest parts *Heteromastus filiformis* replaces the bivalves as the most common taxa found. Crabs, mainly *Helice crassa*, occur throughout the estuary where areas of muddy sediments are found. In these areas crabs play an important role digging, burrowing and mobilising sediments.

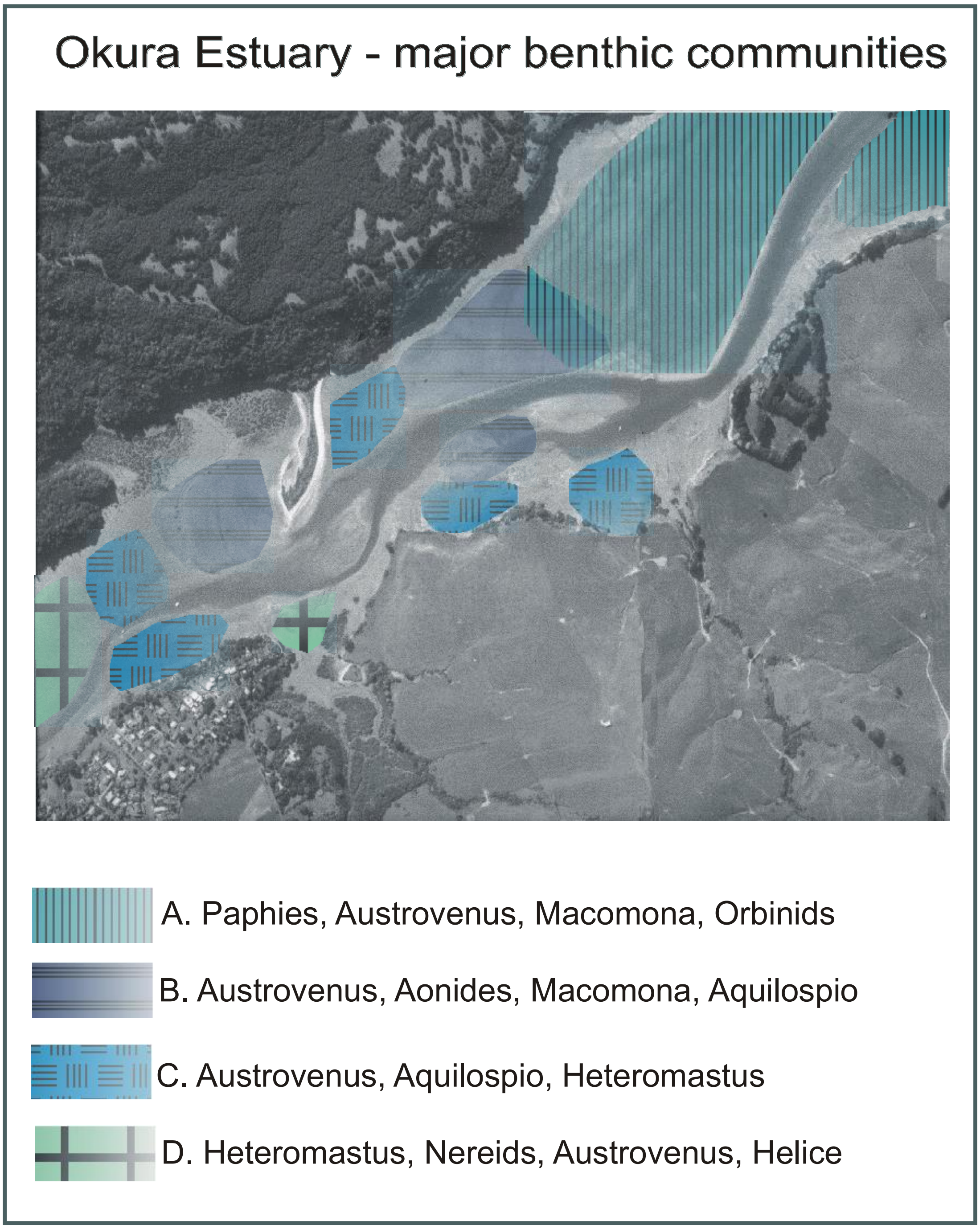


Figure 3: The distribution of major macrofaunal communities in the estuary. The dominant taxa in terms of abundance are listed for the different areas.

Aquarium experiments

Paphies: *Paphies* used in the experiment were adults ranging in size from 13.8 to 27.4 mm, with a mean of 19.3 mm ($\pm$2.6 mm standard deviation). *Paphies* are bivalves that live in mobile sediments, and usually have a good ability to crawl through layers of sand, as sand waves move across the sediment surface. However, none of the *Paphies* moved up through the layers of clay/silt at any of the depths tested in this experiment. By the end of the experiment (after 6 days) all animals were found on the surface of the sand at the sand/clay interface. In the 3 cm treatment, *Paphies* managed to extend their siphons through the clay/silt-layer. In the deeper treatments their shells were closed. All *Paphies* survived the experiment.

Generally, reburial rates of animals from the controls were fast (Fig. 4). Re-burial rates in the controls differed significantly from all clay/silt treatments at all times (i.e 24, 72 and 144 h). Even after only 24 h, a clear stress-response to clay/silt was observed. All the control bivalves had buried within 30 min, whereas less than half of the bivalves in the other treatments had re-buried over the same time period. Reburial capacity of bivalves tended to decrease with increasing clay/silt depth (Fig. 4) for example, only the bivalves in the 3 cm treatment had all re-buried themselves within two hours. After 144 h of stress, reburial rates were very slow in all the clay/silt treatments; only some of them completely reburied and others remained at the sediment surface. Over 60 min was required for 50% of the bivalves to re-bury. Reburial in the 3 cm treatment was significantly faster than the 6 and 9cm treatments until 144 h. All treatments showed decreasing rates of reburial with increasing length of stress, except for the 9 cm treatment where no differential re-burial responses could be detected after 72 h. This suggests a more pronounced stress response in the 9 cm treatment compared to the other treatments. However, reburial of the control animals sampled after three days (72 h) were slow, indicating stress. The reason for this is unknown.

It is likely that higher temperatures (e.g. 20 ºC recorded in the field experiment), would have led to considerable mortality as individual metabolic rates double with every 10 degree increase in temperature.

