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Interactions between heavy metals, sedimentation and cockle feeding and movement

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1 Executive Summary

The objective of this project is to link contaminant deposition and burial, and the ecotoxicology and ecophysiology of cockles, with the valuing of ecosystems. It is designed to be a three year project; this report details the findings of a series of laboratory and field experiments on interactions between cockle size, density, mobility, feeding and contaminants conducted in Years 1 and 2. This overall project will determine whether the interactions between suspension feeders and contaminants are important enough to be considered in the management of stormwater inputs and models of contaminant dispersal and accumulation. Ultimately, results can be used to determine the likely environmental consequences of cockle declines in sandflat systems stemming from stressors such as over-harvesting, sedimentation, or sediment toxicity.

The project concentrates on cockles as they are important to ecosystem functioning for a number of reasons. In particular, they are an important food source for humans, birds and fish. They influence the smaller invertebrates that live in the sediment around them. They also bioturbate the sediment, affecting nutrient recycling, contaminant partitioning and sequestration. Importantly, they are suspension feeders, filtering sediments, algae and other suspended particles from the overlying seawater thereby influencing turbidity and the dispersal of particle-bound contaminants.

Our results suggest that the ambient feeding rate of cockles is lower, and cockles are less selective when feeding, at sites with higher levels of storm-water associated contaminants. This finding has ecosystem effects beyond that of the direct effect on cockles, as suspension feeders remove particulate-bound metals from the water column and, through biodeposition, affect the redistribution and availability of metals in sediment and water. Thus, increased storm-water contamination will decrease the filtering capacity of estuaries and harbours at a much faster rate than that predicted by decreases in abundance of cockles. Guidelines derived from contaminant effects on mortality will be set too high to preserve this function. Models of contaminant dispersal that do not include the filtering effects of suspension feeders may be compromised, however, interactions between hydrodynamics and filtering mean that the modelling carried out in the next stage of this project is required before this can be determined.

Although cockles from all sites showed a decrease in feeding rate when presented with food that had higher levels of contamination, cockles from more contaminated sites were better able to cope (i.e., had higher feeding rates at the same level of contamination). This suggests that thresholds of responses to storm-water contaminants are likely, with cockles being able to adapt until the threshold is passed. Thus guidelines based on gradual change are likely to place the environment at risk. Feeding rates were higher for smaller cockles than larger and the negative effect of contaminants on feeding rates was stronger for small cockles. Contaminants also decreased the density threshold above which cockle feeding rates declined.

Feeding rates decreased with increased ambient sediment contamination, particularly increased copper concentrations measured on the < 500µm sediment size fraction (hereafter called "totals"). The strong relationship with copper matches the results of analyses of other ARC data, under FRST funding, which observed abundance of cockles to be more strongly related to total copper concentrations than to zinc or lead.

Cockles appeared more able to accumulate copper in their tissue than zinc or lead. However, copper concentrations in biodeposits from the cockles fed contaminated sediment were not significantly different from the input sediment, whereas lead and zinc concentrations were slightly elevated. This suggests that the sediment filtered out of the water column by cockles is a sediment fraction which has heavy metals bound to it. This also suggest that copper is more readily stored within the cockle tissue, while the other two metals are passed out in biodeposits.

Movement by cockles created deep tracts in the top 1 – 2 cm of sediment which is likely to facilitate nutrient recycling and exchange, hence contributing to ecosystem function. Mobility of cockles in the field was affected by cockle density at each site and small changes in cockle size, but also decreased with increasing metal contamination, and there were indications that current and wave conditions were important. Under laboratory conditions the movement of cockles was dependent on size and density of cockles and the presence of cockles reduced the level of sediment resuspension in the overlying water. Under field conditions, cockle movement had a positive effect on the amount of sediment in the water column, suggesting an interaction between hydrodynamics and the effect of cockle movement on resuspension, as has been found in other studies on the bioturbation effects of benthic macrofauna. This interaction will be explored by modelling in the next phase of this project.

A numerical model of the complex interactions we have observed has been developed. This model is a successful adaptation of a model developed under FRST funding in the programme "Effects-based management of contaminants (C01X0307)". This model provides a way to link all the measured responses together, to explore how interactions may occur and assess their relative importance, and to determine the most likely way that these relationships will play out under varying hydrodynamic conditions. It also allows the results of the experiments to be integrated with models predicting contaminant and sediment dispersal and accumulation in the upper and central Waitemata areas and to predict potential thresholds above which degradation may occur at an accelerated rate.

2 Introduction

2.1 Background

Heavy metals (copper, lead and zinc) associated with stormwater inputs are accepted by the ARC as the major contaminant in the intertidal marine sediments surrounding Auckland City. This area is highly urbanised and showing strong upward trends in the concentrations of copper and zinc in estuarine sediments at many sites (Reed & Webster 2004, McHugh & Reed 2006). Macrofauna living in and on the seafloor of the Waitemata and Manukau Harbours can be affected by the contamination associated with storm-water runoff (Thrush et al. 2008, Hewitt et al. 2009), even when concentrations of copper, lead and zinc are below ARC adopted TEL guidelines.

