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Macrofaunal Sensitivity to Fine Sediments in the Whitford Embayment

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Macrofaunal Sensitivity to Fine Sediments in the Whitford Embayment

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Contents

1 Executive Summary

This report provides new information on the sensitivity of benthic invertebrates to fine sediments (silt/clay) by: (1) using information on the distribution of species and communities in relation to sediment characteristics in Whitford embayment as a proxy for their sensitivity, and (2) describing results from short-term laboratory experiments on macrofaunal responses to thin depositions of terrigenous clays.

By sampling a wide range of habitats we were able to clearly partition the macrobenthic communities on the basis of broad-scale habitat characteristics. Some taxa showed clear declines in abundance and/or dramatic threshold responses to increasing levels of silt/clay, whereas other exhibited wider distributions and more gradual declines in abundance. Importantly, only a few taxa favored sediments containing high silt/clay.

Thin terrigenous clay layers (0.5, 1.0 and 1.5 cm) failed to elicit a clear response from common macrofauna in the laboratory experiments. With exception of the polychaete, *Aonides oxycephala*, all test animals were able to move into the thin clay layers and they did so in increasing numbers as the thickness of the clay layer increased. For all test animals, migration in and out of the clay layer varied with the duration of the experiment. Generally, a high percentage of the buried animals remained in the clay in the deepest treatments over the entire experiment.

The emerging pattern for these laboratory experiments is one of weak and inconsistent responses to short-term exposure to thin clay layers. While these results partly reinforce the concept proposed in previous study in Okura Estuary that clay layers less than 2 cm thick will have minimal effects in the short-term, they also highlight the potential negative effects of exposure to thin depositions of clay over longer time periods. This emphasises the importance of integrating short-term laboratory studies and field experiments with surveys which reflect community responses over broader time scales.

The species sensitivity curves and community-sediment affinities derived in this study can help predict the implications of change in the Whitford embayment on longer-term macrofaunal distributions. The species sensitivity information can be integrated with catchment and hydrodynamic modelling to assess the risks to the estuary of changes in land use.

₂ Introduction

Estuarine environments are rich in both structural and biological diversity and play an important role in the functioning of coastal ecosystems (Heip et al., 1995). Although these environments are characterised by large fluctuations in the quantity and quality of suspended sediment in their waters (Navarro & Widdows, 1997), changes in land-use and modification of coastlines due to human development have increased rates of sedimentation and changed the areal extent of depositional environments in estuaries (Edgar & Barrett, 2000).

The Auckland Region is a rapidly expanding area with a current population of 1.1 million, which is projected to reach two million by the year 2050. To accomodate this expanding population, the Auckland region is undergoing continual urban and semi-rural development and expansion of the infrastructure which is necessary to support this development. Urban development usually results in higher than normal amounts of storm-water contamination by sediment, which eventually ends up in the region's rivers, estuaries and coastal ecosystems. There is growing recognition that sediment loading or deposition pose a threat to the biodiversity of estuaries and coastal areas (Gray, 1997). Episodic events such as landslides, extreme rain events and flooding can result in catastrophic deposition of sediments and elevated suspended sediment concentrations, which may have a profound influence on the structure and function of macrobenthic communities (Ellis et al., 2000a).

The ARC is determining the risk that the urban development process poses to the receiving environment of the Whitford Embayment in a series of studies.

Catchment modelling will determine the potential for sediment entry into the three estuaries entering the embayment.

Hydrodynamic modelling will investigate dispersal within and through the system, concentrating on potential areas for increases in sediment deposition and suspended sediment concentrations.

Studies of mangrove and salt marsh communities of the estuaries and fringing environment of the larger embayment will determine their sensitivity to increased deposition and their effect on sediment depositional patterns.

Laboratory and field experiments will determine macrofaunal species, communities and habitats sensitive to sediment deposition.

Laboratory and field experiments will determine the potential for sublethal effects of increased suspended sediment concentrations on the macrofauna.

The objectives of this study were to:

- derive species sensitivity curves from environmental and species/community data;

- corroborate and extend sensitivity evaluation with laboratory experiments on key species.

2.1   Study rationale

In previous studies conducted for the ARC on the Okura estuary, Norkko et al. (1999) and Nicholls et al. (2000) measured the responses of a variety of benthic macrofauna to burial by different depths of terrigenous clay. The animals studied were common to sandy and muddy habitats within the Okura estuary. In the laboratory, deposition events that resulted in clay layers of 3, 6 and 9 cm depth were mimicked and the ability of the selected taxa to surface through these layers and/or survive short term burial was observed. Results suggested that mobility and the size of the animal relative to the thickness of the clay-layer were important indicators of how an animal might cope with a sedimentation event. For example, highly mobile species such as shrimp, *Alpheus* sp., and the crab, *Helice crassa*, fared better than small and/or slow-moving molluscs (Norkko et al. 1999, Nicholls et al. 2000). Based on the laboratory experiments and complementary field experiments, Norkko et al. (1999) identified a critical burial depth of 2-3 cm, although the impact of this depth was found to vary according to the animal's size and mobility. Nicholls et al. (2000) illustrated this by showing that a small bivalve and a slow-moving gastropod were both affected by clay less than 2 cm thick but that the impact was greater with layers close to 2 cm. In the Okura study, these mechanistic findings were complemented by broad-scale habitat mapping which identified negative (albeit non-linear) changes in the diversity of benthic macrofaunal communities along a gradient of increasing proportion of fine sediments. This research demonstrated that accelerated deposition of land-derived sediment results in physically smothering of the habitat and deoxygenation of the underlying sediments resulting in changes to the abundance and distribution of benthic organisms within the estuary.

These field and laboratory findings are based on experimental studies that track biological responses following a single catastrophic disturbance event. They provide a powerful insight into the ecological consequences of catastrophic sedimentation. However, they are limited in the temporal scale of ecological responses they encompass and in the range of disturbance events they mimic. Therefore it is important to integrate these experiments that reveal cause-effect relationships with other broader-scale studies that may provide useful information on the consequences of chronic and long-term accretion of fine sediments within the estuarine environment.

Typically quantities and rates of sediment deposition and suspended sediment concentration to some extent co-vary with the natural gradients in sediment grain-size. Thus one approach is to determine the broad-scale range of sensitivity of individual species (and community parameters) to current broad-scale natural gradients in sediment grain-size.

The information provided on species sensitivity in this report stems from the *"Whitford habitat survey"* which was designed to provide a comprehensive overview of the different habitats and associated macrofaunal communities within the embayment (NIWA report to Manukau City Council [MCC] due for completion in 2002). The habitat survey involved extensive intertidal and subtidal sampling which resulted in a spatial mapping of species distributions in the area, and allowed us to assess the distribution of key macrofaunal species and taxa in relation to important environmental variables.

The information on species distributions was also used to select species for laboratory experiments. These laboratory experiments allowed us to extend information gained from Okura studies by determining sensitivities of species important in Whitford and by validating the robustness of previous predictions on critical clay depths, and by assessing whether species respond the same way at different locations (e.g. Okura vs. Whitford).

Hence the approach of this report is two-fold: (1) to use the information on the distribution of species and communities in relation to sediment characteristics as a proxy for their sensitivity to fine sediments, and (2) to corroborate and extend the findings from the Okura laboratory experiments on short-term behavioural responses to depositions of terrestrial clays and silts. By providing information on species sensitivity to fine terrestrial and marine sediments (silts/clays), the results in this report will provide a better understanding of the effects of the broad-scale and long-term consequences of habitat change to the distribution of macrofaunal species and communities. Once predicted changes in the rates and patterns of erosion and sedimentation within the estuary become available from the catchment and hydrodynamic modelling, this information will aid in predicting how benthic macrofaunal communities could change in the Whitford embayment in response to changes in habitats dominated by sandy sediments to habitats dominated by fine clays and silts.
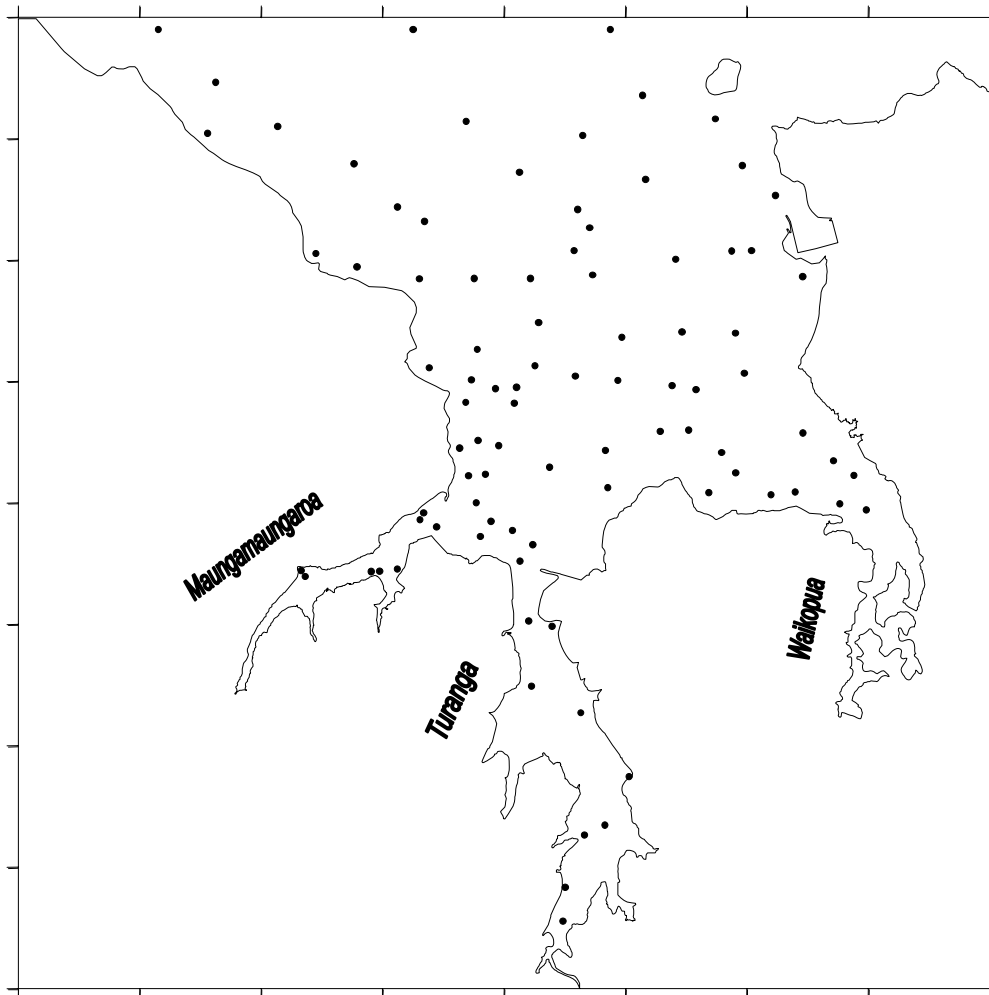
₃ Methods

3.1 Field survey on species distributions in relation to environmental variables

This report makes use of data obtained from the Whitford embayment habitat survey. The full details regarding the methods and results from the survey will be given in the report to MCC. Briefly, a total of 90 different sites throughout the estuary were sampled for benthic macrofauna and associated sediment characteristics (Figure 1). These sites were positioned in the subtidal zone in the main embayment, the outer intertidal sandflats, the main outer channels, the inner estuary intertidal mudflats (*Maungamaungaroa*, *Turanga* and *Waikopua*) and, the inner estuary subtidal channels. The survey thus covered all the major marine habitat types within the embayment, except for fringing vegetation (see Craggs et al. 2001).

From each site three macrofaunal cores (15 cm diam. x 13 cm deep) were taken, spaced 5 m apart. Smaller core samples (2 cm diam., 2 cm deep) near each macrofauna core were analysed for sediment chlorophyll *a*, sediment particle size, and organic matter. The macrofauna samples were sieved on a 0.5 mm mesh, preserved in 70% Isopropyl alcohol (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 for particle size analysis were pre-treated by digesting sediments in 6% hydrogen peroxide for 48 h to remove organic matter, and dispersed using Calgon. Subsequenty, % volumes for sediment fractions (gravel, coarse, medium and fine sand, silt and clay) were determined by wet-sieving (particle size > 63 μm) and by using a Galai particle analyser (Galai Cis - 100; Galai Productions Ltd., Midgal Haemek, Israel) for particle sizes < 63 μm. Organic content of the sediment was measured as loss on ignition (LOI) in 12 h at 440 °C, after drying the samples at 40 °C for 6 h.