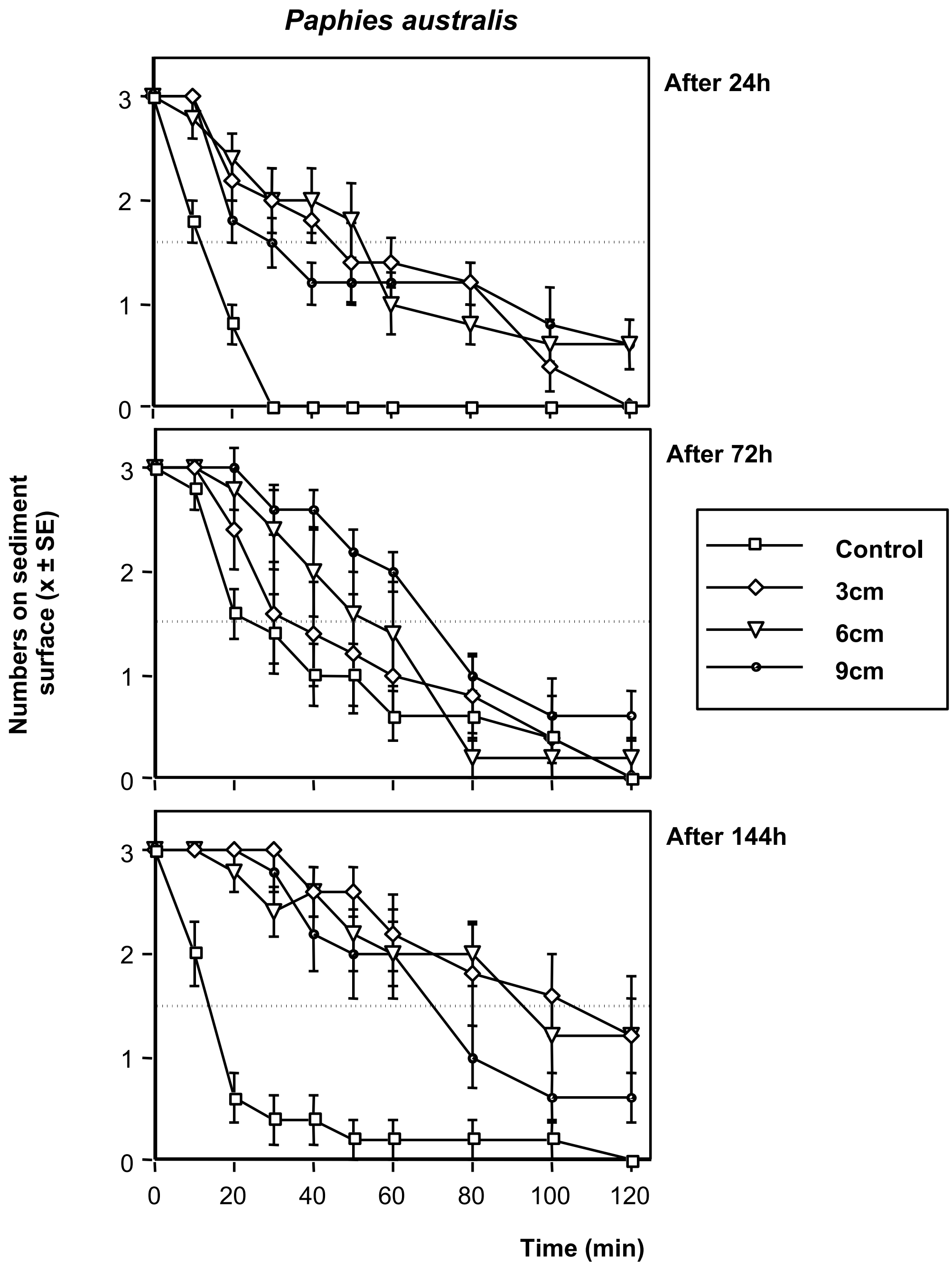


Figure 4: Re-burial rates of *Paphies* from each treatment into sandy Okura sediments. Reburial was measured over 2 h.. Values are expressed as mean $\pm$ standard error.

Austrovenus: *Austrovenus* used in the experiment were adults ranging in size from 16.6 to 33.8 mm, with a mean of 25.3±2.6 mm (sd). Similar to *Paphies*, none of the *Austrovenus* managed to surface through the clay/silt layers and all were found near the old sand surface at the end of the experiment. The cockles exhibited slow overall re-burial rates (Fig. 5). Significantly lower reburial rates were found between all treatments and controls on all times, although these were barely significant after 24 h. Clear differences between the control and the clay/silt treatments were only apparent after 144 h. Complete burial did not occur, even in the controls, reflecting that *Austrovenus* either has a poor re-burial capacity, or adaptation for dispersal. Generally, no significant differences were found between the reburial rates of animals from different treatments. After 144 h many had gaping shells and an inflated foot (a bivalve stress response), but recovered over the 2 h observation period in well oxygenated water.

Macomona: *Macomona* used in the experiment were adults ranging in size from 19.5 to 34.4 mm, with a mean of 26.3±3.2 mm (sd). Over the course of the experiment *Macomona* moved up to the top of the sandy sediment, but did not move into the clay/silt. *Macomona* have long siphons and in the 3 and 6 cm clay/silt treatments visible openings created by siphons were observed on the clay/silt sediment surface. Similar to *Austrovenus*, significantly lower reburial rates were found between all treatments and controls on all times, although these were barely significant after 24 h (Fig. 6). However, after 72 h a clear stress-response was apparent (Fig. 6). After 144 h, 20% of the *Macomona* in the 6 cm, and 60% in the 3 and 9 cm clay/silt treatments were dead. Of the live individuals from claysilt treatmenst after 144 h, virtually none re-buried, whereas all the control *Macomona* had re-buried within 40 minutes (Fig. 6). Similar to *Paphies*, there is a trend of animals buried under deeper clay/silt layers to exhibit slower rates of reburial, and this trend is accentuated through time.

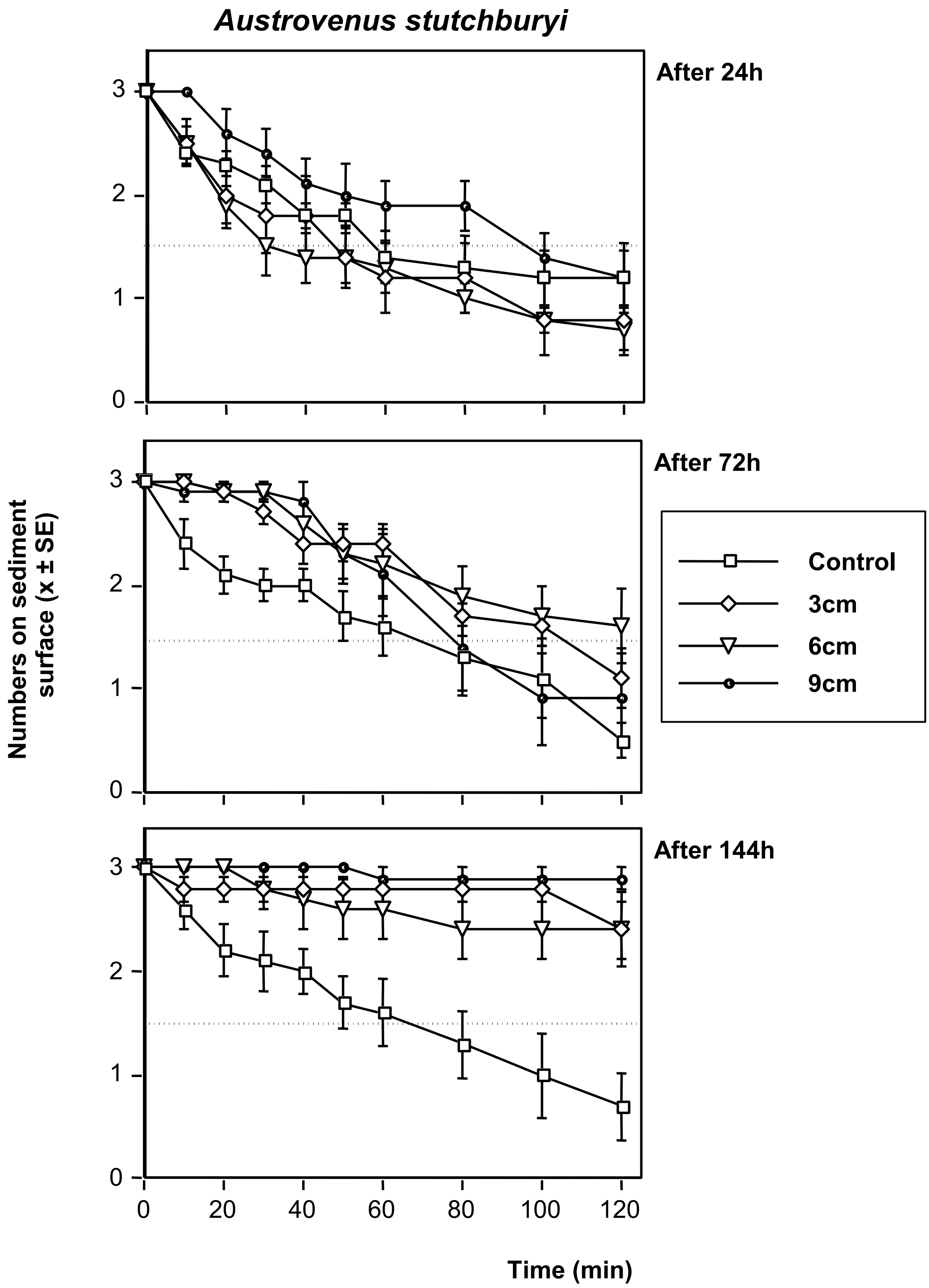


Figure 5: Re-burial rates of *Austrovenus* from each treatment into sandy Okura sediments. Reburial was measured over 2 h.. Values are expressed as mean ± standard error.