Decreases in the abundance and distribution of benthic macrofauna have a number of consequences for ecosystem processes and the goods and services utilised by humans such as:

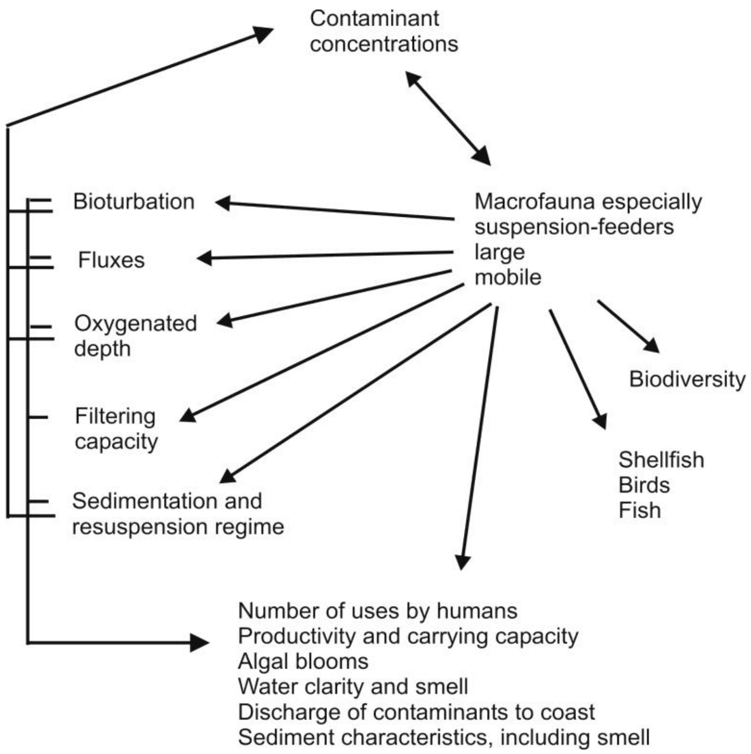
- Loss of biodiversity.
- Loss of culturally important shellfish populations (e.g., cockles, pipis, mud snails).
- Loss of food sources for bird and fish species.
- Changes in the flux of nutrients from the seafloor to the water, resulting in changes to water productivity and algal blooms.
- Changes in the carbon storage capacity of soft-sediment habitats.
- Changes in the oxygen concentration of bottom sea-water and sediment pore-water. The depth of oxygenation penetration into sediments influences redox conditions, which interacts with nutrient fluxes to affect system productivity and carrying capacity.
- Changes in the deposition and resuspension of fine sediment particles, which will affect water clarity and potentially change sediment characteristics of certain areas.
- A reduction in the filtration capacity of estuaries and harbours. One of the functions of estuaries and harbours is to trap sediments (and any attached contaminants) by gravitationally induced settling before they reach coastal areas. Many benthic living macrofaunal species are suspension feeders and feed by filtering particles (both algae and sediment) from the water column and either ingesting them or binding and ejecting them as mucous-packaged pseudofaeces. This enhances the filtration capacity of estuaries and harbours.
- Reduced bioturbation rates. Organism-mediated sediment mixing (bioturbation) is a process central to nearly all aspects of soft-sediment community dynamics and geochemistry (e.g., nutrient fluxes, oxygen concentrations, organic matter reminalisation, macrofaunal recruitment and system productivity). Most benthic macrofauna contribute to bioturbation, either through movement of the whole body or feeding appendages or by ingesting and excreting sediment and detritus

particles. The level of bioturbation and the subsequent stimulation of benthic processes are dependent on the size of the dominant bioturbators, their densities, and their rates of movement. In New Zealand estuaries, bivalves are often numerically dominant and key drivers of bioturbation.

Benthic species behaviour and action in the sediment are also likely to be important in determining how contaminants entering the harbour are processed and stored (Figure 1). Decreases in the abundance or activity of suspension feeders due to species sensitivity to contamination would allow a greater flow through of contaminants and sediment from the land to the coastal waters. Vertical bioturbation can result in the subduction of material from surface to depth (Aller and Dodge 1974), and the re-exposure of sediment back to the surface with consequences on contaminant binding/availability. Oxygen concentrations in the sediment affect the portioning and availability of trace metals while changes in the sedimentation regime affect how widely contaminated sediments are dispersed. In particular, Williamson et al. (1994) suggested that bioturbation played an important role in determining whether contaminants in sediments could be immobilised and made biologically unavailable. Bioturbation also plays a role in determining the residence times of contamination. Even after inputs of contaminants cease and new layers of cleaner sediment are deposited, biogenic mixing can result in the re-emergence of contaminated material (e.g., Williamson et al. 1995).

The interactions between benthic organisms and their environment are complex. Consequently there is potential for feedbacks between changes in the abundance and distribution of benthic fauna, ecosystem goods and services, and contaminant sequestration and dispersal to occur (Figure 1). This suggests that understanding the relationships between these factors is important for setting contaminant guidelines, managing stormwater inputs into coastal waters and evaluating the consequences of management strategies. Despite this, existing contaminant guidelines are largely based on ecotoxicological studies of a limited range of species. Existing models of dispersal of stormwater contaminants also do not take into account the potential for filter feeders to increase settling rates of contaminated sediment or influence resuspension of previously deposited sediment. This study investigates whether the interactions between a suspension feeding species and contaminants are important enough to be considered in the management of stormwater inputs and predictive models of contaminant dispersal and accumulation. The suspension-feeder used is the New Zealand cockle, *Austrovenus stutchburyi,* which is often numerically and biomass dominant in New Zealand estuaries and harbours.

Figure 1:
Interactions and feedbacks between macrofauna, contaminants, ecosystem function and ecosystem goods and services.