Figure 1. The distribution of all 90 sampling sites for benthic macrofauna andassociated sediment characteristics in the Whitford embayment. Map scale on 1 km grid.

3.2 Analytical procedures for determining species sensitivity

3.2.1 Multivariate analysis

The variability in macrofaunal community structure in relation to the changing sediment characteristics was examined using multivariate analyses. To identify relationships between the community structure and the environmental variables, data were analyzed using canonical correspondence analysis (CCA) and partial canonical correspondence analysis (PCCA) using CANOCO (Ter Braak, 1986, 1987). Environmental variables included sediment grain size (% <63 μm, 63 μm, 125 μm, 500 μm, 2 mm), sediment organic content, sediment chlorophyll *a* content, and geographical position (latitude and longitude). The ordination produces a plot where samples with similar communities are plotted close together in the ordination space in relation to key environmental variables. From these ordinations we are able to

determine the relationships between different habitat types (containing similar macrofaunal assemblages) and between groups of species with preferences for particular sites/habitats. Species habitat preferences were corroborated by a second multivariate technique. We used a classification procedure based on Bray-Curtis similarities calculated from raw data with a similarity of percentages procedure (SIMPER; Warwick et al. 1990) to identify which species were important in determining groupings within the classification. Thus we could ordinate sites based on macrobenthic community composition and also determine species-habitat affinity.

3.2.2 Univariate analysis – sensitivity curves

We derived species sensitivity relationships by relating species abundance patterns to gradients of increasing silt/clay content of the sediment. One method of formally assessing the distribution and ranking of species in terms of their sensitivity is to calculate the magnitude and direction (e.g. positive or negative relationships) of faunal abundance in relation to spatial gradients in environmental variables (Ellis et al. 2000b). This kind of analysis requires that the majority of species exhibit similar statistical distributions in order to be useful for comparing sensitivities and rankings. However, many species occurred in low numbers and exhibited skewed distributions indicating strong threshold responses, while other species occurred in high abundances and exhibited more wide tolerance to sediment type. Although a total of 90 sites were sampled, the sites were not positioned to cover each habitat in equal proportion. We therefore proceeded by categorizing the data so that we could average species abundances over categories of five percent intervals (e.g. 0-5%, 5-10% etc). A total of 163 taxa were recorded; however, the great majority of these were patchy in their distribution and only occurred in low abundances. To provide the best available assessment we thus selected a total of 38 dominant species/taxa for the sensitivity analysis. The criterion for selecting species was that they occur at least 5 sites and with an average of at least 2 individuals per core at one of the sites. These taxa were then plotted by category to visually determine the optimum sensitivity response curve. The data was plotted using either linear regression or non-linear exponential functions (single, 3 parameter function for exponential growth or decay). Data was only plotted if either one of these functions produced a reasonable fit.

3.3 The laboratory experiments

3.3.1 Taxa used in the experiments

The taxa used in these experiments are common in the mid to lower reaches of Whitford embayment, and are expected to have varying degrees of tolerance to the deposition of clay/silt.

Two species of bivalves were used; the cockle, *Austrovenus stutchburyi*, which is a suspension-feeder that inhabits surface sediments throughout the intertidal zone, and *Nucula hartvigiana*, a deposit-feeder that inhabits surface sediments from the mid to

low water zone. Bivalves are often able to tolerate sediment deposition by either moving to the surface of the new sediment layer or by switching, for a brief period of time, to anaerobic respiration, although this second strategy is energetically expensive and may increase susceptibility to predation or disease. Previous experiments have suggested that the effect of deposition on bivalves is related to the depth of clay/silt deposited compared to the size of the animals (Norkko et al. 1999, Nicholls et al. 2000).

The other taxa used in the current study were the deposit-feeding sand dollar, *Fellaster zelandiae*, the deposit-feeding polychaete worms, *Aonides oxycephala*, species belonging to the Orbinid family (both *Orbinia papillosa* and *Scoloplos cylindifer*), oligochaete worms, as well as the total number of worms and worm taxa naturally residing in the sediment. *Fellaster* is common in the lowest reaches of the intertidal zone, living on, or just under, the surface of the sand. It is highly mobile and should therefore cope well with burial. The tube-dwelling *Aonides* is considered to prefer sandy sediments and may be more susceptible to burial by terrigenous sediments than others. Orbinids are burrowing, mobile deposit feeders, which might be fairly tolerant of sediment deposition. Oligochaetes are often found in muddy sediments and previous experiments have suggested that they may be resilient to deposition (Nicholls et al. 2000).

3.3.2 Depth of added sediment

Four depths of terrigenous clay were used in these experiments for all taxa – 0 (control), 0.5, 1 and 1.5 cm. These depths represent a range below the critical depth of 2-3 cm, identified by Norkko et al. (1999), and are similar to those used by Nicholls et al. (2000). For *Fellaster*, an extra treatment with a clay layer that was 6 cm deep was included. This depth was used by Norkko et al. (1999) and Nicholls et al. (2000) and represents a mid-point between the largest depth used in the Okura estuary experiments (9 cm) and a depth corresponding to the size of the largest bivalves observed in that estuary (3 cm). It also corresponds to the size of *Fellaster*, which are approximately 6 cm in diameter.

3.3.3 Experimental design and running the experiments

Animals and sediment were collected from Whitford embayment and transported back to the laboratory within 3 hours of collection. Only individuals in good condition were used. All experiments were conducted in a controlled temperature room at 18 °C with a 9:15 light:dark period.

For most experiments, sediments were sieved (2 mm mesh size) to remove large macrofauna and placed in small cores (15 cm diam., 11.5 cm height for *Fellaster* and 8 cm diam., 20 cm height for others). For the experiments on polychaete and oligochaete worms, the cores were filled in the field with a plug of natural muddy sediment that contained resident worms. All experimental cores were placed into large baths of carbon-filtered seawater that were continually aerated. For the experiments on bivalves and *Fellaster*, animals were placed on the sediment surface

(two *Austrovenus*, ten *Nucula* and one *Fellaster* per core) and allowed to acclimate for 24 hours. In every experiment, all animals burrowed into the sediment within this time period.

A clay slurry was made up with clay collected from earthworks at the Sandstone landfill site and carbon-filtered seawater (1 part clay to two parts seawater) and buffered with NaOH to pH 7.2 (Berkenbush et al. 2001). The slurry was added to the individual cores to achieve layers of 0.5, 1.0 and 1.5 and, in the case of *Fellaster,* 6 cm. No clay was added to the control cores. For *Austrovenus*, *Nucula* and worms, five replicate cores of each depth were sampled after one, three and six days. For *Fellaster*, we sampled three replicate cores of each depth at each time.

On each sampling time, the position of each animal in the core, whether it was alive or dead and any evidence of burrowing or movement was recorded. *Austrovenus*, *Nucula* and *Fellaster* individuals were also tested for stress. These animals were taken from each core and placed directly on to fresh, sieved sediment (2 mm mesh size) in carbon-filtered seawater. The number of animals that had reburied was recorded every ten minutes for two hours. Rate of reburial is a standard measure of condition because burying is a natural response for most infaunal taxa to escape predators (Norkko and Bonsdorff, 1996).

3.3.4 Statistical methods

Data were examined prior to analysis using boxplots. To meet the assumptions of analysis of variance (ANOVA), percentage data were arcsine square-root transformed and count data $\log_{10}(x+1)$ transformed (Zar 1996). Comparison of parameters (% of animals buried in the clay layer for all taxa, % of animals reburied after two hours for *Austrovenus*, *Nucula* and *Fellaster,* total number of worms and worm taxa, and number of *Aonides*, orbinids and oligochaetes) were made using two fixed factor (treatment and sampling time) ANOVAs. If a significant effect ($p<0.05$) was detected, a Tukey's HSD test was performed to determine where differences lay. Rates of reburial were examined graphically.

In all the bar graphs in this report the "error bars" are standard errors. These are defined (see e.g., Zar 1996) as the standard deviation of the reported quantity divided by the square root of the number of replicated samples. They give us a measure of the precision of our estimated quantities. It is important to note that they do NOT depict the variability in the data collected. For example, in Figure 7 the height of the gray bar for *Austrovenus* (about 80%) is the average proportion of individuals emerging into the clay over the five replicated samples. The standard error, as shown, is about ± 20%. This means that the standard deviation (not shown on the graph) is about ± 22% (i.e., 20√5). Were we to have used say 10 replicates we could expect the standard deviation to be about the same (i.e., around 45% - sample standard deviations are technically "unbiased" estimators of their true values), but the standard error would then be about ± 14% (being 45/√10).

4 Results

4.1 Ordination of macrobenthic communities demonstrate distinct macrobenthic communities associated with habitats containing high silt/clay content of the sediment

Sediments containing high silt and clay content (i.e. around 30% with a grain size < 63 µm) generally occur in areas experiencing low levels of physical forcing by tidal currents and waves. Such depositional environments are typically found in the intertidal margins of the upper reaches of estuaries, and in the deeper subtidal areas at the mouth of estuaries (Figure 2). In contrast, the main intertidal flats are characterised by sandy sediments reflecting their exposure to wind-wave disturbance and are hence low in silt/clay content (Figure 2). We predicted that these distinct sediment types found in the estuary would support contrasting faunal communities. Identifying such communities is useful as it (a) allows us to make predictions on possible trajectories of communities subject to increasing sedimentation and, (b) helps us identify how individual species/taxa respond to such changes, as indicated by their sensitivity curves.

4.1.1 Ordination of benthic communities

The first four axes of the initial unconstrained correspondence analysis accounted for 76% of the total variation in macrofaunal community composition at the different sites. Figure 3a indicates the position of the 90 sites on the first two axes. Based on species composition, CCA grouped sites as a function of sediment type and quality. Based on these site groupings, we derived six different habitat categories: Estuary intertidal, Estuary subtidal, Embayment intertidal, Embayment channel, Embayment shallow (< 3m) and Embayment deep (>3m). Intertidal sites in *Turanga*, *Waikopua* and *Maungamaungaroa* estuaries ("Estuary intertidal") grouped as more similar to each other than sandy intertidal sites in the "Whitford Embayment". Although showing overlap the subtidal sites in the main Whitford embayment, e.g "Embayment shallow" and "Embayment deep", were also separated in the ordination space relative to "Estuary subtidal" (i.e. the subtidal of the inner estuaries) and the "Embayment channel" sites (i.e. the channels leading out from the estuaries to the embayment; Figure 3a). Hence all these habitat categories supported distinctly different macrofaunal assemblages. Partial canonical correspondence analysis suggests that this variability was statistically significantly (correlation=0.8882, F-ratio=6.778, p=0.0050) related to sediment characteristics described by grain size (clay&silt, fine sand, medium sand, coarse sand and gravel), the organic content, and the Chlorophyll *a* content of the sediment (Figure 3b). For example, the estuary intertidal sites are associated with high silt/clay, i.e. compare Figure 3 a & b.