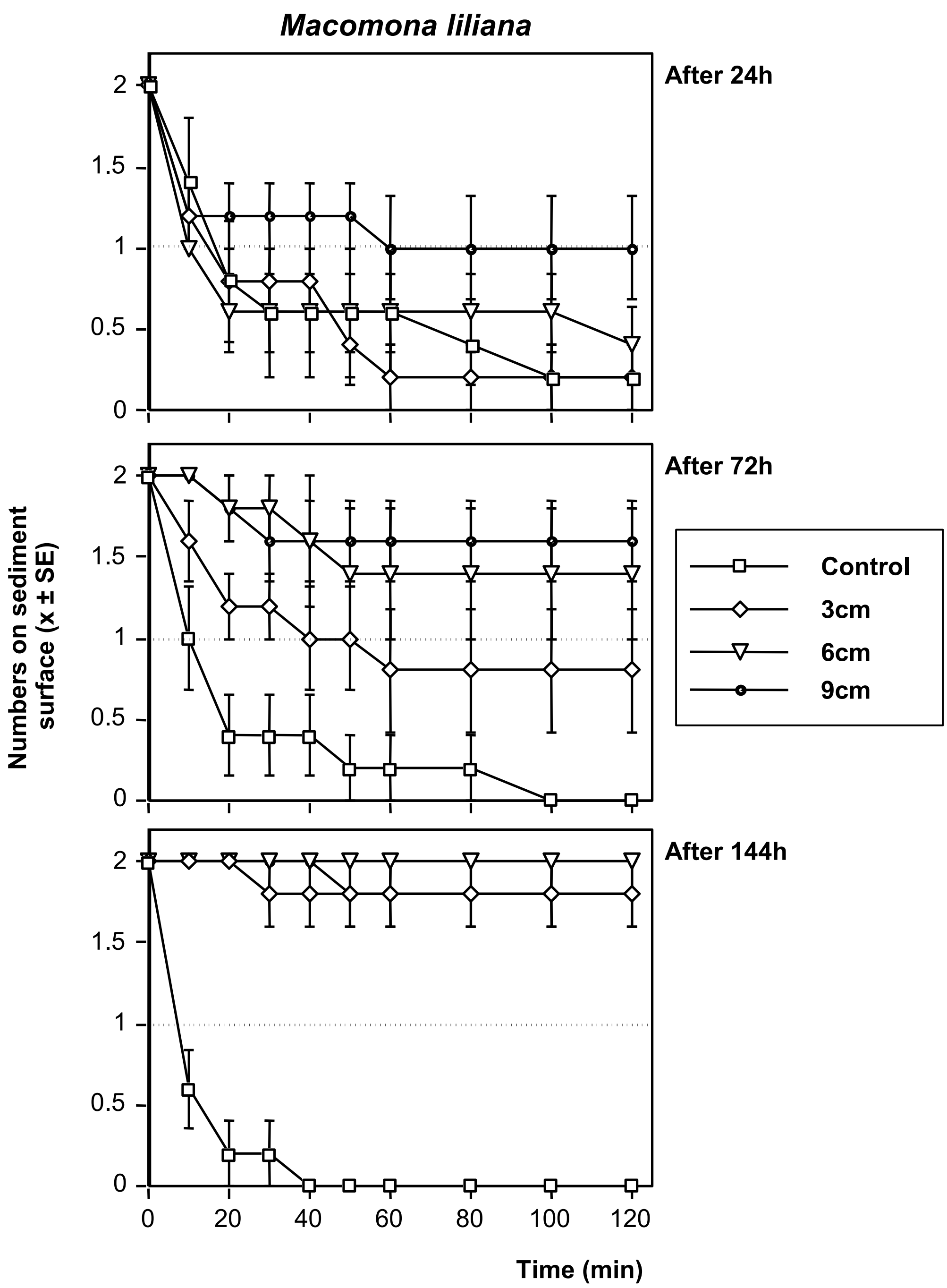


Figure 6: Re-burial rates of *Macomona* from each treatment into sandy Okura sediments. Reburial was measured over 2 h.. Values are expressed as mean $\pm$ standard error.

Crabs and polychaetes

The crabs used in the experiment, *Helice crassa*, create burrows in muddy sediments, and were common throughout muddy sediments in Okura estuary. The crabs had an average carapace width of 9 $\pm$ 1 mm (sd). All the crabs emerged through the clay/silt treatments. Indeed, in all treatments, at least one of the five crabs used had emerged within the first hour. Within 3 h all the crabs had emerged in the 3 and 6 cm treatments, and within 7 h all the crabs in the 9 cm treatments had emerged.

As only a few polychaetes were obtained for the experiments, the results should be interpreted cautiously. Glycerid polychaetes showed a mixed response; although one individual managed to emerge through the 9 cm clay/silt-layer within 6 h and another one after 24 h, the others never emerged and were found dead in the sandy sediment at the termination of the experiment after 6 days. The experiment on orbinids only used the 3 cm clay/silt treatment. None of the orbinids emerged through the 3 cm clay/silt layer, and only 20% of the worms survived after 6 days, compared to a 100% survival in the control.

Field experiment

*General observation*s

At the start of the experiment, and over the next 4 to 5 days, weather conditions were calm and sunny. No immediate re-working of the sediments occurred and the clay/silt surface on the experimental plots dried, forming a very viscose (rubbery) surface. At both sites, crabs were observed crawling up through the clay/silt as it was being deposited and, later, burrowing into the clay/silt layer (Fig. 7). No other large animals were observed to colonising the clay/silt, with the exception of the occasional cockle and gastropod which were sometimes found generally in cracks in the clay/silt sediment surface (caused by shrinkage of the clay/silt as it dried). Clay/silt layers at both sites changed very little over the first 28 days of the experiment except for exhibiting this slow drying process. At the more exposed site (Site 2), a storm occurred between the 28th of November and 2nd of December, which removed the clay/silt layer. Maximum wind speeds of 24 m s^{-1} from the SE and heavy rain was recorded during this storm. Occasional chunks of clay/silt have subsequently been found at the site, buried 5-10 cm below the sandy sediment surface.

The sheltered site (Site 1) was unaffected by the storm. At this site, the clay/silt has been increasingly broken up, mobilised by crabs and cracked through de-watering. After 99 days, crab colonisation was highly obvious and detected in the benthic samples (Fig. 8). The clay/silt plots appear to be slowly sinking into the natural muddy-sandy sediments, and natural sediment is gradually accumulating on the top of the plots. These effects were most obvious in the 3 cm treatment.

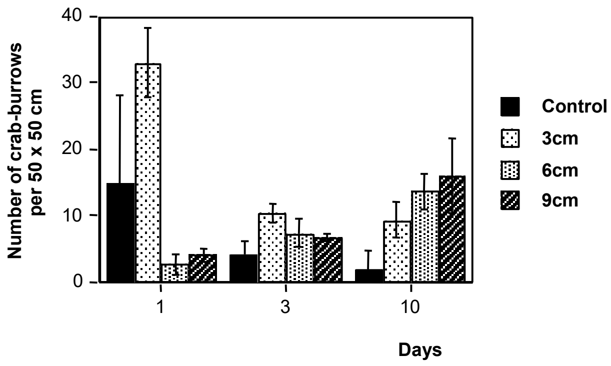


Figure 7: Colonisation of crabs, *Helice crassa*, into the experimental plots on Site 1 measured as number of burrows. Values are expressed as the mean ± standard error.

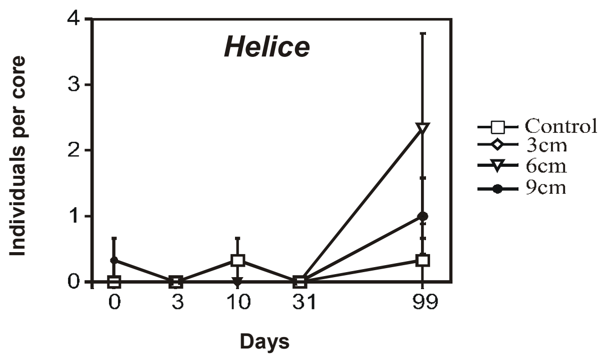


Figure 8: Colonisation of crabs, *Helice crassa*, into the experimental plots on Site 1 as detected in benthic cores. Values are expressed as the mean ± standard deviation.

Hydrodynamic conditions and the storm event

The experimental sites are both situated at similar tidal heights and covered by water 49% of the time. However, in terms of wave climate, the sites differ substantially (Table 3). Consequently the clay/silt layer was removed from Site 2 during the storm event one month after the initiation of the experiment, whereas Site 1 remained intact. During the storm event, average and maximum wave heights and periods were significantly larger at Site 2 compared to Site 1 (Table 3). Correspondingly, maximum orbital flow speeds at thew bed of 60 cm/s were recorded at Site 2 compared to only 13 cm/s at Site 1. The storm event lasted for 4 days and had maximum wind speeds of 24 m/s from the South East. The largest event recorded prior to this storm produced maximum orbital flow speeds at bed of 27 cm/s at Site 2 (Table 3). This occurred one week before the storm and failed to remove the clay/silt layer.

Table 3: Wave climate at Site 1 & 2 during the storm event 28 days after the initiation of the experiment. As a comparison, the wave climate for the largest event prior to the storm is also described.

Wave climate	Site 1	Site 2
Storm event:		
Average wave height (m)	0.03	0.16
Average wave period (s)	1.7	4.1
Average orbital speed (cm s^{-1})	5	27
Maximum wave height (m)	0.1	0.4
Maximum wave period (s)	2.2	6.0
Maximum orbital speed (cm s^{-1})	13	60
Largest event prior to storm:		
Average wave height (m)	0.02	0.06
Average wave period (s)	1.2	3.2
Average orbital speed (cm s^{-1})	0.04	0.11
Maximum wave height (m)	0.04	0.17
Maximum wave period (s)	1.5	4.5
Maximum orbital speed (cm s^{-1})	8	27

Physical sediment characteristics

The physical sediment characteristics of the control plots illustrate the differences in physical regime between the two sites. At Site 1, silts and clay/silt comprise 7.2% of the sediments compared to less than 1% at Site 2 (Table 4). Correspondingly, Site 2 has a higher proportion of medium to coarse sands. The experimental clay/silt deposits had all very similar sediment characteristics and were dominated by medium to very fine silts (Table 4); silts and clay comprised between 86.6 and 57.4% of the volume. In terms of number of particles, the clays dominate the clay/silt deposits, however.