2.2 Study species

The New Zealand cockle is an abundant, ecologically important and often dominant suspension-feeder (Stephenson 1980) in Auckland's estuaries and harbours. Cockles are often found in interface areas between mud and sand habitats, where hydrodynamic conditions make deposition of sediment likely. FRST-funded research on multiple stressors, associated with data collected by the ARC for the development of its benthic health model, has shown that cockles are likely to be sensitive to storm water contamination (Hewitt et al. in press, Thrush et al. 2008). Other studies of the response of cockles to contaminants have observed changes in their energetics under environmental sublethal stress (de Luca-Abbott 2001) and accumulation of metals and other contaminants in their tissues (Peake et al. 2006, Purchase and Fergussen 1986, Scobie et al. 1999).

Austrovenus stutchburyi is one of the more studied species in New Zealand. Cockles are typically intertidal animals, living 0-5 cm below the sediment surface when the tide is out. When the tide comes in they move up to the sediment surface. They suspension feed through a short inhalant siphon and often exhibit a tidal rhythm, with the most active feeding occurring either side of high tide (McClatchie 1992, Beentjes and Williams 1986). However, when food is available they will often remain feeding but clearance rates can change rapidly. Filtration rates of 0.3 L hr^{-1} per animal (McClatchie 1992, Hewitt et al. 2001) have been reported, though Pawson (2004) reported filtration rates of 1.16 L hr^{-1} g^{-1} at 15°C, for South Island cockles, with animals active for 40% of the submersion period.

When not feeding, cockles can often be seen on the sediment surface moving through the sediment, producing track marks and mixing the sediment (Plate 1 and 2). Movement rates are highly variable, ranging from a few centimeters to >1m per tidal inundation (Mouritsen 2004, Stewart and Creese 2000, 2002, Cummings et al. 2007, Hewitt et al. 1996). Mouritsen (2004) also observed that cockle movement on the sediment surface was unaffected by density of cockles, however, Whitlatch et al. (1997) and Cummings et al. (2007) observed that cockles in high density patches were less mobile than those in low density patches.

Plate 1:
Cockle track marks from movement at Whitford, Auckland (Photo, D. Lohrer).

Cockles play an important role in mediating exchanges between the sediment and the water column. Pawson (2004) suggested that feeding by cockles controlled the availability of food in the water column (as algal biomass) in Papanui Inlet on the Otago peninsula. Sandwell (2006) and Thrush et al. (2006) both demonstrated the effect of cockles on the release of nutrients (i.e., utilizable nitrogen) into the water column. Sandwell (2006) also observed their feeding and movement destabilising the sediment. Townsend et al. (2008) observed cockle movement to result in reduced material being brought to the sediment surface (Plate 2).

The active nature of this large benthic species coupled with its high abundance and widespread distribution means that a reduction in its abundance and behaviour is likely to have consequences both on ecosystem services and on the sequestration of contaminants in estuarine and coastal systems.

Plate 2:
A cockle producing track marks as it moves through the sediment. Buried sediment is brought to the surface during this process.

2.3 Objectives

The overall goal of the study was to define linkages between contaminant trapping and dispersal and the occurrence, ecotoxicology and ecophysiology of cockles, with the valuing of ecosystems by answering the following questions:

- What roles do filter-feeders play in affecting sediment contaminant levels, through removal of sediment and contaminants from the water and sediment resuspension?
- Does the role depend on filter-feeder density and health, i.e., do contaminant levels affect the feeding and mobility of the animals?
- What happens if the filter-feeding community is removed (due to over-harvesting, sedimentation or sediment toxicity)?

To answer the above questions, the study was divided into a series of modules:

1. Collation of available information on cockle feeding rates and biodeposit production.
2. Field and laboratory studies to determine the relationship between cockle movement and resuspension of sediment relative to cockle density and sediment contamination.
3. Laboratory studies into the relationship between contaminant levels and feeding rates.
4. Laboratory studies into the relationship between contaminant levels and biodeposit production, including whether cockles discriminate between contaminated and non-contaminated sediment when feeding.

5. Complex system modelling to determine feedbacks between cockle density, feeding rates and stormwater contamination, including whether there is an interaction between the stress associated with sediment and contaminant levels. The model provides a way to link all the measured responses together, to explore how interactions may occur and assess their relative importance, and to determine the most likely way that these relationships will play out under varying hydrodynamic conditions.
6. Field survey targeting specific habitats to determine community types that are most likely to replace cockle communities.
7. Expert estimation of differences in the way that these replacement community types would deal with water-borne sediment contamination relative to cockles.

Modules 1, 2 and part of module 3 were conducted in 2007-8 with many of the results presented in Townsend et al. (2008). The rest of module 3 and modules 4 and 5 were conducted in 2008-9. This report presents a complete summary of the work conducted in both years (modules 1 – 4) along with the development of the complex system model (module 5). While funding is primarily from the ARC, a FRST-funded project (CO1X0307) also investigated species movements in response to stressors, in particular, testing methods for measuring movement. As such, that project funded much of the first laboratory experiments on cockle movement and also contributed some funding to the field investigations in the second year.

The objectives of this report are to:

- Determine whether interactions occur between:
  - contaminant levels, cockle feeding rates and biodeposit production using laboratory studies (Section 4). As size and density of cockles may be important factors in their response, these measurements were made relative to these factors.
  - cockles and sediment contaminant levels due to differential uptake of contaminants while feeding using laboratory studies (Section 5).
  - contaminant levels, cockle movement and resuspension of sediment using field and laboratory studies (Section 6).
- Use the results of experiments and field investigations to provide input parameters for modelling.
- Develop a complex system model (Section 7) that can determine feedbacks between cockle density, feeding rates and stormwater contamination, including whether there is an interaction between the stress associated with sediment and contaminant levels.