Figure 2. The spatial distribution of fine silt/clay sediments (< 63µm) in the Whitford embayment.
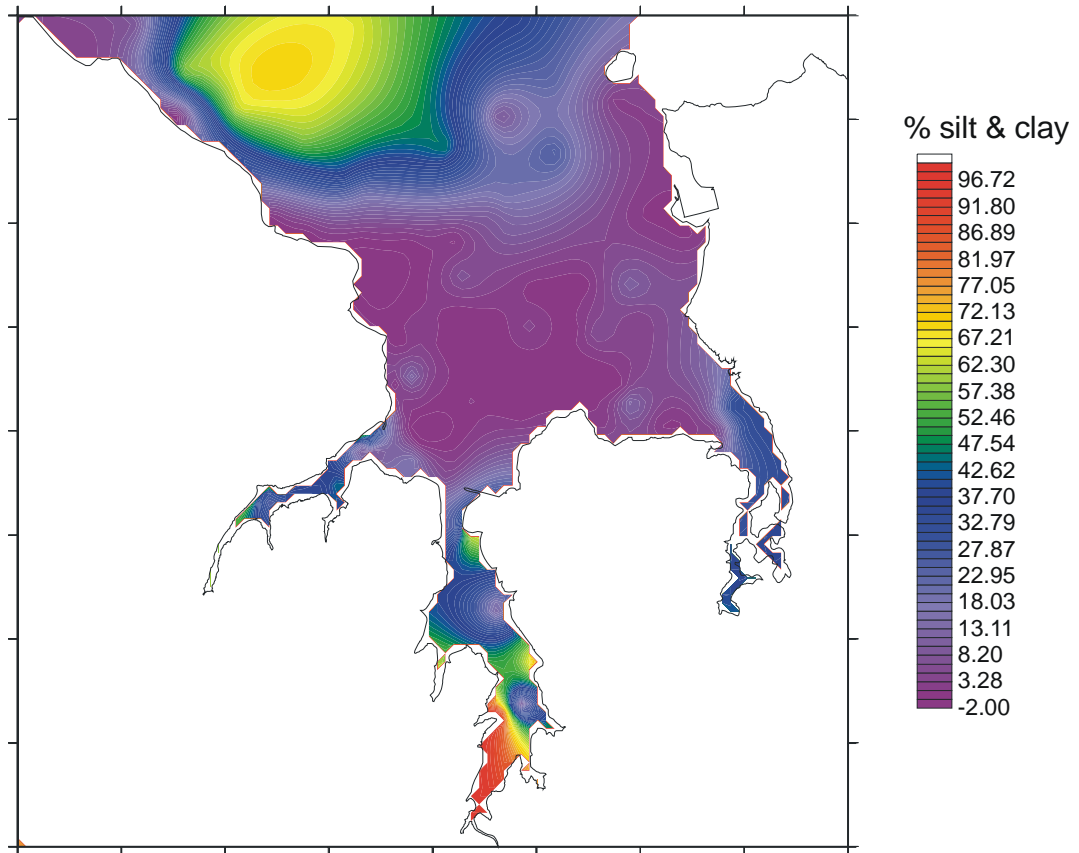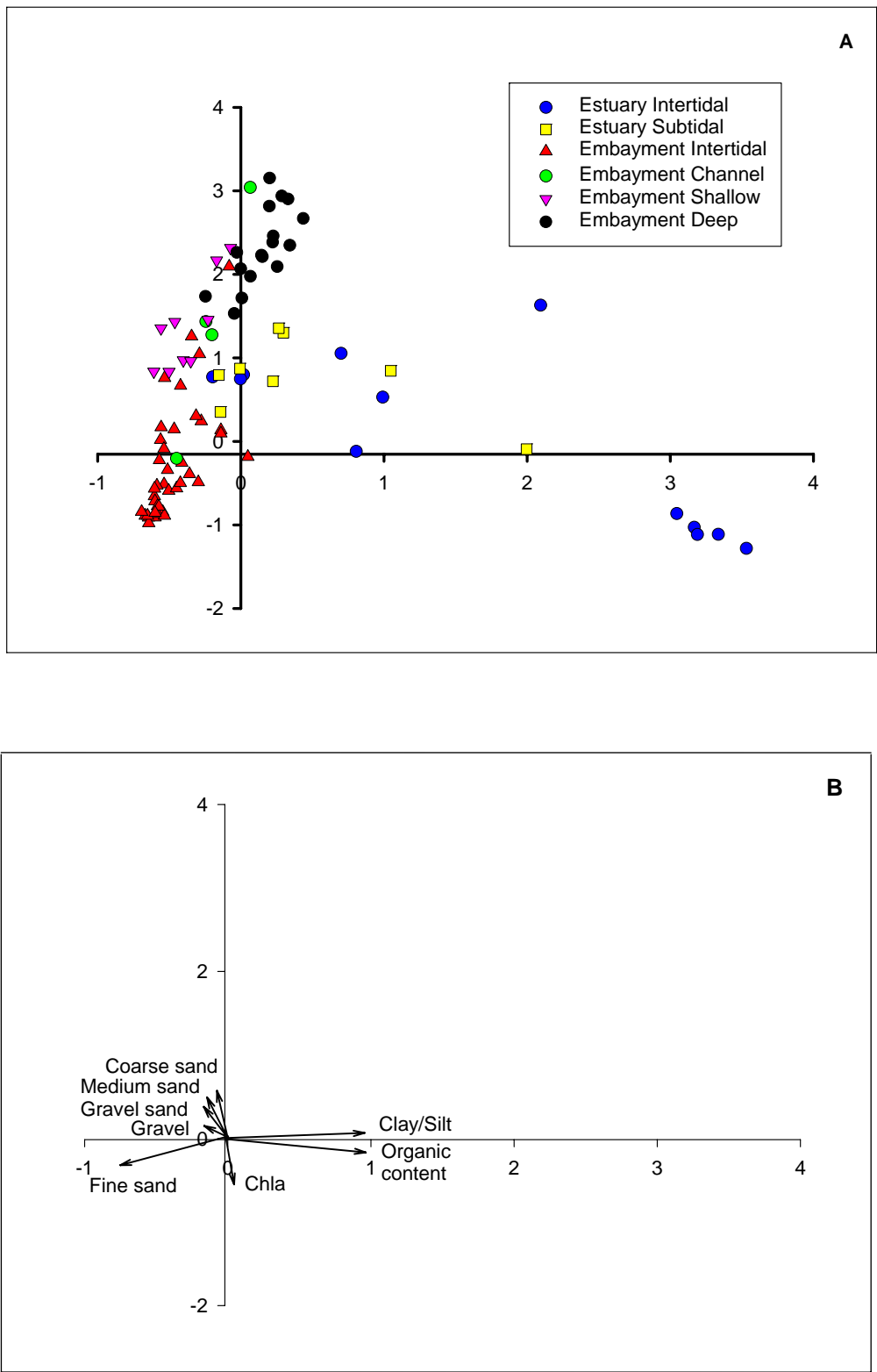
Figure 3. CCA ordination plots of (A) the macrofauna community data at the different sites and habitat categories, (B) the sediment variables. The direction and length of the arrows indicate the strength of the relationship, i.e. on the x-axis clay/silt and organic content are strongly associated with "Estuary intertidal" sites.

The different habitat types exhibited distinctly different environmental characteristics and macrofaunal communities (Table 1). The differences between these habitat categories are particularly clear when examining the distribution of fine clays and silts. On average the mudflats of the "Estuary intertidal" had the highest clay/silt content (>64%) whereas the sandflats of the "Embayment intertidal" had the lowest (2.5%). High clay/silt contents were also found in the "Estuary subtidal" and the deeper parts of the embayment, i.e. "Embayment deep". The coarsest sediment were found in the high flow environments in the "Embayment channel" and the "Embayment intertidal" (Table 1).

Table 1: Sediment characteristics, depth and the average number of taxa and individuals associated with the main marine habitat types identified in the Whitford embayment and sub-estuaries. Number of taxa and number of individuals are mean values per core. Dissimilarity = average Bray-Curtis dissimilarity in macrobenthic community composition between habitats. Sediment grain sizes and LOI (loss on ignition of the sediment) are expressed as percentages. Benthic chlorophyll a is expressed as mg g-1 sediment. Data are presented as the mean ± standard error (in brackets).

	Estuary Intertidal (n=12)	Estuary subtidal (n=8)	Embayment intertidal (n=40)	Embayment channell (n=4)	Embayment shallow (n=9)	Embayment deep (n=17)
Clay & silt	64.1 (7.8)	15.5 (3.9)	2.5 (0.5)	8.4 (2.1)	3.8 (1.3)	33.3 (5.0)
Medium & fine sand	35.3 (7.8)	70.4 (5.6)	93.2 (1.4)	72.7 (13.2)	93.7 (1.9)	65.3 (5.3)
Coarse sand & gravel	0.2 (0.1)	14.1 (7.5)	4.2 (1.4)	18.9 (11.6)	2.4 (1.8)	1.4 (0.6)
Chlorophyll *a*	10.8 (0.5)	8.1 (1.4)	7.9 (0.6)	3.9 (1.0)	7.7 (1.0)	5.3 (0.4)
LOI	5.8 (0.9)	2.2 (0.2)	1.0 (0.1))	1.3 (0.1)	0.7 (0.1)	2.4 (0.2)
Depth (m)		2.1 (0.4)		3.0 (0.6)	1.7 (0.2)	4.7 (0.2)
Number of taxa	11.2 (1.7)	11.6 (0.9)	18.1 (1.0)	25.3 (2.3)	11.0 (2.0)	12.7 (0.6)
Number of individuals	50.0 (8.6)	32.2 (11.6)	60.5 (8.2)	80.8 (21.6)	21.8 (5.7)	14.9 (2.6)
Dissimilarity (%) between sites						
Estuary Intertidal	0	82.9	82.8	77.4	90.9	91.1
Estuary subtidal		0	74.6	73.8	79.6	83.3
Embayment intertidal			0	80.7	82.8	90.4
Embayment channel				0	81.3	77.9
Embayment shallow					0	79.3
Embayment deep						0

These clear differences in clay/silt content between habitat types are matched by the distribution of organic matter in the sediment (Table 1). Also the average number of taxa and number of individuals differed between habitats. Although variable, the "Embayment channel" contained the highest numbers of taxa and individuals and the "Embayment shallow" and "Embayment deep" the lowest. It is interesting to note

that the shallow (< 3 m) subtidal waters surrounding the main intertidal sandflats contrasted markedly in macrobenthic community composition from both the "Embayment intertidal" and the "Embayment deep" despite having very similar physical characteristics to the intertidal areas (Table 1). This shallow subtidal is an area likely to experience prolonged exposure to elevated suspended sediments and wind wave disturbance. In fact the differences in macrobenthic community composition were very large between all habitat types as indicated by the average dissimilarity between habitats (Table 1). Average dissimilarity in community composition between habitat types was high, ranging from around 74 to 91 percent (Table 1).

SIMPER analysis reveal the importance of different taxa in accounting for variability in macrobenthic community composition in the different habitat types. In the "Estuary intertidal" habitat the five top-ranked taxa explained over 73% of all the variability within the habitat (Table 2). This high explanatory power of only 5 taxa demonstrates low macrobenthic diversity of these mud-enriched habitats. The amphipod *Paracorophium excavatum* and the mud crab *Helice crassa* together explained nearly 50% of this variability, and the spionid polychaete *Aquilaspio aucklandica*, nereid polychaetes and the capitellid polychaete *Heteromastus filiformis* accounted for another 23% (Table 2). Some taxa are obviously widespread throughout different habitat types and, for example, *Aquilaspio*, is also a dominant in the "Estuary subtidal" as well as "Embayment intertidal" sandflats. These sandflats respectively are dominated by the wedge shell *Macomona liliana*, *Aquilaspio*, the cockle *Austrovenus stutchburyi,* the nut shell *Nucula hartvigiana* and the crustacean *Colurostylis lemurum* (Table 2). The lower explanatory power of the five most dominant taxa (48%) demonstrate the comparatively high macrobenthic diversity of these sandflats as many other species/taxa are needed to more accurately explain within site variability. Even taking into account the 10 most dominant taxa, only 69% of this variability was explained. The intertidal sandflats of the "Embayment intertidal" and the mudflats of the "Estuary intertidal" serve as two contrasting end-points in a likely range of macrobenthic communities from sediments dominated by sands to sediments dominated by silt and clay (Figures 4 & 5).

Figure 4. Mudflat in the Waikopua estuary.

Figure 5. Typical intertidal sandflat in the Whitford embayment.