Table 4: Volumetric composition (%) of the surficial sediments at the start of the experiment. C = control; 3, 6, 9 cm = experimental treatment (depth of clay/silt layer).

Sediment particle size (microns)	**Site 1 %**				**Site 2 %**			
	C	**3cm**	**6cm**	**9cm**	**C**	**3cm**	**6cm**	**9cm**
Clay (0-3.9 µm)	0.2	11.0	10.5	6.9	0.0	9.5	9.4	8.4
Medium to very fine silt (3.9-31 µm)	1.1	51.0	43.4	27.6	0.2	40.4	37.0	38.2
Coarse silt (31-62.5 µm	5.9	24.6	21.2	22.9	0.5	15.9	18.8	28.6
Fine to very fine sand (62.5-250 µm)	84.5	11.2	12.0	30.2	82.7	16.8	17.0	21.0
Medium sand (250-500 µm)	4.4	2.2	4.7	7.8	7.6	5.5	5.6	3.8
Coarse sand (500-2000 µm)	3.9	0.0	8.2	4.6	9.0	11.9	12.2	0.0

The actual depths of clay/silt deposited at the start of the experiment differed slightly from the ones used as denoting the different treatments. Nevertheless, consistent differences between treatments were apparent. The actual depths deposited were around 4 cm, 8 cm and 10 cm at both Site 1 & 2 (Fig. 9). Despite a slight compaction of clay/silt, these values have remained consistent over time at Site 1. For clarity the treatments are still referred to as 3, 6, and 9 cm.

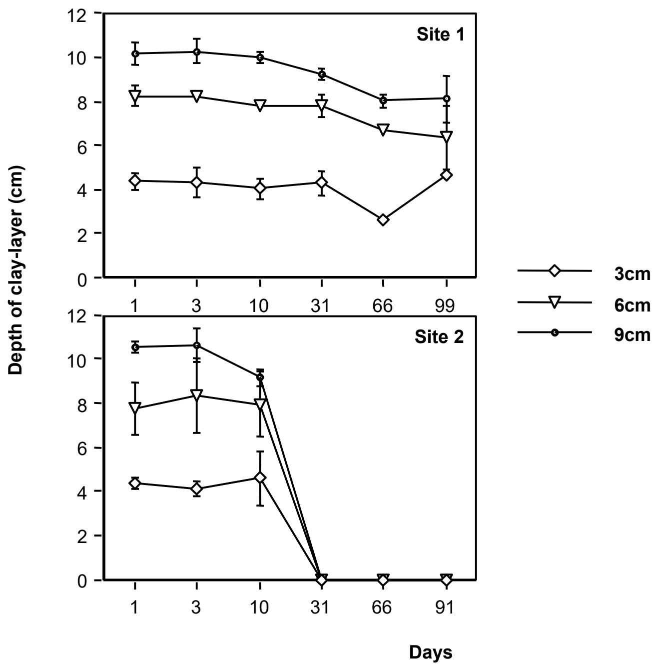


Figure 9: Changes in the depth of the clay/silt layer in the experimental plots at Site 1 & 2 over time. Values are expressed as the mean ± standard error.

The water content of the sediment remained fairly constant in the controls at both sites at around 22-26%. The clay/silt plots, however, showed a steady de-watering. At Site 1, sediment water content in the clay/silt treatments was reduced from around 43-48% (by weight) at the start of the experiment to around 30% after 99 days. Similarly at Site 2, the clay/silt gradually de-watered until the storm removed these deposits. The re-exposed sand exhibited similar water content to that in the control plots (Fig. 10).

The organic content of the sediment in the controls was significantly higher at Site 1 compared to Site 2 (Mann-Whitney; $p<0.0082$), illustrating the difference in the physical regime at the two different sites. While the control treatments at both sites generally had less than 1%, the organic content of all clay/silt treatments from between 4 and 7%. These values remained similar over the course of the experiment.

Average shear strength values in the controls at Site 1, and at Site 2 prior to the storm, remained similar over time, with readings at around 2. Because of de-watering, average shear strength values in the clay/silt treatments, at both sites, increased from 0 at the start to a maximum of around 7 during of the experiment (Fig. 11). At Site 1, shear stress values were lower in the 3 cm treatment compared to the 6 and 9 cm treatments. This could possibly be due to differences in immersion time between treatments causing the sediment surface to remain softer (i.e. water would cover the 3 cm treatment for a longer period of time than the 6 and 9 cm treatments). After the storm, average shear strength at Site 2 was reduced significantly, even in the controls

(Fig. 11). This overall drop in shear strength could possibly be due to the significant losses in sediment chlorophyll, indicating reduced densities of sediment microalgae that have an important role in binding the sediment.

The penetrometer readings at Site 1 also illustrate the gradual de-watering and hardening of the clay/silt plots. After 99 days the 6 and 9 cm treatments showed identical values to those in the control treatment, whereas the 3cm treatment was still softest (Fig. 11). Penetrometer readings obtained from Site 2 were always slightly lower in the clay/silt treatments compared to the control until the last sampling occasion, i.e. 91 days after the start of the experiment (Fig. 11). The terrigeneous clay/silt has substantially different geotechnical characteristics than the natural muddy sediments in the inner reaches of the Okura estuary (c.f. average penetrometer readings of 0.8 and average shear readings of 0.5 (Hewitt et al. 1998). Readings from the terrigeneous clay/silt are initially lower but increase with de-watering, finally equalling or exceeding readings from muddy sediments.

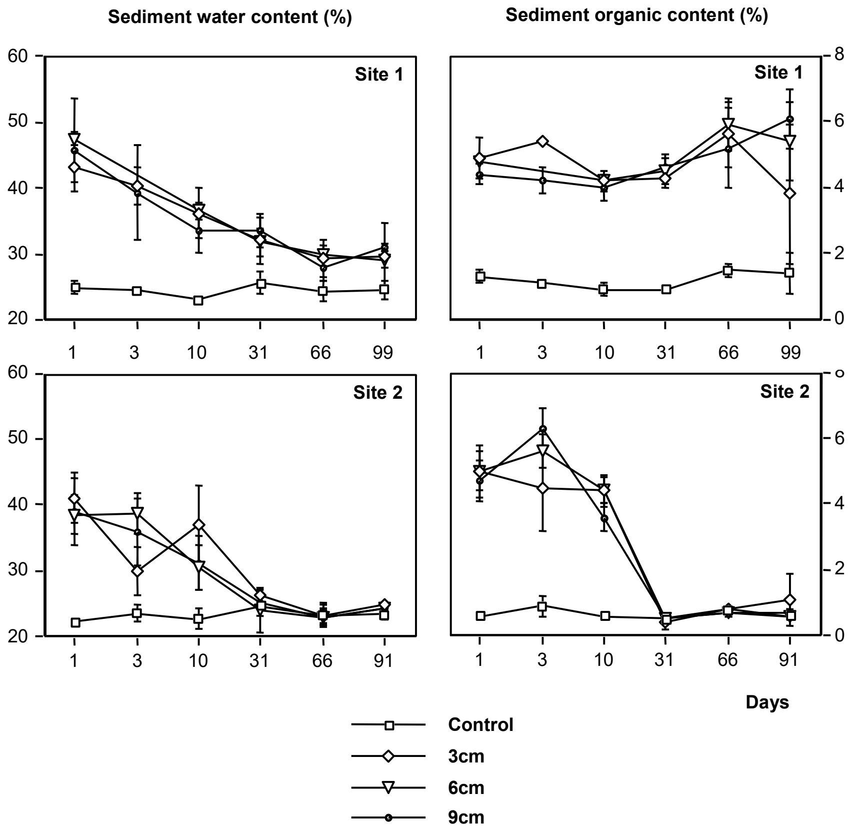


Figure 10: Sediment water and organic content in the experimental plots at Site 1 & 2 over time. Values are expressed as the mean ± standard error.