3 Study locations

Eight sites have been used over the course of the study (Table 1, Figure 2). Most sites chosen for study in this project had adult cockle populations and similar sediment grain sizes (medium to fine sand). They also covered a gradient in contaminants. Five sites are common to both years (Pollen Island, Hobsonville, Whakataka, Cox's Bay and Hobson), with Hobsonville being the least contaminated (Table 2). These five sites were initially selected from information supplied by the ARC stormwater RDP programme, and from the NIWA FRST project "Estuarine Ecodiagnostics" as exhibiting a range of contamination in copper, zinc and lead (Table 2). Following discussions with Melanie Skeen (ARC) and Shane Kelly (ARC), this gradient needed to be extended to cover higher levels of contamination. In the first year, a site on the Upper Whau, with high concentrations of total copper, zinc and lead was chosen for a transplant experiment as no cockles were present naturally. In the second year, two new sites extended the gradient in both directions. and both were located in the Manukau Harbour. The 'Airport' site was located off the Wiroa Island on the central eastern side of the Manukau. The sediment at this site was similar to Cox's Bay with a high sand percentage, but exhibited the lowest level of metal contamination of all sites (Table 2). The 'Anne's Creek' site was situated in the north eastern corner of the Mangere inlet (Figure 2). While the majority of this inlet is comprised of fine silty sediment, the site was located on the edge of the creek channel and so contained coarser material with a relatively high gravel fraction. Sediment granulometry at the 'Anne's Creek' site was most similar to Whakataka (Table 1). Contamination at this site was high and comparable with Cox's Bay and Whakataka sediment (Table. 3.2).

Table 1:

Location and sediment type for the sites at which studies were conducted. Information from the ARC stormwater RDP programme, and from the NIWA FRST project "Estuarine Eco-diagnostics". New sites, Airport and Anne's Creek data from 2009.

Site	% coarse >500µm	% medium-fine 500µm - 63µm	% Silt-clay <63µm	Easting	Northing
Pollen Island	4	89.40	7	2660470	6479877
Hobsonville	7.10	90.80	2.12	2660106	6487972
Whakataka	14.91	72.95	12.15	2671621	6481222
Hobson	0.25	91.32	8.43	2670318	6481539
Cox's Bay	0.44	96.31	3.26	2664141	6482090
Whau	0.35	65.02	34.63	2659908	6476560
Airport	0.55	99.31	0.13	2671705	6463215
Anne's Creek	18.47	79.66	1.87	2672462	6472930

Figure 2:

a- Site locations in the Central Waitemata 1.) Hobsonville 2.) Pollen Island 3.) Cox's Bay 4.) Hobson 5.) Whakataka & 6.) The Whau transplant site.

b- Site locations in the Manukau Harbour 7.) Anne's Creek 8) Airport.

Table 2:

Information on zinc (Zn) , copper (Cu) and lead (Pb) concentrations (as mg.kg-) for both the waek extraction of the <63µm fraction and the total extraction from the < 500µm fraction, in 2008 and 2009 are from the locations in which cockles were sampled. Cumulative contamination level or CCU (Cumulative Criterion Units). CCU was derived by normalising the individual metal levels against the NOAA sediment guideline TEL value and summing across all metals.

Site	Date	<63 µm sediment weak extraction				<500 µm sediment total extraction			
		Zn	Cu	Pb	WCCU	Cu	Zn	Pb	TCCU
Airport	2008	x	x	x	x	x	x	x	x
Airport	2009	58	5.8	12	0.98	0.7	10	1.8	0.1
Hobsonville	2008	120	21	31.7	2.47	2.6	24.3	6.1	0.5
Hobsonville	2009	120	23	33	2.56	2.3	25	5.8	0.4
Pollen Island	2008	150	19.7	37.7	2.85	5.5	44	13.3	0.9
Pollen Island	2009	150	20	39	2.89	6.5	52	15	1.1
Hobson	2008	113.3	22	47.3	2.89	8.7	69.7	26.7	1.7
Hobson	2009	130	26	57	3.41	5.8	62	21	1.3
Cox's Bay	2008	163.3	31.3	50.3	3.64	2.2	37.7	5.8	0.5
Cox's Bay	2009	150	31	48	3.46	3.2	44	6.8	0.6
Whakataka	2008	102.3	17	36	2.34	12.3	106.7	30	2.2
Whakataka	2009	110	20	42	2.65	6.4	81	20	1.4
Whau	2008	358	48	102	7.17	30.2	288	40	4.3
Whau	2009	x	x	x	x	x	x	x	x
Anne's Creek	2008	x	x	x	x	x	x	x	x
Anne's Creek	2009	130	16	24	2.19	19	140	24	2.6

4 Contaminant effects on cockle feeding

4.1 Introduction

Cockle feeding has the potential to have an important effect on the degree to which contaminated sediment leaves the water column and is deposited at a site. The rate at which cockles feed can potentially be used a sublethal measure of response to contaminant levels, and is certainly affected by the amount of sediment suspended in the water column (Hewitt et al. 2001). We conducted an initial laboratory experiment (2008) to investigate the potential effect of storm-water contamination on feeding rates of large cockles and interactions between these and effects of suspended sediment concentrations.