Table 2. Rankings of the five most dominant macrofaunal taxa in each habitat category. Percent explained = percentage of community variability explained by each individual taxa. Cumulative percentage explained = cumulative percentage of macrobenthic community variability explained by taxa.
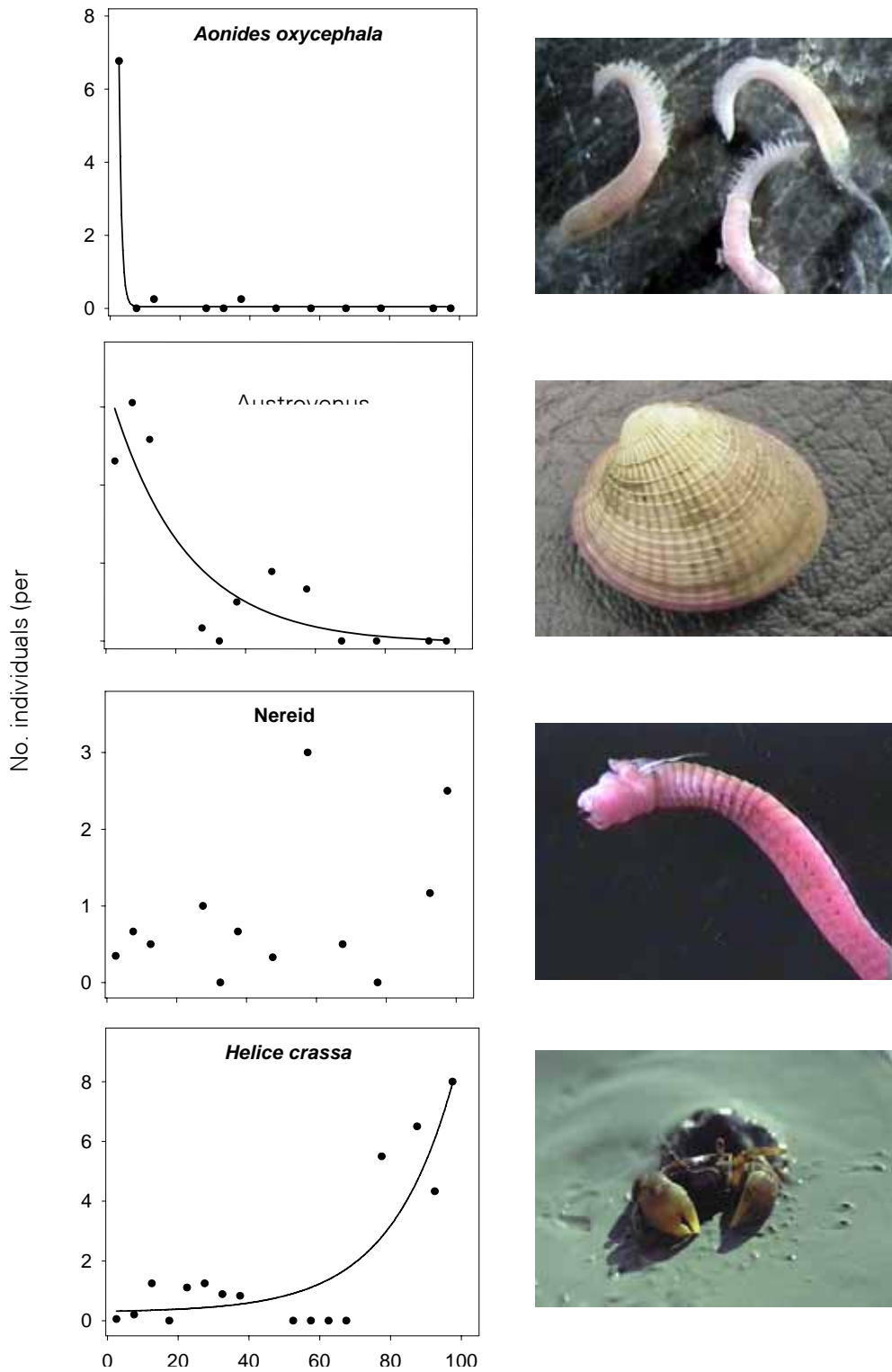
Habitat & dominant Taxa	Faunal group	Percent explained	Cumulative percentage explained
Estuary intertidal			
Paracorophium excavatum	Amphipod	26.5	26.5
Helice crassa	Crab	22.3	48.8
Aquilaspio aucklandica	Polychaete	12.0	60.8
Nereid	Polychaete	6.8	67.6
Heteromastus filiformis.	Polychaete	5.6	73.2
Estuary subtidal			
Capitellid	Polychaete	21.6	21.6
Oligochaeta	Oligochaete	13.2	34.8
Aquilaspio aucklandica	Polychaete	10.8	45.6
Helice crassa	Crab	8.6	54.2
Cossura sp.	Polychaete	8.1	62.3
Embayment intertidal			
Macomona liliana	Bivalve	13.0	13.0
Aquilaspio aucklandica	Polychaete	10.6	23.6
Austrovenus stutchburyi	Bivalve	9.5	33.1
Nucula hartvigiana	Bivalve	9.3	42.4
Colurostylis lemurum	Cumacean	6.0	48.4
Embayment channel			
Nucula hartvigiana	Bivalve	13.3	13.3
Heteromastus filiformis	Polychaete	11.7	25.0
Glycerid	Polychaete	10.3	35.3
Boccardia syrtis	Polychaete	10.0	45.3
Oligochaeta	Oligochaete	8.4	53.7
Embayment shallow			
Waipirophoxus waipiro	Amphipod	41.0	41.0
Aricidea sp.	Polychaete	11.4	52.4
Tanaid	Crustacean	9.6	62.0
Exogonid	Polychaete	9.1	71.1
Cossura sp.	Polychaete	4.2	75.3
Embayment deep			
Theora lubrica	Bivalve	20.0	20,0
Cossura sp.	Polychaete	13.4	33.4
Lumbrinereid	Polychaete	12.8	46.2
Waipirophoxus waipiro	Amphipod	10.7	56.9
Sigalionidae	Polychaete	9.2	66.1

4.2 Species sensitivity and the relationship between species abundance and silt/clay content of the sediment

Amongst the 38 taxa selected for sensitivity assessments, we found large variability in the distribution patterns in relation to the silt/clay content of the sediment. As already shown in the CCA ordination and the SIMPER analysis, some taxa showed high affinity for specific sediment types whereas others were widely distributed and occurred over a broad range of sediment characteristics. As already mentioned, this makes it difficult to find a single explanatory statistical function that could be fitted to the species data to describe individual species sensitivity across all taxa. Figure 6 gives an example of varying degrees of sensitivity of four key taxa to increasing silt/clay content of the sediment. For example, the polychaete *Aonides oxycephala*, has a very strong affinity to sediments low in silt/clay, exhibits a threshold response, and is clearly highly sensitive to increasing silt/clay (Figure 6). Other taxa such as the cockle *Austrovenus* and the mud crab *Helice* have wider distributions and exhibit more gradual negative or positive responses to increasing silt/clay content of the sediments. Despite having broad distribution ranges, they might still have a narrow optimum range were densities are high. For example, low abundances of cockles were found in sediments containing up to 60% silt/clay in the sediment but their highest abundances were found in sediments containing less than 10% silt/clay. Similarly, the mud crab *Helice* is found in different sediment types but occur in highest numbers in sediments containing high silt clay (e.g. > 90%; Figure 6). In contrast some taxa, such as nereid polychaetes, have very broad distribution ranges. To create sensitivity curves or make predictions on such taxa is very difficult as their distribution is variable and not easily modeled statistically (Figure 6). We plotted all 38 taxa and fitted curves where possible (i.e. similar to Figure 6). These are included as appendices 1-5.

From these plots we created an overall compilation of species sensitivity based on their peak abundance, and their range of distribution across different sediment types (Table 3). Based on their distribution we ranked the taxa as (a) highly sensitive taxa, *SS*, which exhibit a narrow distribution, (b) sensitive taxa, *S*, which exhibit a more wide distribution but still a negative response, (c) intermediate taxa, *I*, which exhibit a broad distribution occurring across all sediment types, (d) taxa tending to increase in abundance in sediments with high silt/clay content, *P*, and, (e) taxa that clearly benefit and increase in abundance with high silt/clay content, *PP* (Table 3). Of all the 38 taxa assessed, 26 were found to be highly or slightly sensitive, 5 were found to be intermediate and 7 were found to be, slightly or strongly, positively affected by increasing silt/clay content of the sediment. Sensitive species are generally those found on exposed intertidal sandflats and the positively affected ones are commonly found on intertidal mudflats or muddy subtidal environments. This emphasises the appropriateness of decisions to focus earlier benthic ecological studies in Okura estuary on the sandflat habitats.

Figure 6. Examples of typical distribution patterns of invertebrates to increasing silt/clay content of the sediment ranging from strong negative effects to strong positive effects.

A common characteristic for the highly tolerant taxa is their comparatively high mobility. Hence, the taxa cover a range of different faunal groups exhibiting different life-history characteristics in terms of their mobility, size and feeding strategy. It is interesting to note that the functionally important group - suspension-feeding bivalves, generally are sensitive. Six out of the seven bivalves were found to be sensitive to fine sediments. The two most tolerant species, *Musculista senhousia* and *Theora lubrica* are both subtidally occurring invasive species in New Zealand waters. A general characteristic for many invasive species is their tolerance to a wide range of environmental conditions.

Table 3. Sensitivity of macrobenthic taxa to increasing silt/clay content of the sediment using density gradients. Optimum range = the percent silt/clay were taxa exhibit their highest abundances. Distrib. range = total range of occurrence over different silt/clay concentrations. Curve fit = r2 and p-values for non-linear (exp) or linear (linear) curve fits. Na = not applicable. SS = highly sensitive; S = sensitive, I = no response; P = slightly positive response; PP = highly positive response.

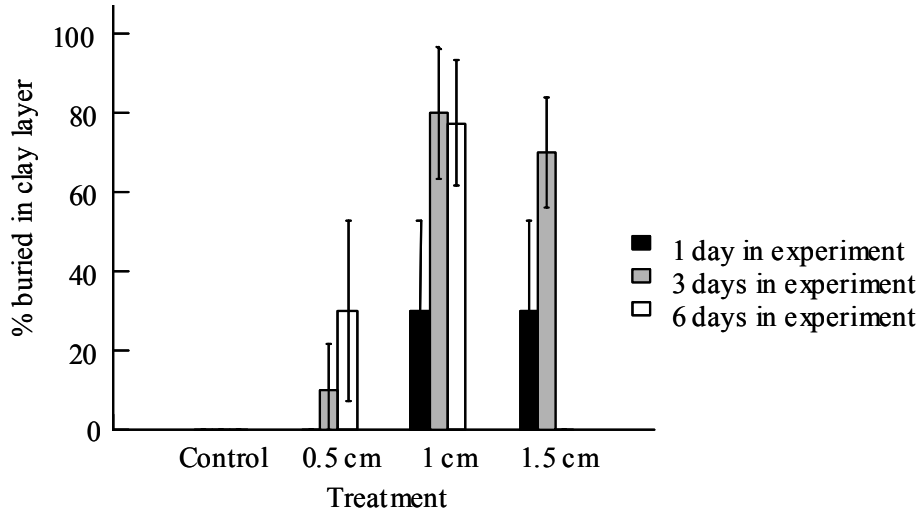| Taxa	Faunal group	Optimum range (%)	Distrib range (%)	Curve fit	Sensitivity
Aonides oxycephala	Polychaete	0 - 5	0 - 5	0.997 (exp); p<0.0001	SS
Travisia olens	Polychaete	0 - 5	0 - 5	Na	SS
Paphies australis	Bivalve	0 - 5	0 - 5	Na	SS
?Waitangi sp. aff. *W. chelatus*	Amphipod	0 - 5	0 - 5	Na	SS
Notoacmea helmsii	Gastropod	0 - 5	0 -10	0.974 (exp); p<0.0001	SS
Cominella glandiformis	Gastropod	5 - 10	0 - 10	Na	SS
Anthopleura aureoradiata	Anemone	5 - 10	0 - 15	Na	SS
Diloma subrostrata	Gastropod	5 - 10	0 - 15	Na	SS
Macomona liliana	Bivalve	0 - 5	0 - 40	Na	S
Orbinia papillosa	Polychaete	5 - 10	0 - 40	Na	S
Colurostylis lemurum	Cumacean	0 - 5	0 - 60	0.812 (exp); p=0.0005	S
Boccardia syrtis	Polychaete	10 - 15	0 - 50	0.360 (exp); p=0.0547	S
Nucula harvigiana	Bivalve	0 - 5	0 - 60	0.780 (exp); p<0.0001	S
Scoloplos cylindrifer	Polychaete	0 - 5	0 - 60	Na	S
Austrovenus stutchburyi	Bivalve	5 - 10	0 - 60	0.784 (exp); p=0.001	S
Syllid	Polychaete	25 - 30	0 - 40	Na	S
Waipirophoxus waipiro	Amphipod	0 - 5	0 - 70	0.684 (exp); p=0.0006	S
Macroclymenella stewartensis	Polychaete	10 - 15	0 - 60	Na	S
Paracalliope ?novizealandiae	Amphipod	35 - 40	0 - 50	Na	S
Goniada emerita	Polychaete	50 - 55	0 - 60	Na	S
Cirratulid	Polychaete	10 - 15	5 - 70	Na	S
Aricidea sp.	Polychaete	35 - 40	0 - 70	Na	S
Arthritica bifurca	Bivalve	55 - 60	5 - 70	Na	S
Cossura sp.	Polychaete	20 - 25	5 - 65	Na	S
Musculista senhousia	Bivalve	55 - 60	0 - 60	Na	S
Tanaid	Crustacean	10 - 15	0 - 100	0.240 (exp); p=0.2880	S
Glycerid	Polychaete	10 - 15	0 - 95	0.205 (exp); p=0.2252	I
Heteromastus filiformis	Polychaete	10 - 15	0 - 95	Na	I
Aquilaspio aucklandica	Polychaete	65 - 70	0 - 95	Na	I
Nemertina	Nemertean	55 - 60	0 - 95	Na	I
Macropthalmus hirtipes	Crab	45 - 50	0 - 95	Na	I
Lumbrinereid	Polychaete	30 - 35	0 - 65	0.344 (linear)	P
Theora lubrica	Bivalve	45 - 50	5 - 65	0.242 (linear)	P
Nereid	Polychaete	55 - 60	0 - 100	Na	P
Oligocheate	Oligochaeta	95 - 100	0 - 100	Na	PP
Scolecolepides sp.	Polychaete	25 - 30	0 - 100	Na	PP
Helice crassa	Crab	95 - 100	5 - 100	0.676 (exp); p=0.0006	PP
Paracorophium excavatum	Amphipod	95 - 100	40 - 100	0.791 (exp); p=0.0008	PP