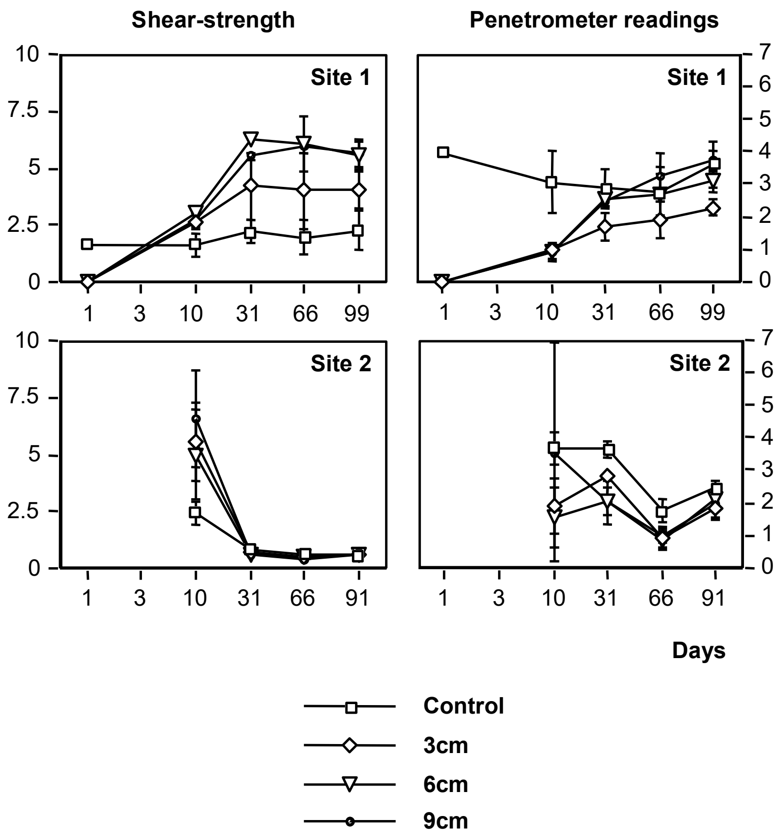


Figure 11: Sediment shear strength and penetrometer readings in the experimental plots at Sites 1 & 2 over time. Values are expressed as the mean ± standard error.

Chlorophyll a

Sediment chlorophyll *a* is measure of food supply to the benthic animals, especially for deposit feeders. More chlorophyll *a* can therefore be considered as being more attractive in general to many animals. Sediment chlorophyll *a* values in the control treatment ranged between 0.002 and 0.004 $mg.g^{-1}$ dwt sediment at Site 1. At both sites, the chlorophyll *a* concentration in the clay/silt layer was lower than in the controls. At Site 2, concentrations of chlorophyll *a* in the treatments increased after the clay/silt layer was removed during the storm event (day 28), and decreased in the control plots (Fig. 12). At Site 1, benthic microalgae gradually colonised the 3 cm clay/silt treatment, with chlorophyll *a* values approaching 0.0002 $mg.g^{-1}$ dwt sediment. A slight increase could also be detected in the 6 cm treatment at day 99. Values in 9 cm remained very low throughout the experiment (Fig. 12).

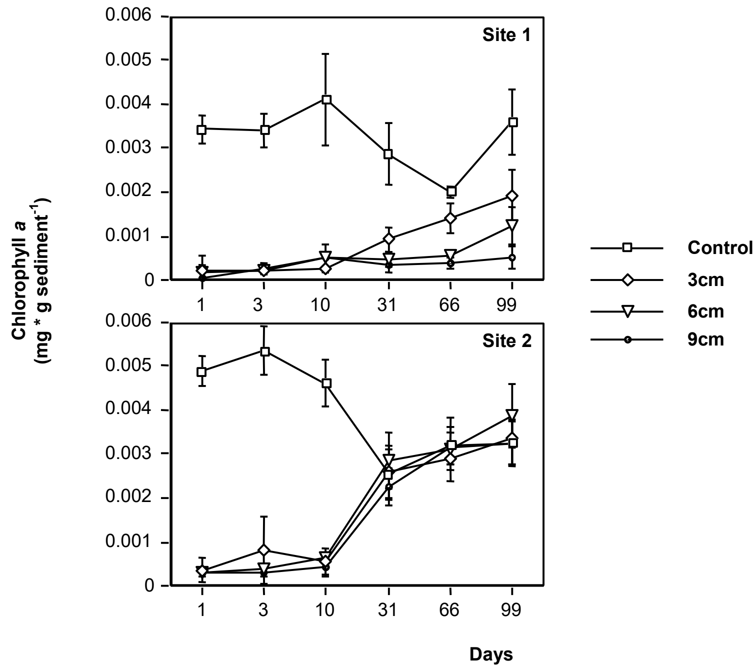


Figure 12: Sediment chlorophyll *a* in the experimental plots at Site 1 & 2 over time. Values are expressed as the mean ± standard error.

Responses of the macrobenthic community

The macrofaunal communities at both sites responded rapidly to the deposition of all depths of sediment. Within 10 days, nearly all the macrofauna in the clay/silt treatments had died (Fig. 13). This disappearance of a large number of taxa and individuals can be put into context by comparisons with the controls. Generally, the numbers of taxa and individuals found in the controls at both sites was stable over time. An exception was the number of individuals in control treatment at Site 2 where a nearly 50% reduction in abundance occurred over the course of the experiment.

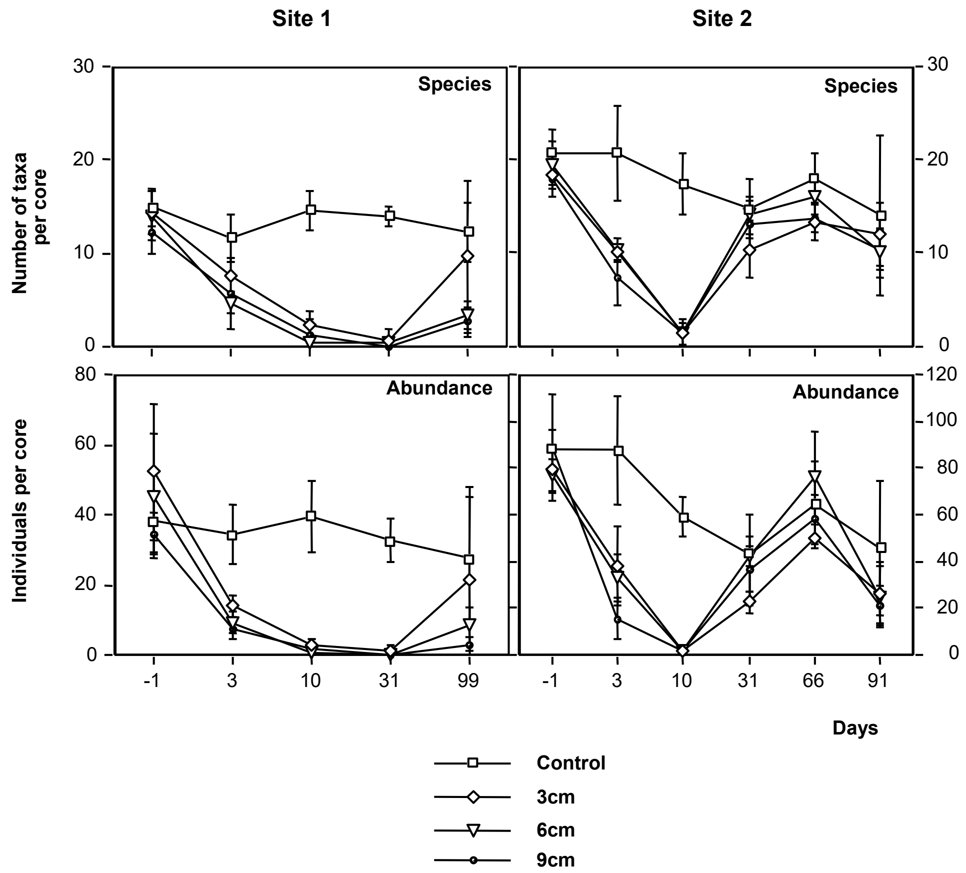


Figure 13: Changes in number of taxa and individuals found at Site 1 and 2 over time. Values are expressed as the mean ± standard error per core. Note the different scales (on the y-axis) used for the number of individuals at each site.

At Site 1, recovery was gradual; the numbers of taxa and individuals in the 3 cm treatment only approaching those found in the control by day 99, after more than two months. This recovery was dominated by near-surface living animals colonising the cracks and burrows present in the clay/silt layer. For example, crabs (see Fig. 7), *Austrovenus* sized 4 – 15 mm and > 15 mm (Fig., 14), Nemerteans, Nereids, *Boccardia*, Corophid amphipods and the small mud-loving bivalve *Arthritica bifurca*. However, the numbers of different taxa and the total number of individuals dwelling deeper in the sediment (2-15 cm deep) were still very different to those found in the controls by day 99 (Fig. 15). For example, there are still fewer large *Macomona* (> 15 mm) in the treatment plots than the controls at day 99 (Fig. 14).