Following this experiment there were still aspects of feeding that remained unmeasured, which could have important implications for cockle-contaminant interactions. All our feeding measures had been based on a particular size of cockle (~21mm longest shell dimension) feeding at a specific density (moderate 5 cockles / 53cm^2 or 900 per m^2). We also had no measures of whether the production of biodeposits was greater when cockles were feeding on contaminated sediment or whether this aspect of feeding was also reduced. To understand these potential relationships we conducted new laboratory experiments in 2009 on:

- The effect of size on feeding rates.
- The effect of density on feeding rates.
- The effect of contaminant on biodeposit production rates.

Information collected from these experiments also allowed us to look at whether there were any relationships between contamination and cockle condition. This would help determine whether the decline in cockle abundance associated with contamination is solely a function of the response of larvae and juveniles, or whether changes we observe in feeding rates lead to decreased health of adult cockles with the potential for decreased reproduction and increased mortality.

4.2 Methods

For all experiments, cockles collected from the field were held in 2 μm filtered seawater over night before initiation of experiments. All experiments were conducted at a constant temperature of 22°C and a light:dark cycle consistent to that of autumn conditions. All aquaria were lightly aerated over the duration of the experiments to provide oxygen and to keep the particles in suspension (and therefore available for consumption). Feeding rates were calculated over a 1 hour period, a time period which had been determined by monitoring removal of chlorophyll *a* (in algae added treatments) at two of the sites. Feeding rates were calculated as the difference between suspended sediment concentrations in controls (no cockles) and treatments (with cockles), divided by the time period of the experiment (1 hr). They were corrected for animal size, either by longest dimension or dry flesh weight. Suspended sediment concentrations were determined by filtration through GFF filters, with the filters being dried overnight at 60°C to constant weight.

4.2.1 Contaminant effects on feeding rates

In 2008, five cockles from each of five sites in Waitemata Harbour (Pollen Island, Hobsonville, Hobson, Whakataka, Cox's Bay), together with Hobson cockles that had been transplanted to a site in the Upper Whau site 1 month previously, were placed in each of 6 aquaria (500ml) which were then randomly selected to have either additions of algae or site sediment (resulting in 3 replicates of each treatment). All sediment was wet-sieved using a 63µm sieve to reduce the sediment to the portion most likely to be resuspended and fed on by cockles. A further 2 aquaria devoid of cockles were set up as controls to determine background settling rates of the treatments. Algal additions were used to give estimates of best feeding rate while site sediment was used to estimate normal feeding rate at the site.

In order to determine whether cockles quickly responded to changes in degree of contamination in sediment by reducing feeding, a further experiment was run. A dilution series of contaminated sediment was made and kept at 1°C for a month prior to the experiment to allow equilibration of the contaminants in the two sediment types. The series consisted of: Sediment Control = clean sediment only (sourced from Hobsonville), T1 = 90:10, T2 = 70:30, T3 = 50:50, T4 = 30:70, T5 = 10:90 (clean: contaminated sediment (sourced from Upper Whau)). All dilutions were made to a final exposure concentration of 100 mg/L sediment. For each site, five cockles were placed in each of 18 aquaria (500ml) which were then allocated randomly to treatments.

4.2.2 Size-feeding rates

In 2009, experiments on smaller sized cockles (15 – 20mm) were run using cockles from 4 sites spread across the contaminant gradient from both Waitemata and Manukau (Airport, Hobsonville, Cox's Bay and Anne's Creek). From each site, five cockles were placed in each of six replicate 4 L containers. Each container was then fed either algae or uncontaminated sediment, sourced from the Airport site (resulting in 3 replicates of each treatment). Feeding rates of these small cockles were compared with those of the large cockles in the second density-feeding rate experiment.

4.2.3 Density-feeding rates

In 2009, two different types of experiments were run on the effect of density.

- The first looked at whether cockles living in different density cockle beds had different feeding rates, and whether this was affected by contaminant levels. Cockles from 7 sites were used in this experiment: the sites used in the 2008 field experiment and two sites from Manukau (Airport and Anne's Creek). Four 0.20 m^2 areas at each site were enclosed by a 100 mm high plastic mesh (10 mm aperture).

Cockles within these enclosed plots were removed and new cockles of appropriate size (small = 15 – 20mm, large = 23-26mm) and number (low density = 255 cockles per m^2, high density = 1200 cockles per m^2) were added. Plots with two cockle densities and two size ranges of cockles were established at 7 sites, although the plots with different size ranges were only utilised for the movement experiments (see section 6.2). After 1 month, five cockles from each different density were randomly allocated to each of three replicate 4 L containers. Each container was then fed algae and water samples were taken and filtered immediately after feeding and then 1 hr later. This experiment was run on cockles from Hobsonville, Cox's Bay, Pollen Island, Whakataka, Hobson and Anne's Creek, as not enough cockles were collected from the Airport to perform both this experiment and the experiment detailed below..

- ❑ In case the response of feeding rates to density happened quickly and could affect the feeding we had measured in our laboratory experiments, a density gradient was also established in the laboratory for 4 of the sites spread across the contaminant gradient (Airport, Hobsonville, Cox's Bay and Anne's Creek). For each site, cockles were randomly allocated to different densities (2, 5, 8, 10, 12, 15, 18 and 20 cockles per 4 L container). Similar to the size-feeding rate experiment, each container was then fed either algae or uncontaminated sediment. Water samples were taken and filtered immediately after feeding and then 1 hr later.