4.3 Short term behavioural responses of marine benthic invertebrates to burial by terrestrial clay

Apart from assessing the distribution of species and their sensitivity to changes in sediment grain size by using data collected in the field survey, we also tested a few of the dominant species occurring in the Whitford embayment for their short-term responses to depositions of clay in laboratory experiments. The brief for choosing taxa was not only to pick important dominant taxa from the Whitford embayment, but to also expand our knowledge-base on similar studies conducted on animals from the Okura estuary (Norkko et al. 1999, Nicholls et al. 2000). As already outlined in the introduction, it is important to note that these two approaches for studying species sensitivity (i.e. field survey *vs.* laboratory experiments) are markedly different. Laboratory experiments provide information on short-term behavioural responses to sudden depositions of clay, whereas the field survey integrates the history of previous sedimentation events (and other sources of environmental variability) to provide us with more broad-scale information on how gradual changes in sediment grain size might affect the overall distribution of species/taxa. Hence a direct comparison of results between these two approaches is not necessarily meaningful. Both approaches expand our knowledge of the potential effects of sedimentation events, only over different time and space scales. Laboratory experiments are powerful as they allow us to closely examine the mechanisms of how animals cope with sudden and dramatic changes in the sedimentary environment.

4.4 The cockle, *Austrovenus stutchburyi*

The *Austrovenus* used in the experiments had an average size of 21.5 mm. No mortality was recorded during the experiment. Likewise, no mortality was found in previous experiments using deeper clay layers (Norkko et al. 1999), suggesting that overlying clay up to a depth of 9 cm does not kill the animals in the short term. However, overlying clay may affect long-term survival by affecting the animal's ability to stay near the sediment-water interface and feed normally. That the animals were attempting to maintain their normal position at the surface is evident as the number of *Austrovenus* found in the clay or at the interface between the original sandy sediment and clay was higher in the deeper clay layers (Figure 7). Similarly, more animals shifted position and moved out of the sand into the clay layer over time in the 0.5 and 1 cm treatments. In the 1.5 cm treatment, the number of cockles found in the clay also increased from day 1 to day 3 but by day 6, all the animals had moved back into the sandy sediment. This is supported by the observation that open siphons were observed at the clay surface in all treatments on days 1 and 3 but none were visible by day 6.
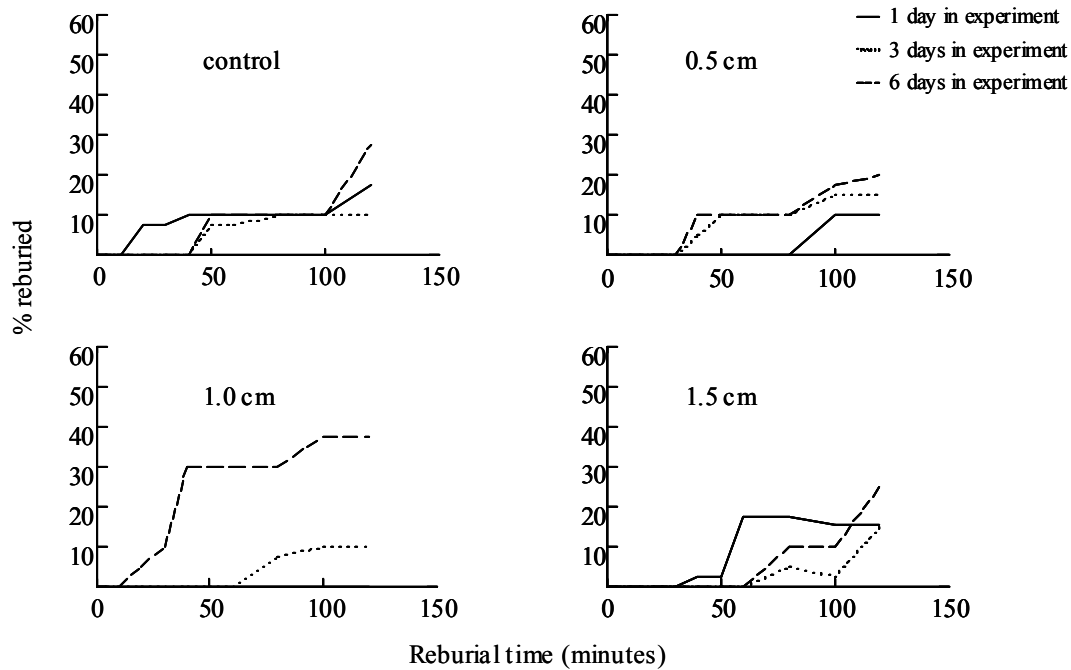
Figure 7: The percentage of Austrovenus that had emerged from the sandy sediment into the clay layer in each treatment, on each sampling time.

4.4.1 Reburial

Austrovenus had a poor reburial capacity, with only 10 to 45% reburying after two hours across all treatments and times. Norkko et al. (1999) observed a similar response with *Austrovenus* from the Okura estuary. In clay depths used in the present study (i.e. < 2 cm), the reburial response of *Austrovenus* was variable across treatments and over sampling times and was not significantly affected by the either presence or depth of overlying clay, or by exposure time (Figure 8). Thus, for example, in the 0.5 cm treatment faster reburial was recorded at day 6 compared to day 1, whereas the opposite was true for the 1.5 cm treatment. This contrasts with Norkko et al. (1999) who observed consistent differences in the rate of reburial between controls and all clay depths greater than 2 cm after six days.
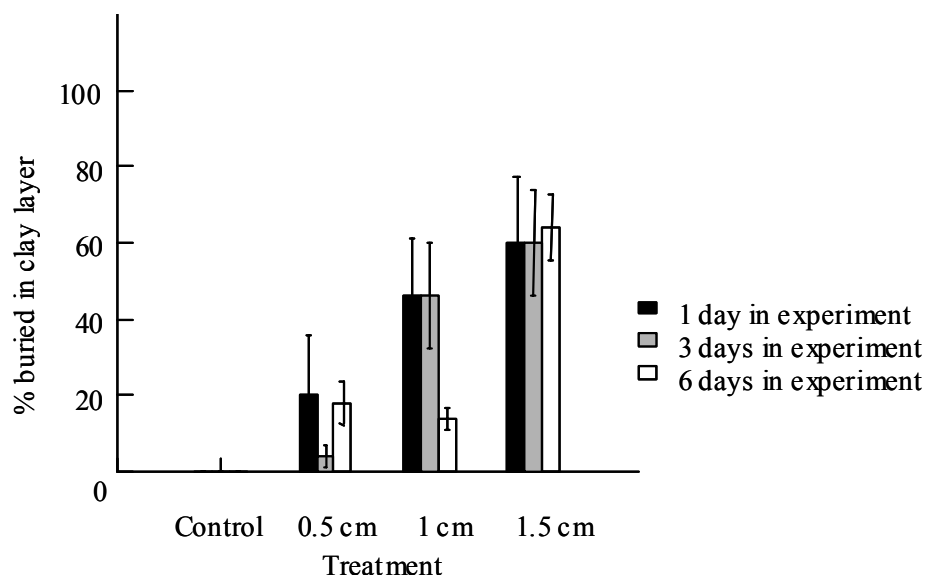
Figure 8: Average reburial over time for Austrovenus collected from four treatments on three sampling times.

4.5 The nut shell, *Nucula hartvigiana*

The *Nucula* used in the experiments had an average size of 5.9 mm. All of the animals in the control, 0.5 and 1.0 cm treatments were recovered alive whereas two were found dead in the 1.5 cm treatment after 6 days. This is consistent with the findings of Nicholls et al. (2000) who found significant negative effects to occur at this clay depth. As with *Austrovenus*, the number of *Nucula* found to emerge from the sand into the clay layer increased with increasing clay depth (Figure 9). Again it is likely that this migration is an attempt to maintain their normal position at the sediment-water interface. Such migrations do not necessarily occur when thicker clay layers are involved. Nicholls et al. (2000) found that, in deeper clay layers (i.e. 3, 6 and 9 cm), the majority of *Nucula* remained in the natural sediment. This suggests that when the overlying clay is greater than 2 cm deep, *Nucula* cannot cope. Potential reasons for this are speculative but could be attributed to difficulties in creating voids through the clay for respiration. In the thin clay layers used in the present study, some voids were found in the clay. Animals able to maintain respiration would have more energy for migration through clay.

Figure 9. The percentage of Nucula found buried in the clay layer in each treatment, on each sampling time.

4.5.1 Reburial

Reburial by *Nucula* was rapid, with 76 to 100% having reburied after two hours across treatments and different times. Nicholls et al. (2000) observed similar rates for *Nucula* from the control cores. No difference in reburial rates between treatments was observed, which contrasts with the results obtained by Nicholls et al. (2000) who found that, after six days, a higher percentage of *Nucula* from control cores had reburied after two hours compared to those exposed to clay (Table 4). From these results, it appears that *Nucula* from the Whitford embayment are less sensitive to clay deposition than those from the Okura estuary. This difference in response may relate to past exposure to sedimentation events, but it may also be due natural variability in response to these thinner clay layers.
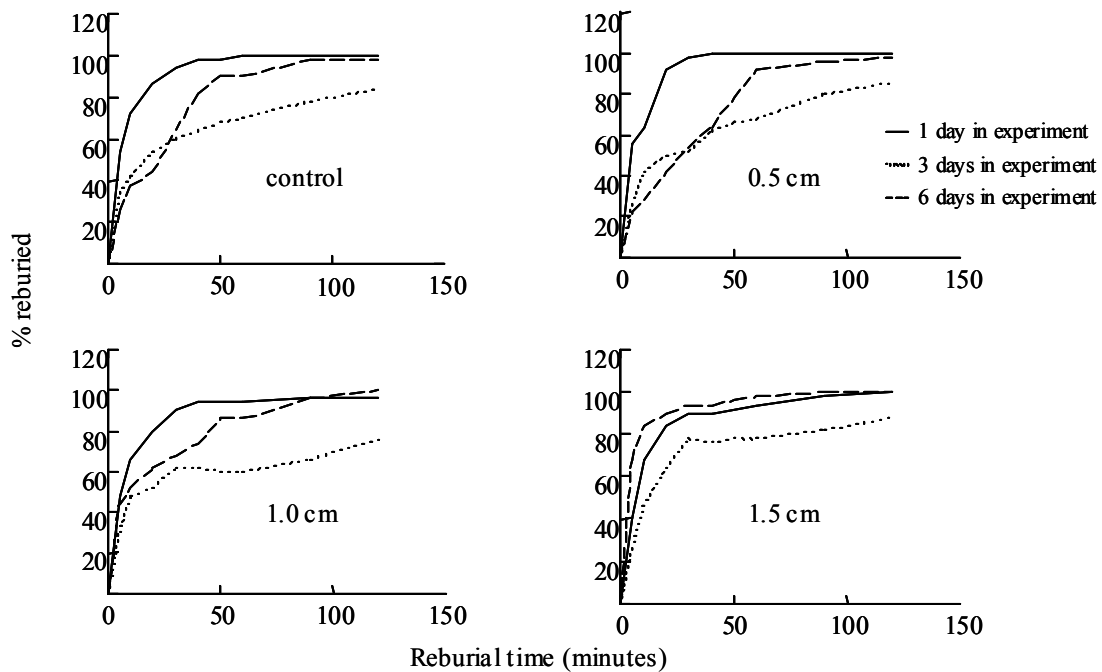
Table 4: The percentage of Nucula reburied after two hours, from exposure to different clay depths over six days.