Overall community responses to the deposition of clay/silt are clearly demonstrated by ordination (Fig. 16). While communities from the control plots change little over time, communities in the treatment plots exhibit large haphazard changes. These changes represent defaunation of plots and the subsequent recovery dynamics over time. The most coherent pattern is shown by the 3 cm treatment, for which the community approaches the position of the control communities after 99 days.

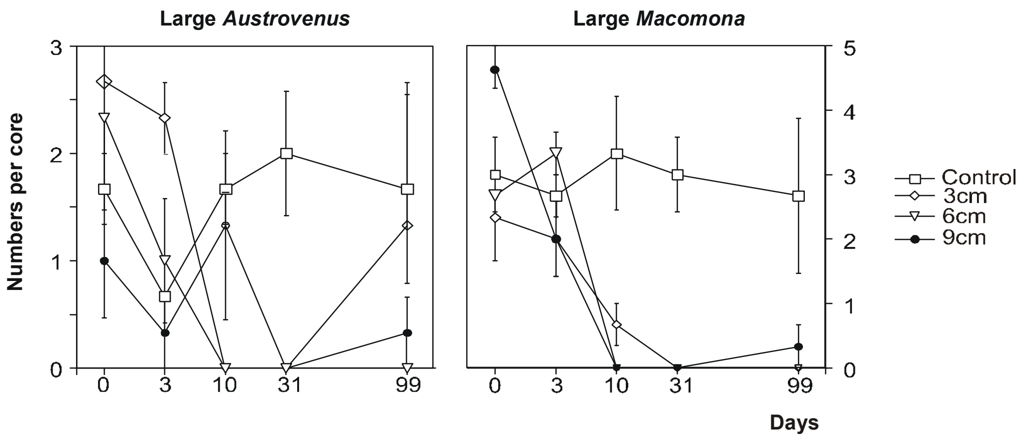


Figure 14: Changes in number of large *Austrovenus* and *Macomona* found at Site 1 over time. Values are expressed as the mean ± standard error per core.

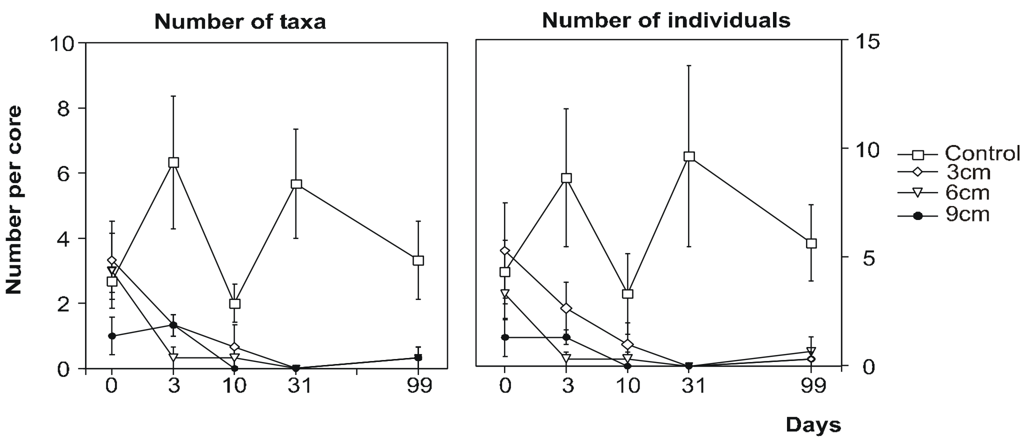


Figure 15: Number of taxa and individuals found in the deeper layers (2-15 cm) of the sediment at Site 1 over time. Values are expressed as the mean ± standard error per core.

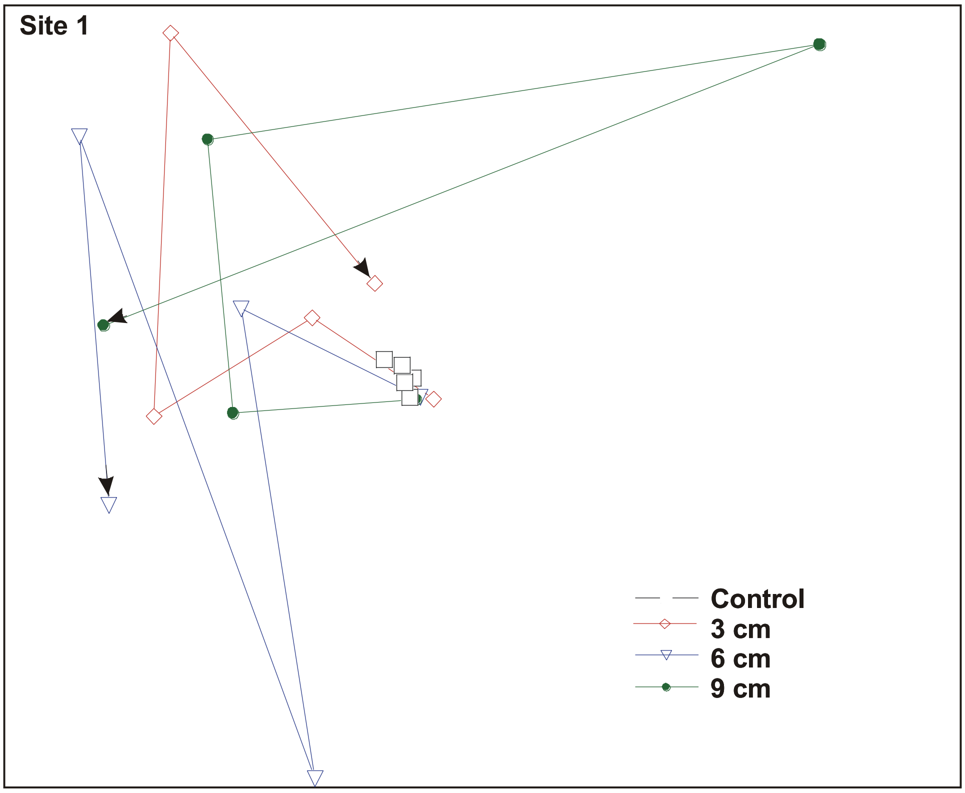


Figure 16: Multidimensional scaling analysis of community structure found in the different treatments over time, based on species abundance at Site 1. The arrows indicates how the community composition changes over time., and denote their final position after day 99. The axes have no labels as they have no meaning in absolute terms. Distances between sample points indicate the relative magnitude of differences between communities.

At Site 2, the wind-wave disturbance that removed the clay/silt layer from the surface of the treatment plots also removed many of the surface dwelling animals making the control plots more similar to the treatment plots. This is illustrated by the changes in the numbers of individuals (Fig. 13), which suggest that the macrofaunal communities quickly recovered once the silt/clay-layer was removed. However, the ordination plot of community structure shows a slightly different story (Fig. 17). Similarly to Site 1, the controls show little change over time, while the communities in the treatment plots exhibit large haphazard changes (at the time of defaunation). The positions exhibited by the treatments on day 91 are not all within the area marked out by movement of the controls, but suggest partial recovery as they fall close to this area.