4.2.4 Contaminant-biodeposit production rates

For each of 7 sites (Airport, Hobsonville, Cox's Bay, Pollen Island, Whakataka, Hobson and Anne's Creek) a set number of cockles were randomly allocated to 4 large (12 L) containers. The number of cockles varied for each site from 30 – 50. Numbers used depended on how many cockles had been collected in the field. The maximum possible was used for each site as the aim was merely to collect as much biodeposit material as possible. Each container was then allocated to be fed twice daily either uncontaminated or contaminated sediment. At the end of 50 hrs, the cockles were removed and kept over night in filtered seawater before being frozen, and all biodeposits were removed and stored in the dark at 1°C. Non-contaminated sediment was sourced from the Airport site while contaminated sediment was sourced from Anne's Creek. Contaminated sediment had approximately twice the contaminant levels of non-contaminated sediment. In both cases the sediment was collected a month prior to the experiments and sieved on 63μm mesh.

4.3 Contaminant effects on feeding rates (laboratory experiment 2008)

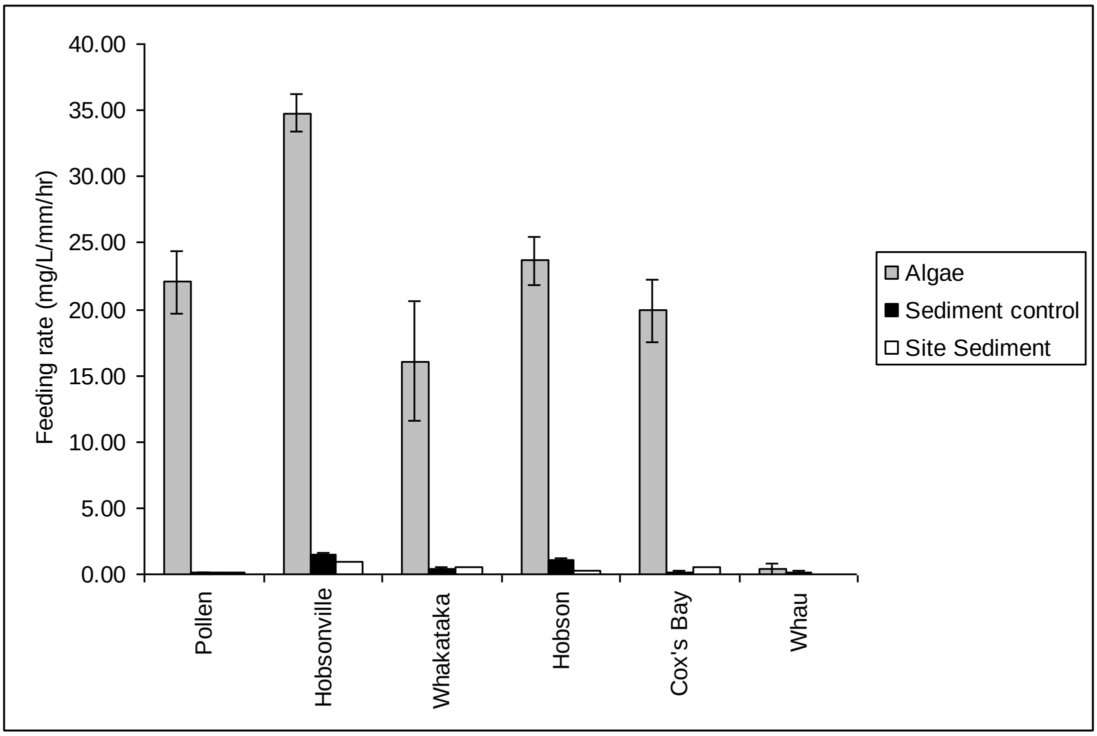
4.3.1 Site contaminant effects on feeding rates

All cockles other than those that had been transplanted from Hobson to the Upper Whau site ("Whau") one month before collection for the laboratory feeding experiment, displayed much greater feeding rates when fed algae than when fed sediment slurries (Figure 3). The "Whau" cockles did not appear to feed at all, regardless of what they were fed. This response suggests that site contamination may be a factor contributing to the lack of cockles occurring naturally at the Upper Whau site.

Negative correlations were observed between all metals and both best (algae) and normal (site sediment). The strongest correlations were with the metal concentrations measured on the < 500µm fraction (total metals). For algae, all correlations with the total metals were > 0.90; for site specific sediment, correlations with total copper and total zinc were > 0.90.

Figure 3:

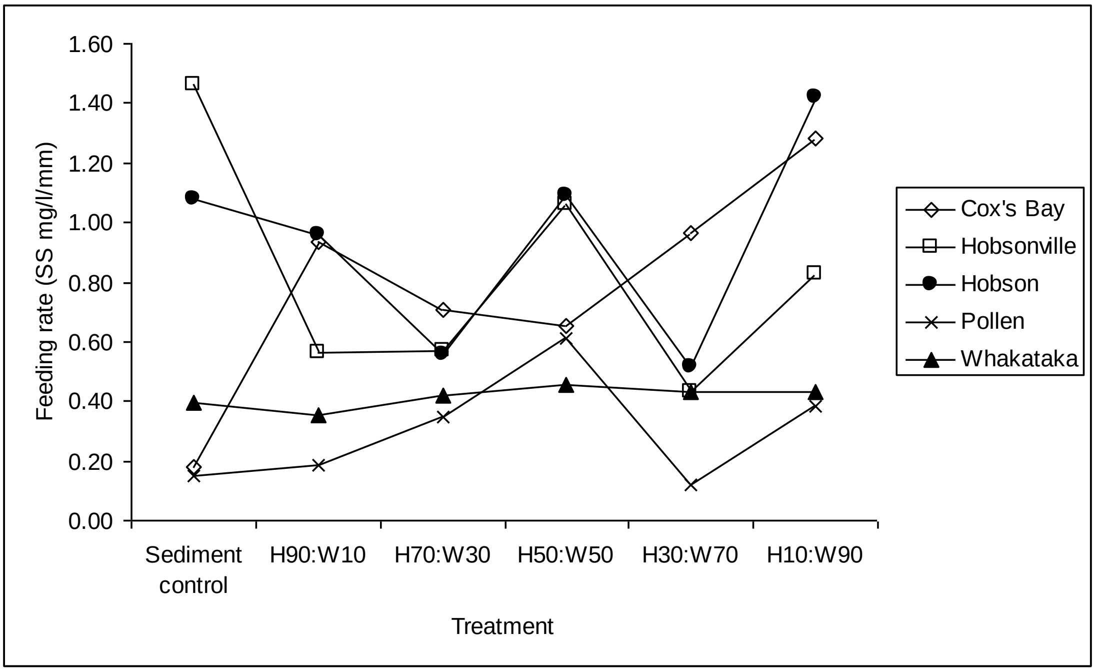
Size normalised feeding rates of cockles from five sites in the Waitemata Harbour, plus Hobson cockles that were transplanted to the Upper Whau site.



4.3.2 Responses to changing contamination

The response of cockles to the dilution series of contaminated food varied considerably (Figure 4), with cockles from some sites showing an apparent positive relationship i.e., displaying higher feeding rates with increasing contaminant level (e.g., Cox's Bay) and others a neutral or negative relationship (Whakataka, Hobsonville). Analysis of Variance (ANOVA) revealed a significant site difference (p=0.004) but no significant difference in feeding rates associated with treatment (p=0.37), due mainly to high variability. However, when feeding rates were normalised against the uncontaminated sediment control (by dividing the feeding rate for each treatment by the feeding rate for the sediment control) a clearer pattern was revealed. Analysis of Variance (ANOVA) of the normalised feeding data revealed a significant site difference (p<0.0001) and a marginally significant treatment difference (p=0.056) of decreasing feeding rates with increased contamination.

Figure 4:
Feeding rates (suspended sediment removed (mg/L/hr) adjusted for cockle size in mm) of cockles from 5 sites exposed to 6 treatments (a mix of uncontaminated (H) and contaminated (W) sediment).



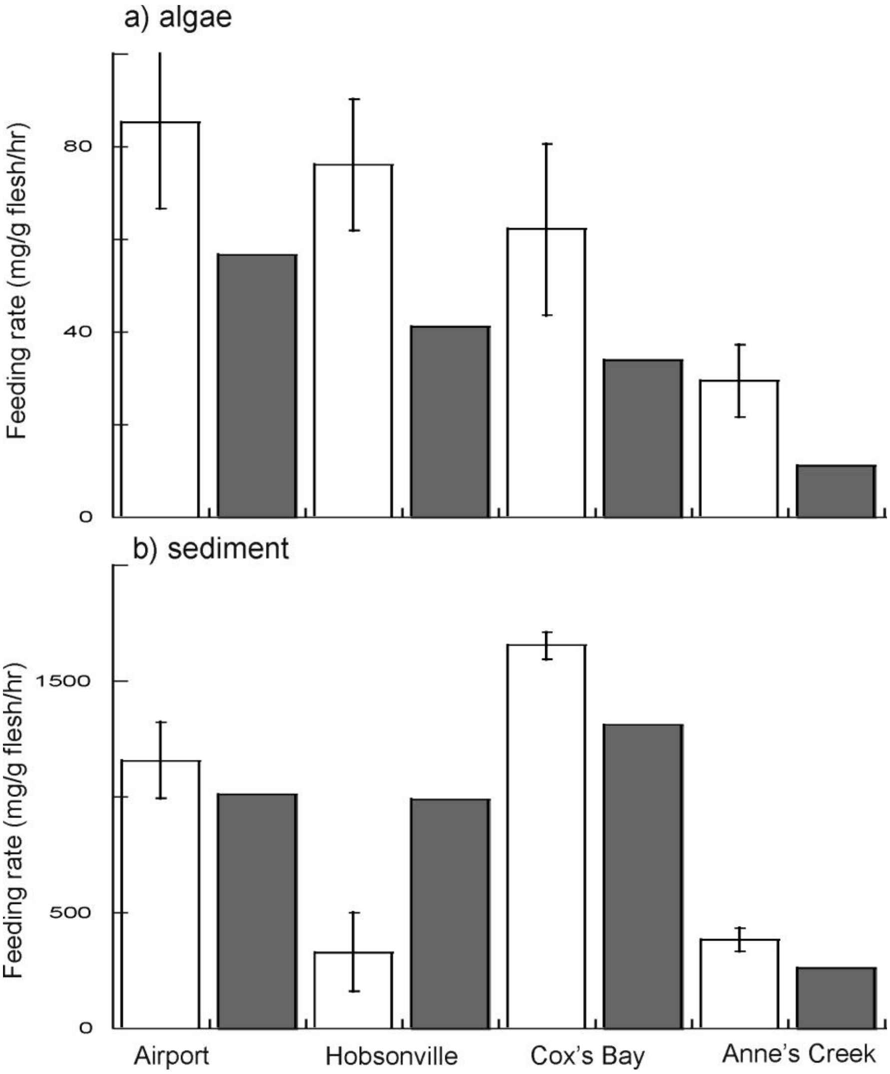
Results suggest that cockles from the more contaminated sites are feeding at a lower rate on clean sediment (sediment control). The variability in the response of cockles from different sites to the dilution series results in a weak overall response to the dilution series. Together these results suggest that the cockle feeding response is not directly linear and that there may be "trigger levels" of contamination which initiate a change in feeding response.