Clay depth (cm)	0	0.5	1.0	1.5	3.0	6.0	9.0
Nicholls et al. (2000)	90.9	25.7	20.7	14.2	14.0	10.0	8.5
Present study	98	98	100	100	n/a	n/a	n/a

In terms of rate of reburial, animals reburied faster on day one than on days three and six for the control, 0.5 and 1 cm treatments (Figure 10). However, in the 1.5 cm treatment, where the impact should be the most severe, animals reburied faster on day six, indicating that exposure time is probably not affecting reburial rates. Exposure

time did affect reburial rates for *Nucula* gathered from the Okura estuary, but only after six days and in deeper clay layers than those used in the present study[1].

Figure 10: Reburial over time for Nucula collected from four treatments on three sampling times (mean ± SE).
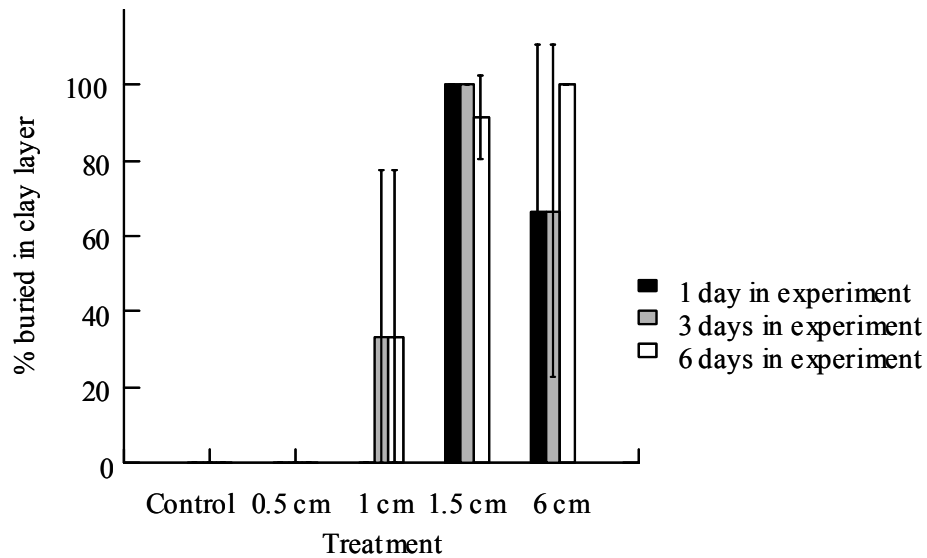

4.6 The sand dollar, *Fellaster zelandiae*

The *Fellaster* used in the experiments had an average size of 56 mm. No mortality was recorded during the experiment, indicating that overlying clay to a depth of 6 cm does not kill *Fellaster* in the short term. As for *Austrovenus* and *Nucula*, the number of *Fellaster* found in the clay layer or at the clay/sediment interface increased with increasing clay depth. Again, this may represent an attempt to maintain the normal position of being close to the sediment-water interface. In the deepest treatment (6 cm), all animals had emerged from the sandy sediment into the clay or onto the clay surface. Due to a large, flat surface area, *Fellaster* would be able to maintain its position on the clay surface more easily than *Austrovenus*.

The percentage of *Fellaster* found in the clay layer did not change much over the different sampling times (Figure 11). There were never any *Fellaster* in the clay layer in the 0.5 cm treatment and consistently higher numbers of animals in the 1.5 cm treatment, regardless of whether the animals were recovered after one, three or six days.

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[1] In Nicholls et al. (2000), only one exposure time (6 days) was used for clay depths less than 2 cm thick so cross-comparisons could not be made with other times.
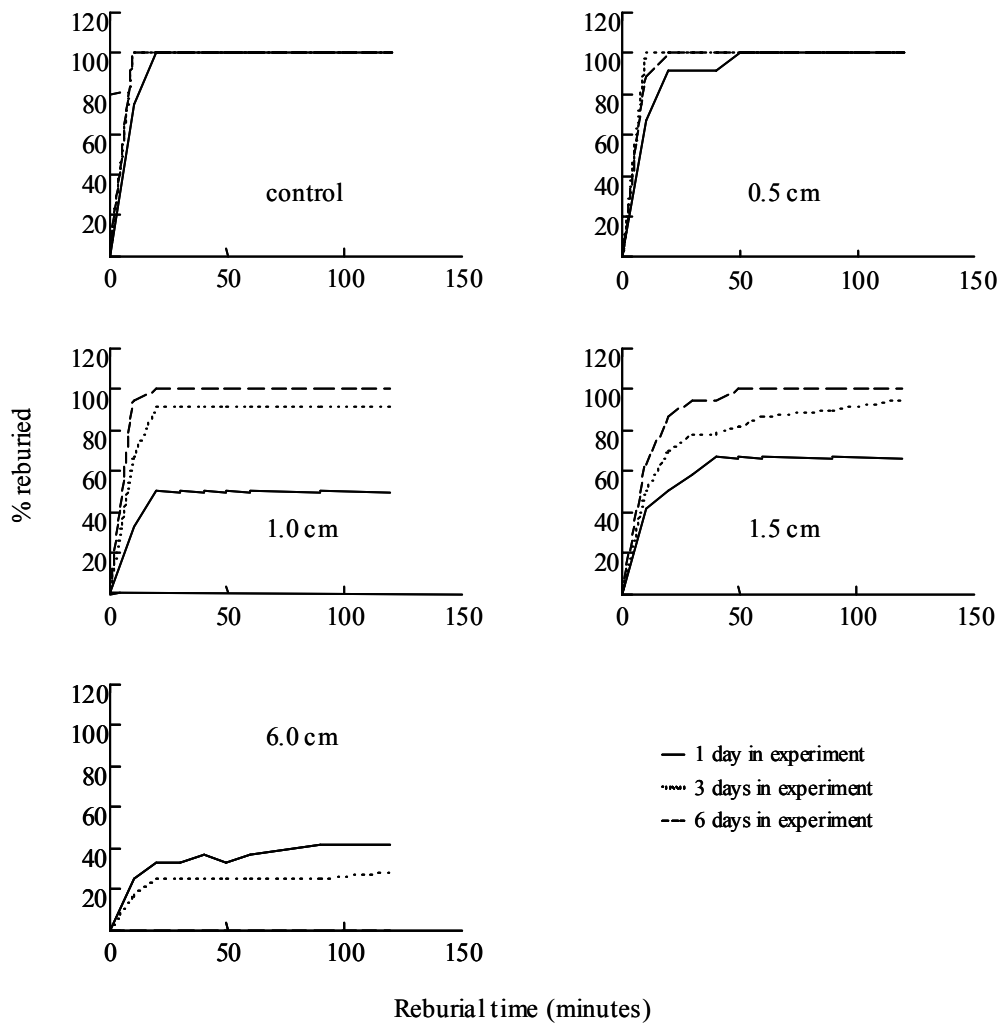
Figure 11: The percentage of Fellaster found buried in the clay layer in each treatment, on each sampling time.

4.6.1 Reburial

Reburial by *Fellaster* was rapid for animals from the control and 0.5 cm treatment, with 100% buried after two hours, whereas in the 1.0 and 1.5 cm treatment reburial varied from between 50 and 66%. Only in the 6 cm treatment did we find clear and statistically significantly negative effects by clay on rates of reburial. The effect of exposure time to clay layers less than 2 cm thick was variable over time (Figure 12). However, for *Fellaster* from the 6 cm treatment, there was a clear response of slower reburial with increasing exposure time. By day 6, *Fellaster* from the 6 cm treatment did not rebury at all. This combination of depth and exposure time was therefore critical for *Fellaster*.

Figure 12: Reburial over time for Fellaster collected from five treatments on three sampling times.

Reburial time (minutes)

4.7   Polychaete and oligochaete worms

The polychaete and oligochaete worms resident in the sediments also exhibited migration into the clay layer that increased with the thickness of overlying clay (Figure 13), although the numbers of worms and worm taxa were always higher in the underlying sediments than in the clay. In general, orbinid and oligochaete worms were more common in the clay than in natural sediment. As for *Autrovenus*, *Nucula* and *Fellaster* the connection through the clay to the overlaying water-column is vitally important to sustain life. However, polychaetes, such as orbinids, are mobile sub-surface deposit feeders and acclimated to life in the sediments. Hence they will cope as long as burrows, allowing for respiration, can be maintained through the clay (Figure 14). While Nicholls et al. (2000) also found that oligochaetes were unaffected by clay deposition and related this to a tolerance of anoxic conditions, Norkko et al. (1999)

found that orbinids were sensitive to clay, albeit in deeper clay layers than those used in the present study. *Aonides* was only found in the natural sediment, never in the clay, confirming intolerance. This sensitivity to clay is also consistent with the results from the field survey and the field experiments conducted by Berkenbusch et al. (2001). The total number of worms and of the most common worm taxa (*Aonides,* orbinids and oligochaetes) did not differ between treatments (Figure 14). This is consistent with Nicholls et al. (2000) who also found that worm numbers were unaffected at the shallower clay depths, but at depths of 3 cm and greater, the number of nereids, *Aquilaspio aucklandica* and *Boccardia* sp. decreased with depth of clay and exposure time.

Other polychaete worms found in the cores, but only in low numbers, included the nereid, *Nicon aestuarinensis*, the spionids, *Aquilaspio aucklandica*, *Boccardia* sp. and *Prionospio* sp., the orbinids, *Orbinia papillosa* and *Scoloplos* sp., Magelonids, Glycerids, Cirratulids and Capitellids.

Figure 13: The percentage of total worms found buried in the clay layer in each treatment, on each sampling time.
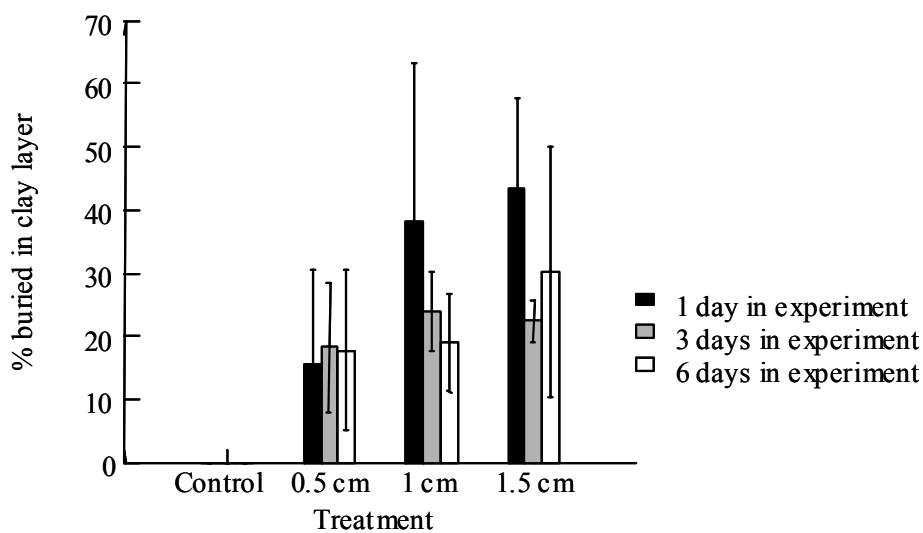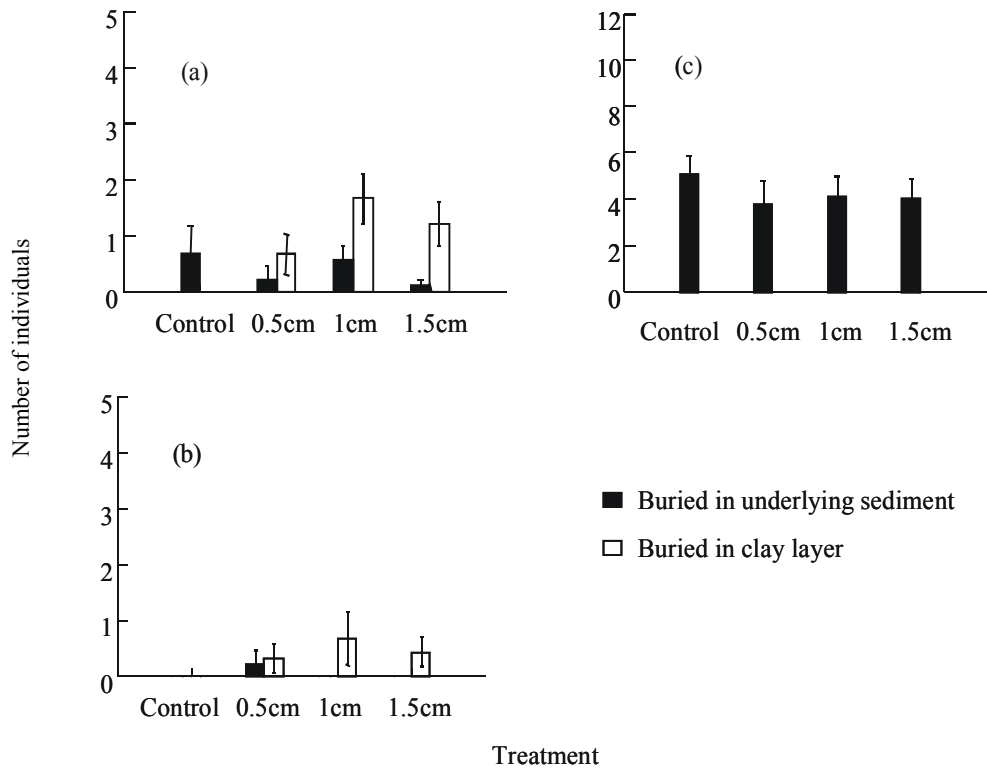
Figure 14: The number of (a) orbinids, (b) oligochaetes and (c) Aquilaspio found in each treatment in the clay and underlying sediment.