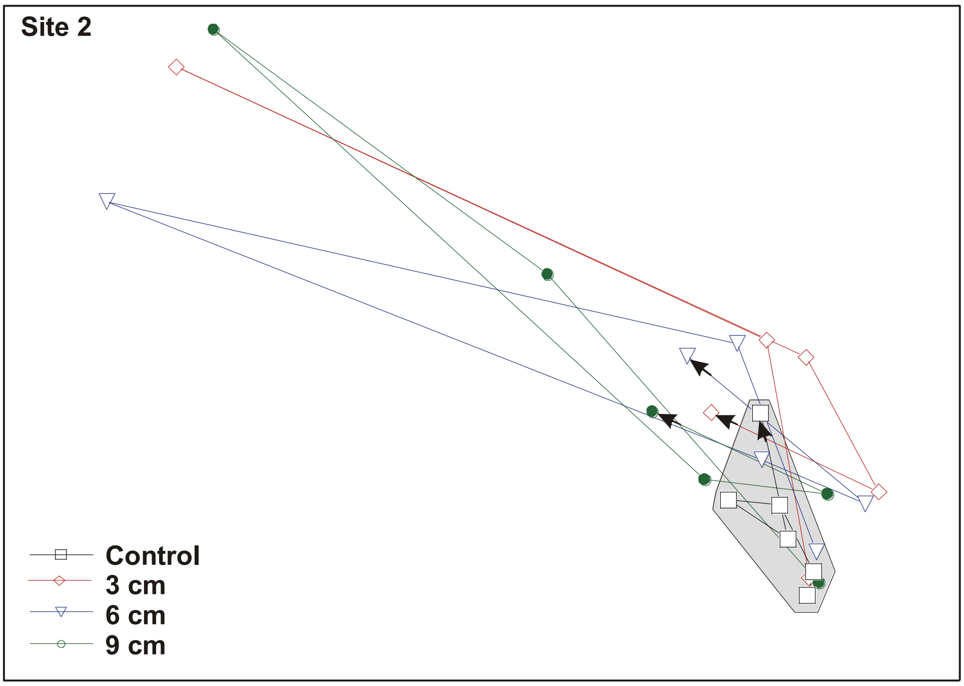
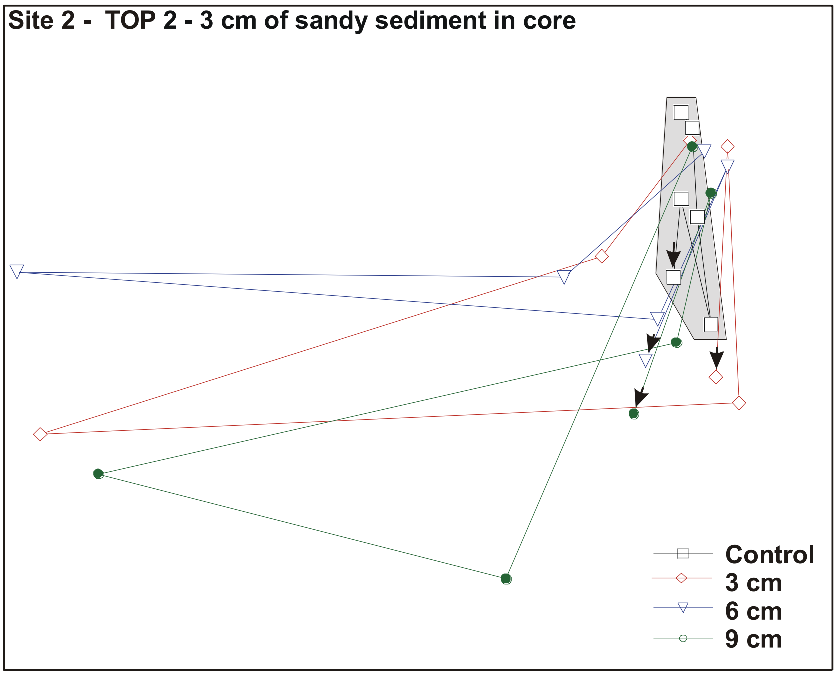


Figure 17: Multidimensional scaling analysis of community structure found in the different treatments over time, based on species abundance at Site 2. The shaded area represents the area in which the controls are located. The arrows indicates how the community composition changes over time., and denote their final position after day 91. Treatments ending within the area would indicate complete recovery.

Examination of the communities found at different depths within the sediment help explain how recovery is developing and in which way it is not complete (Fig. 18). Most of the recovery has been in the top sediments; by day 91 these communities are approaching those of the control (Fig. 18). However, communities in the bottom sediments are still distinctly different from the controls (Fig. 18).



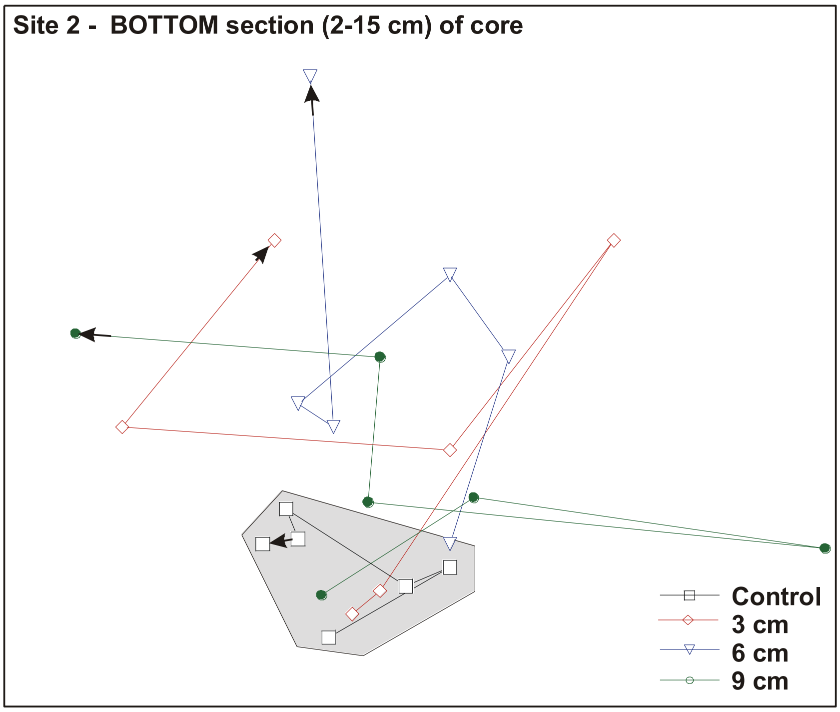


Figure 18: Multidimensional scaling analysis of communities living at different depths in the sediment in the different treatments over time, based on species abundance at Site 2. Again, the shaded area represents the area in which the controls are located. The arrows indicates how the community composition changes over time., and denote their final position after day 91. Treatments ending within the area would indicate recovery.

For example, examination of the numbers of large bivalves show that recovery of these is incomplete. Numbers of *Macomona* in the controls were very similar to those in the treatments by the last sampling occasion (day 91), but this is more due to the controls showing a seasonal decrease, than the treatments increasing (Fig. 19). The plot of large *Paphies* abundance shows a similar trend, although differences still exist between the controls and the treatments at day 91. Surprisingly, differences in numbers of large *Austrovenus* between the controls and the treatments are also still apparent at day 91.

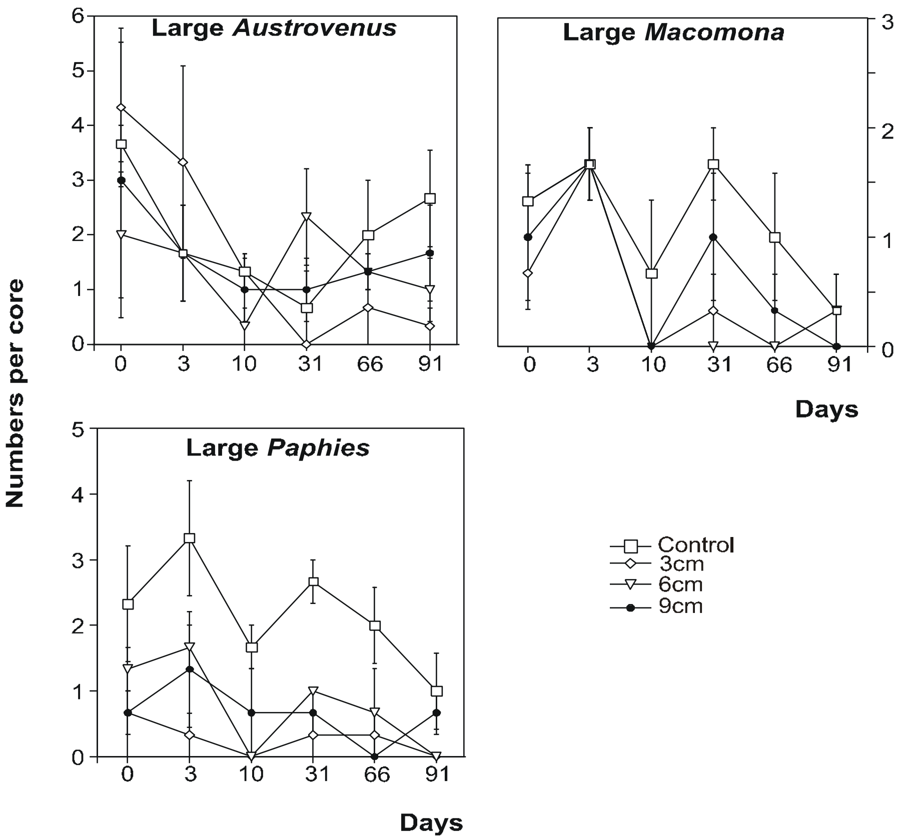


Figure 19: Changes in number of large *Austrovenus, Paphies* and *Macomona* found at Site 1 over time. Values are expressed as the mean $\pm$ standard error per core.

Thus it is clear that while surface-dwelling animals rapidly colonise the disturbed plots, it takes a long time for deeper burrowing animals to colonise and for larger, mobile animals to wish to remain in the area. We are continuing to assess recovery of the experimental plots.