5 Summary

This report presents results of laboratory experiments on macrofaunal responses to depositions of terrigenous clays and develops distribution models of species and communities in relation to sediment characteristics in the Whitford embayment. The laboratory experiments corroborate and extend the findings of our work in Okura Estuary (Norkko et al. 1999; Nicholls et al. 2000) investigating species-specific responses to sudden silt/clay depositions. The models use the information on the distribution of species and communities in relation to sediment characteristics as a proxy for their sensitivity to both elevated suspended sediment concentration in the water column and deposits on the sediment surface.

In the laboratory experiments we found highly variable responses of benthic invertebrates to burial by terrigenous clay (mostly 0.5 – 1.5 cm clay layers). In contrast to the Okura studies (where mostly 3 – 9 cm clay layers were used), very few consistent negative patterns emerged. All of the animals, except the polychaete *Aonides*, were able to move into the thin clay layer and did so in increasing numbers as the thickness of the clay layer increased. This migration is likely to be an escape response with animals trying to maintain their normal positions of being close to the sediment surface, and/or a behavioural response to changes in biogeochemical gradients such as the induction of hypoxia underneath the clay. For all taxa, migration up/through and out of the clay layer varied with over the duration of the experiment. However, in the thickest clay treatments, a high percentage of the buried animals remained in the clay over the entire experiment. The taxa tested in these experiments differed in their ability to rebury themselves after disturbance but, except for the sand dollar *Fellaster*, this did not appear to be related to the thickness of the overlying clay, nor to exposure time. In general, the nut shell *Nucula* and *Fellaster* had greater reburial capacities than the cockle *Austrovenus*. *Fellaster* showed a clear negative response to increasing clay depth, a exhibited a significantly faster reburial in the thinner clay treatments (i.e. 0.5, 1.0 and 1.5 cm) compared to the 6 cm treatment. After six days of exposure to 6 cm of clay, no *Fellaster* reburied at all, indicating that a combination of this depth and exposure time had critically affected stress levels.

Thus the emerging pattern for these laboratory experiments is one of weak and inconsistent responses to thinner clay layers (0.5, 1.0, 1.5 cm). This supports the conclusions drawn from previous studies (Norkko et al. 1999, Nicholls et al. 2000) that clay layers less than 2 cm thick will have minimal effects in the short-term. However, field experiments with thin layers of terrigenous clay, run over 9 – 10 days in Whitford embayment, demonstrate negative effects on a number of species used in these laboratory experiments (e.g., *Austrovenus, Aquilaspio*, Orbinids*,* and *Aonides*; see Berkenbusch et al. (2001)). Hatton et al. (2001) also recorded negative effects on the condition and growth of *Austrovenus* in Whitford studies. When comparing across studies some general patterns on species-specific responses to clay emerge (Table 5). For eight of the thirteen repeatedly tested species, consistent patterns of sensitivity (or tolerance) emerge when comparing the experiments and the field survey. There is high concordance in sensitivity when comparing results from the laboratory

experiments which tested thicker (3-9 cm) clay layers (Norkko et al. 1999, Nicholls et al. 2000) with results from this field survey (Table 5). In contrast, where thinner clay layers have been used, such as in the present laboratory experiments and in the field experiments conducted by Berkenbusch et al. (2001), results are more variable, ambiguous and not necessarily in agreement with results from the field survey (Table 5). However, the field experiments conducted in Whitford compare better with results from the field survey than do the laboratory experiments. Although utilising thin clay layers, the field experiments in Whitford were run over a longer time period than the laboratory experiments described in this report (i.e. 9 - 10 days *vs.* 6 days, respectively). Hence, while these results partly reinforce the concept proposed by Norkko et al. (1999) that depositions of 2 cm of clay are critical in the short-term, they also highlight the potential negative effects of exposure to thin depositions of clay over longer time periods. This emphasises the importance of integrating short-term laboratory studies and field experiments with surveys which reflect community responses over broader time scales.

Furthermore, when used in conjunction with other studies mentioned above, these results increase our understanding of the effects of sediments on macrofauna. For example, information on the sensitivity of particular taxa gained from the survey does show some concordance with the experiments conducted in the laboratory and in the field. There is also some agreement in the trends emerging for some species relative to changing sediment characteristics in the Manukau (Funnell et al. 2001) and Mahurangi monitoring programmes (Cummings et al. 2001), indicating that the spatial trends detected in this study may well reflect long-term temporal trends.

The survey results provide a snapshot of the different habitats, sediment types and taxa distributions throughout the Whitford embayment. Nevertheless, it is reasonable to assume that this snap-shot represents some time-integrated picture of animal distributions. Although we were able to clearly partition the macrobenthic communities within the embayment on the basis of broad-scale habitat characteristics, we found a wide variety of relationships between abundance and sediment silt/clay content for individual species. While some taxa showed clear and dramatic threshold responses to increasing silt/clay, others exhibited wider distributions and more gradual declines in abundance. Importantly, only a few taxa favoured sediments containing high silt/clay.

This information is useful because it characterises community structure and the sensitivity of individual species to present sediment conditions. Previous studies in Okura Estuary have shown a good correlation between the risk of sedimentation events and sediment characteristics (Stroud et al. 1999). Furthermore, current studies in the Whitford embayment support this finding with respect to both suspended sediment concentrations (Hatton et al. 2001) and recently deposited terrigenous sediments (Gibbs et al. 2001). This implies that the species sensitivity curves and community-sediment affinities derived from this study can help predict the implications of change in the embayment on longer-term macrofaunal distributions. The species sensitivity information can be integrated with catchment and hydrodynamic modelling to assess the risks to the estuary of changes in land use.

Table 5: Summary of sensitivity information gained from different studies. "Previous lab experiments" includes effects of thicker clay layers investigated in Norkko et al. (1999) and Nicholls et al. (2000). "Whitford field experiments" were all conducted on thin clay layers (<0.7 cm; Berkenbusch et al. 2001). - = not tested or not applicable. SS = highly sensitive; S = sensitive, I = no response; P = slightly positive response; PP = highly positive response. * = Juveniles less than 5 mm were sensitive, but adults not.

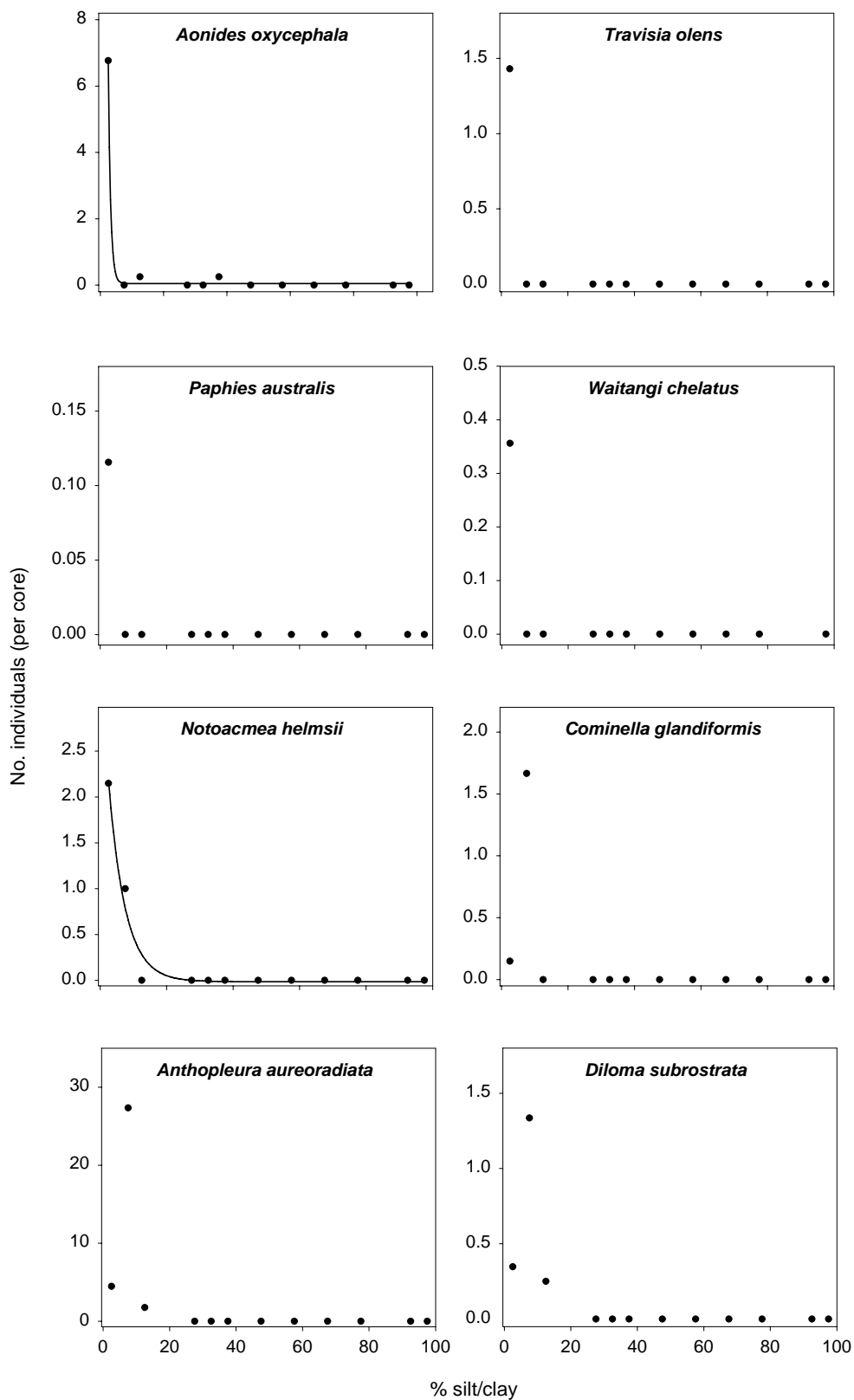| Taxa	Previous lab experiments (mostly 3-9 cm clay)	Present lab experiments (mostly 0.5 – 1.5 cm clay)	Whitford field experiment (0.1 – 0.7 cm clay)	Sensitivity ranking from present survey	Agreement between studies
Alpheus	PP	-	-	-	-
Amphibola	S	-	-	-	-
Aonides	-	S	S	SS	Yes
Aquilaspio	S	-	S	I	No
Austrovenus	S	P	S*	S	No
Boccardia	S	-	-	S	Yes
Fellaster	-	S	-	-	-
Glycerids	I	-	-	I	Yes
Helice	PP	-	-	PP	Yes
Heteromastus	I	-	-	I	Yes
Macomona	S	-	S*	S	Yes
Nereids	S	-	-	P	No
Nucula	S	P	P	S	No
Oligochaetes	PP	P	-	PP	Yes
Orbinids	S	P	S	S	No
Paphies	S	-	S	SS	Yes