DISCUSSION

Habitat mapping of the intertidal area of Okura estuary reveals a general gradation of decreasing muddiness towards the mouth of the estuary. Associated with this is arebroad-scale changes in the composition of the benthic communities. Polychaete worms and cockles (*Austrovenus stutchburyi*) dominate the muddier areas, the wedge shell (*Macomona liliana*) is more common in less muddy sediments, while pipis (*Paphies australis*) dominate the wave exposed sandy areas. Diversity tends to increase in the middle of the estuary due to the mix of species with either sand or mud preferences and the increased small-scale variability of habitats.

Information from the laboratory and field experiments allow us to answer the three questions posed in the Introduction.

What is the critical depth of sediment that kills infauna?

Sandflat dwelling organisms are very sensitive to the deposition events mimicked by our laboratory and field experiments. The dominant effect of sediment deposition is the death of all animals living in the underlying sediment due to smothering. The laboratory experiments show that, although there are some differences between taxa, large polychaetes and bivalves are unable to move up through 3 cm of terrigenous clay/silt. Bivalves did not move higher than the sand – clay/silt interface and, even when able to extend their siphons to the sediment surface, showed signs of stress after 3 days. Stress tended to increase with the depth of the clay/silt layer. Based on our laboratory and field experiment results we can define the critical burial depth as 2-3 cm. The effects of sedimentation events on benthic animals is size-dependent, e.g. depends on the size of the animal relative to the thickness of the clay-layer. The dominant bivalve species in the estuary have an average size of around 2-3cm. Larger animals should thus cope with sediment depths of 2 cm as they would not be covered. Thus, with 2 cm sediment layers we might expect a mixed response as smaller size-class bivalves and other benthic animals would still be buried. Sedimentation events producing 2 cm thick layers have been previously documented for Okura estuary (Hewitt et al. 1998).

This has important implications for short term (< 5 day) deposition events. Even if such events do not kill all the animals before the smothering sediment is removed, individuals may have been sufficiently stressed to be more prone to predation or sublethal effects. Crabs (*Helice crassa*) were the only animals used in the laboratory experiments that were able to climb to the surface through the clay/silt layer and survive via their burrowing activities. These animals aid the breakup and incorporation into the natural sediment of the smothering layer. However, through these processes, elevated crab densities in the clay/silt patches also elevate rates of predation and disturbance on other macrofauna in the plots.

How long does the terrigenous sediment layer have to sit over the natural estuarine sediments to have this effect?

In the field experiment, all of the animals died within 7 days of the start of the experiment, irrespective of whether 3, 6 or 9 cm of clay/silt smothered them. In the laboratory experiments some *Macomona* had died after 6 days in all treatment depths. The only animals to survive the experimental sediment deposits were burrowing crabs. As discussed above, these animals appear to play an important role in mixing and transporting sediments at our experimental site with low wave exposure (Site 1). The negative responses of the benthic community to the terrigeneous sediment layer would be even more rapid in higher temperatures as the metabolic rates of animals increases with temperature. However, even at lower temperatures (i.e. 11°C) the responses were unequivocal, illustrating the severe consequences of terrigeneous sediment cover to benthic animals.

How quickly do defaunated plots get recolonised and recover from this type of disturbance?

Very little has happened to the clay/silt layers at the inner estuary site (Site 1); the underlying sandflats are still smothered by the silt/clay plots and are anaerobic and azoic. At the more exposed site, the clay/silt layer was removed by a storm about 1 month after initiation of the experiment. However, complete recovery of these experimental plots had not occurred by 9th of March, 33 days after the last samples presented in this report (and approx. 120 days after the initial deposition of the silt/clay plots). While small surface dwelling animals, such as gastropods and juveniles different benthic species, move relatively quickly into the experimental plots, the large adults and deeper dwelling members of the community are very slow to reach densities equivalent to those found in adjacent control plots. Although low numbers of juvenile macrofauna were found in clay/silt layer surface samples, densities and species composition were variable from one sampling occasion to the next. There was no sequential colonisation of the clay/silt layer by animals settling into the experimental plots. Again crabs were the exception; large numbers of burrows were apparent in the surface of the clay/silt.

The answers to these questions can be combined with the habitat maps to produce maps of areas with relative risks. However, before doing this we need to consider how appropriate our results are to natural occurrences of sediment deposition and any factors affecting the duration of deposition and recovery of the communities from smothering.

The clay/silt layers deposited during the experiment have been exceedingly persistent. The field experiment involved depositing an approximate 55:45 mix of sediment and freshwater into the experimental plots during low tide. As mixing was done by a large excavator we might expect some variation in sediments from plot to plot, however, observations and geotechnical measurements of the clay/silt were very consistent.

Weather conditions over the 3-4 days following the initiation of the field experiment were sunny, warm, dry and calm. Such conditions are likely to enhance initial dewatering of the clay/silt making it less susceptible to erosion and dispersion. Subsequent experiments conducted in Whangapoua Harbour on the Coromandel as part of the PGSF research programme “Effects of Sediments in Estuaries” have also demonstrated clay/silt layers to be highly persistent. The Whangapoua experiments ensured thorough mixing of clay/silt with either fresh or seawater, changing the ratio of water to sediment, and depositing sediments at either high or low tide. This leads us to believe that our experiment in Okura reflects conditions that could arise following larger-scale natural events. Moreover, we have very consistent results from our laboratory and field experiments, even though the clay/silt deposited in the aquaria remained soft because of constant immersion.

Because, the clay/silt layer was so resistant to removal/reworking except by excessive wave action or by crabs over long time periods, our results are easily extendable from the particular area studied, to areas with similar communities though slightly different environmental regimes. Thus, the results found at Site 1 should apply over all the areas in Fig. 3 with similar communities. Similarly, results at Site 2 apply for all the exposed sandy sediments. Also, as results at the different sites, and in the laboratory experiments with different taxa, were all similar, we can extend our predictions of effects to different communities. This includes the areas in the upper muddy reaches of the estuary.

The very slow rates of mixing and redistribution of sediment from the experimental plots indicates that we need to be not only concerned with the depth of sediment deposited but also factors likely to influence its duration. The critical factors pertaining to this are weather and wave conditions on the first few days after initial deposition. Calm, hot and sunny weather is likely to extend the length of time that deposited clay/silt sediment remains where it was deposited. Furthermore, deposition in areas with short immersion times will restrict the time available for waves and currents to resuspend and transport the clay/silt. The recorded storm event clearly demonstrates the importance of waves to the persistence of sediment deposits. Measurements of wave characteristics (i.e. wave height and period, orbital flow speeds) were approximately four times larger at Site 2 compared to Site 1, illustrating the difference in physical regime.

Thus an event can have different ecological consequences depending on its timing and location, even within areas defined as “ecologically sensitive”. This is not an unusual ecological phenomenon. However this experiment reveals two critical processes, the initial deposition, deoxygenation and defaunation of the plot - followed by recovery once the smothering clay/silt layer has been removed. We are still in the process of sampling the macrobenthic recovery. But by June 1999, over 7 months after the initial deposition, recovery at Site 1 is still incomplete.

The aerial extent smothered by deposited sediment is also important and some of our previous research indicates not only that the ecological responses are likely to be related to the size of the area, but also that the relationship is unlikely to be linear (Thrush et al. 1996). The larger the area disturbed, the more difficult it becomes for large animals to recolonise the area by moving across the patch boundary. In such a situation, the settlement and growth of juvenile life-stages drives recovery within the plot, severely limiting the *rate* of recovery. Moreover as the proportion of a particular habitat disturbed increases, the availability of colonists from within the estuary is reduced. Thus we can reasonably consider our small-scale experiments to be conservative mimics of larger scale events that might occur during catchment development.

When considering the implications of our experimental results to larger scale natural events, it is important to consider how ecological systems may respond to changes on different spatial and temporal scales. Ecological systems change in response to two types of events, single episodic events (such as a major storm/landslide and deposition of sediment) and long-term gradual change (i.e. gradual infilling of an estuary with sediment). These are not independent events - in fact long-term trends are often composed of a series of episodic events. So although we have not explicitly looked at the long-term consequences of elevated rates of sedimentation, it is important to keep in mind the long-term consequences of a number of episodic events.

CONCLUSIONS

We have advanced our understanding of sediment effects and identified critical depths and conditions that are likely to produce significant ecological effects. So, from our studies we are able to define different habitats in Okura estuary such as areas of high biodiversity and areas with beds of suspension feeding bivalves. Clay/silt sediments deposited at depths greater than 2-3 cm, remaining for more than 7 days, represent a significant ecological threat to the estuary, especially given that any event driven by catchment development is likely to deposit sediments over large areas, ie. on the 100's m^2 scale.

Finally, these experiments have enabled us to make predictions about short-term ecological effects. However, these are only predictions and it is very important that monitoring tests the predictions of effects and risks so that their broad-scale relevance can be assessed. It is important to bear in mind that the short-term effects may not be the full story; long-term, sublethal and lethal effects may also occur.

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