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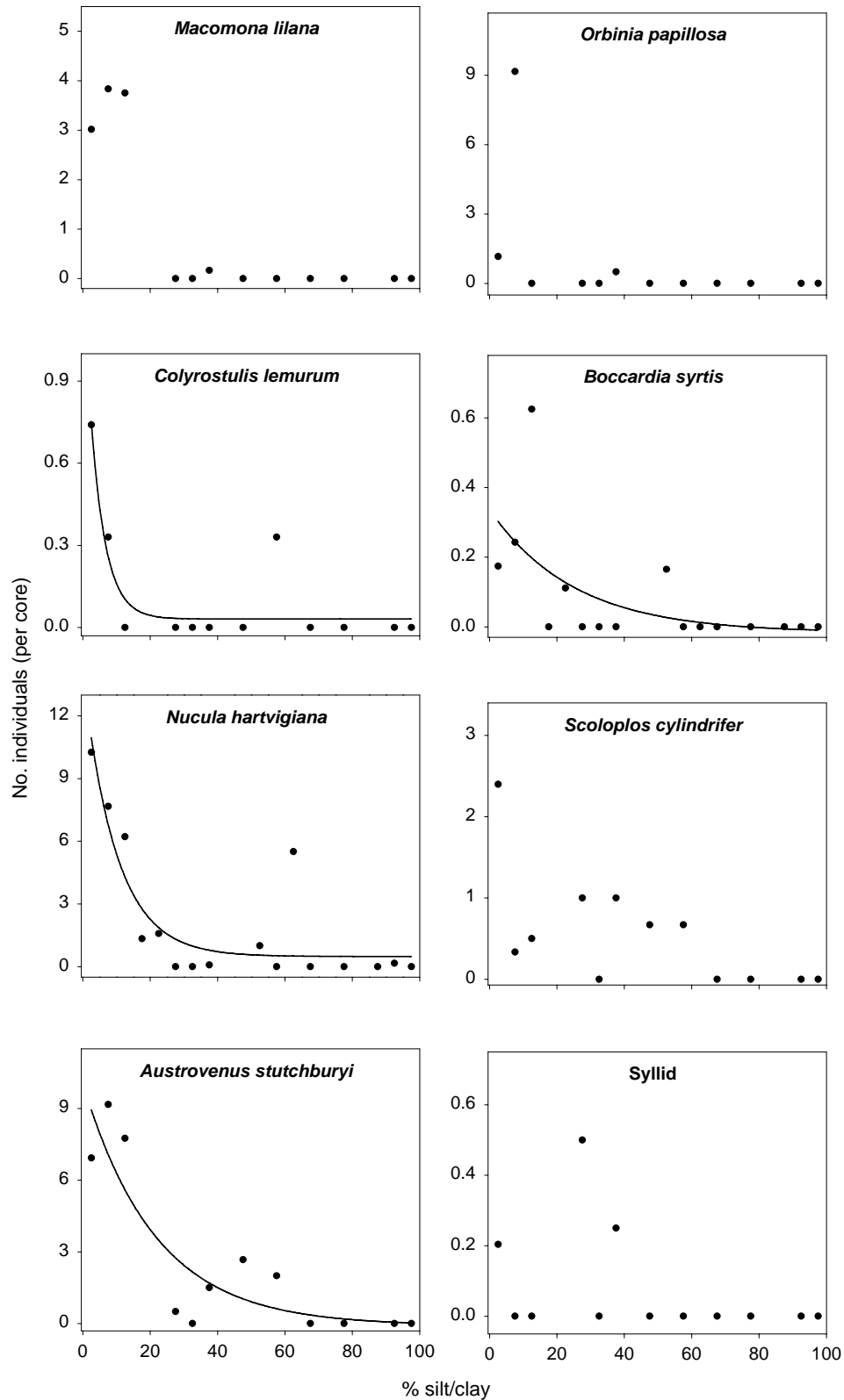Zar, J.H. (1996). Biostatistical analysis, Prentice Hall international, London, 662 pp.

Appendix 1

Distribution patterns of invertebrates to increasing silt/clay content of the sediment.
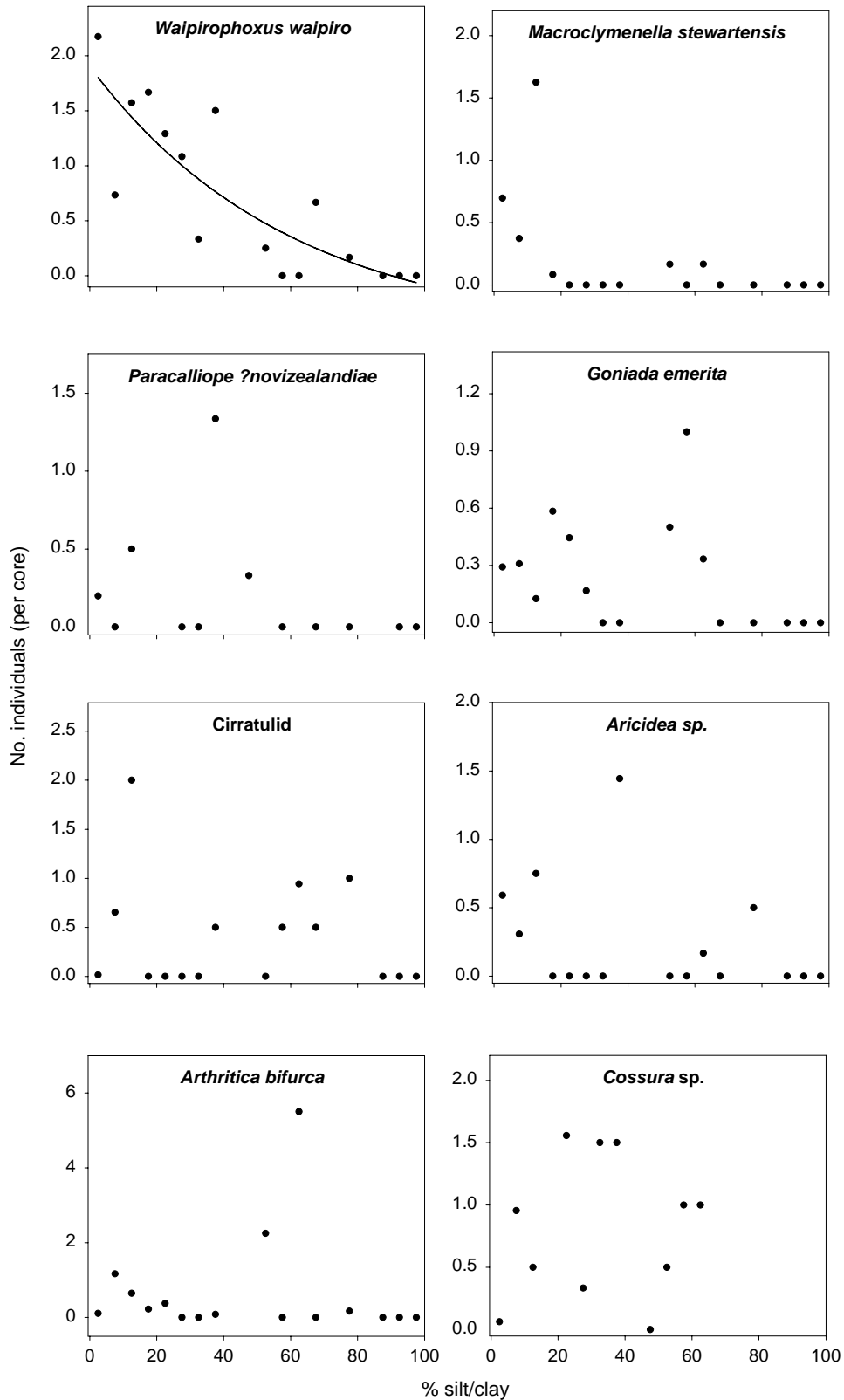
Appendix 2

Distribution patterns of invertebrates to increasing silt/clay content of the sediment.
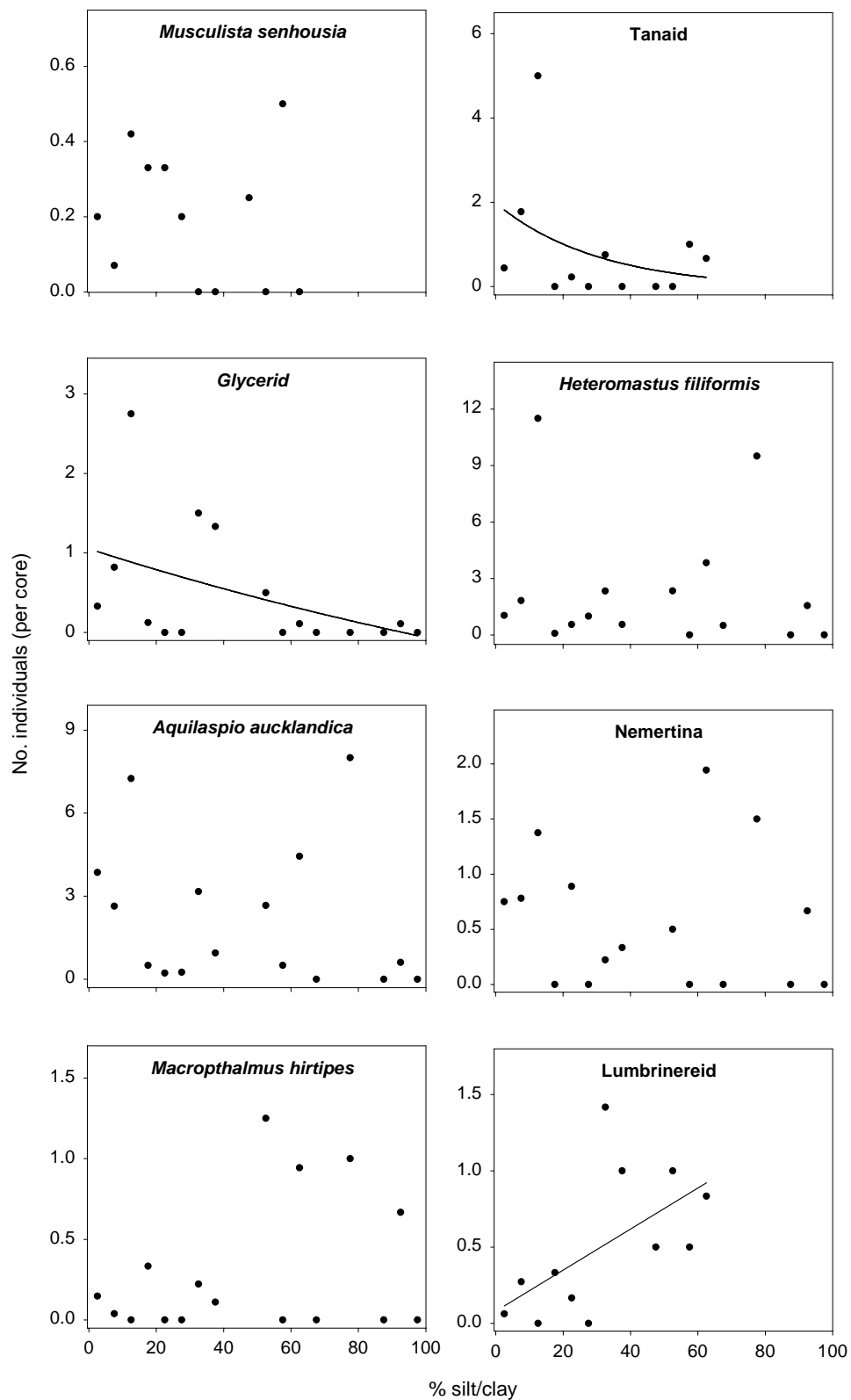
Appendix 3

Distribution patterns of invertebrates to increasing silt/clay content of the sediment.

Appendix 4.

Distribution patterns of invertebrates to increasing silt/clay content of the sediment.

Appendix 5

Distribution patterns of invertebrates to increasing silt/clay content of the sediment.