4.4 Effects of size on feeding

At all sites, smaller cockles exhibited higher feeding rates on algae than larger cockles varying from a 1.5 – 2.6 increase (Figure 5). Feeding rates of both small and larger cockles were less for cockles from more contaminated sites, but this effect was stronger for the smaller cockles. This resulted in a significant negative relationship between the ratio of feeding rates of small vs large cockles with that of total zinc, lead and copper concentrations and the overall TCCU index (Pearson R of -0.98, -0.96, -0.96 and -0.97 respectively).

Small cockles fed on sediment rather than algae generally exhibited similar relationships, however, small cockles from site Hobsonville exhibited highly variable feeding rates.

Figure 5:
Feeding rate exhibited by small cockles (white) compared to large cockles (shaded) when fed a) algae and b) non-contaminated sediment.

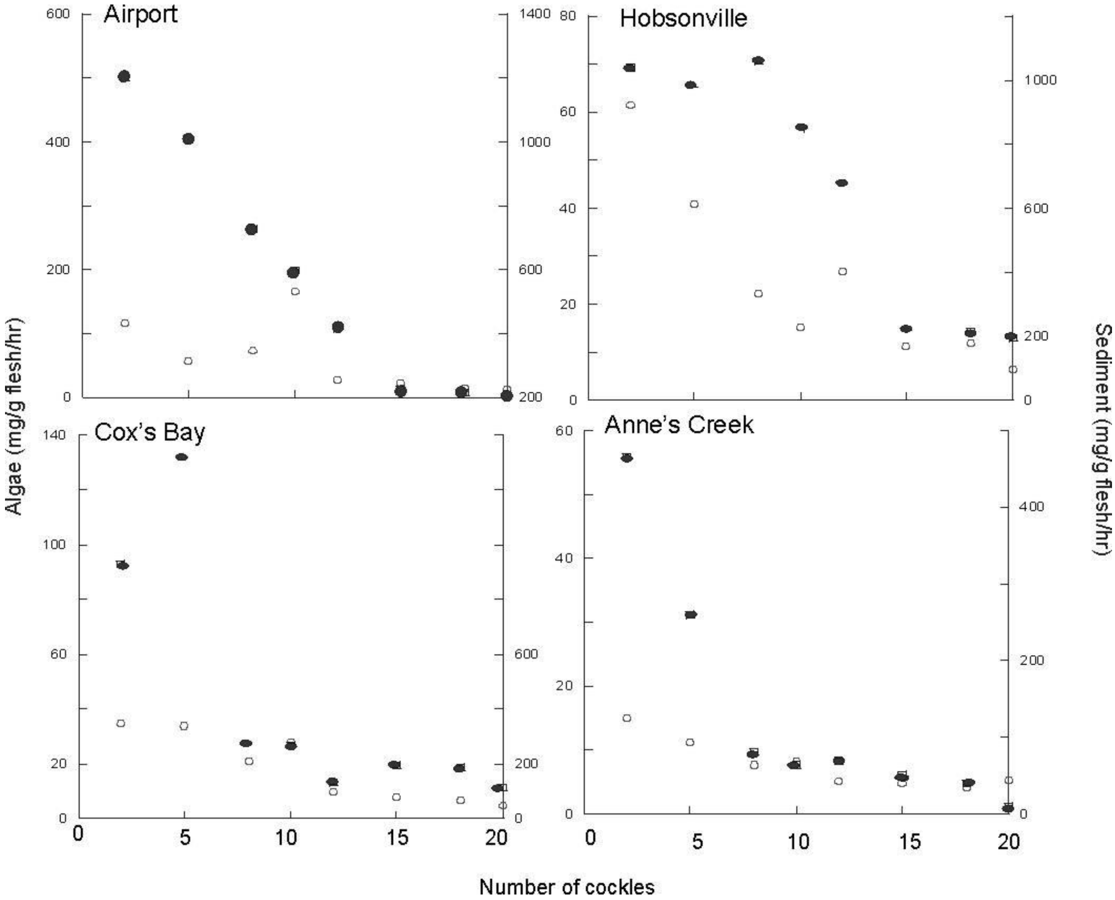


4.5 Effects of density on feeding

Cockles retrieved from different field densities, did not show any significant difference in feeding rates. However, there was a significant negative relationship between the observed feeding rates with that of total zinc and copper concentrations and the overall TCCU index (Pearson R of -0.88, -0.83 and -0.84 respectively). The strongest negative correlation occurred when the contaminant indices created from both the weak and total extracted metals (WCCU and TCCU; Section 3.1) were averaged together to produce a single index (Pearson R of -0.96).

Diminished feeding rates along the density gradient established in the laboratory were observed for cockles from all sites (Figure 6). For cockles fed on algae, feeding was high, although variable, until densities of 8 – 10 cockles were reached when feeding began to decrease. For cockles fed on contaminants, the decrease in feeding began at a lower density. Feeding rates also displayed strong negative responses to contaminant levels.

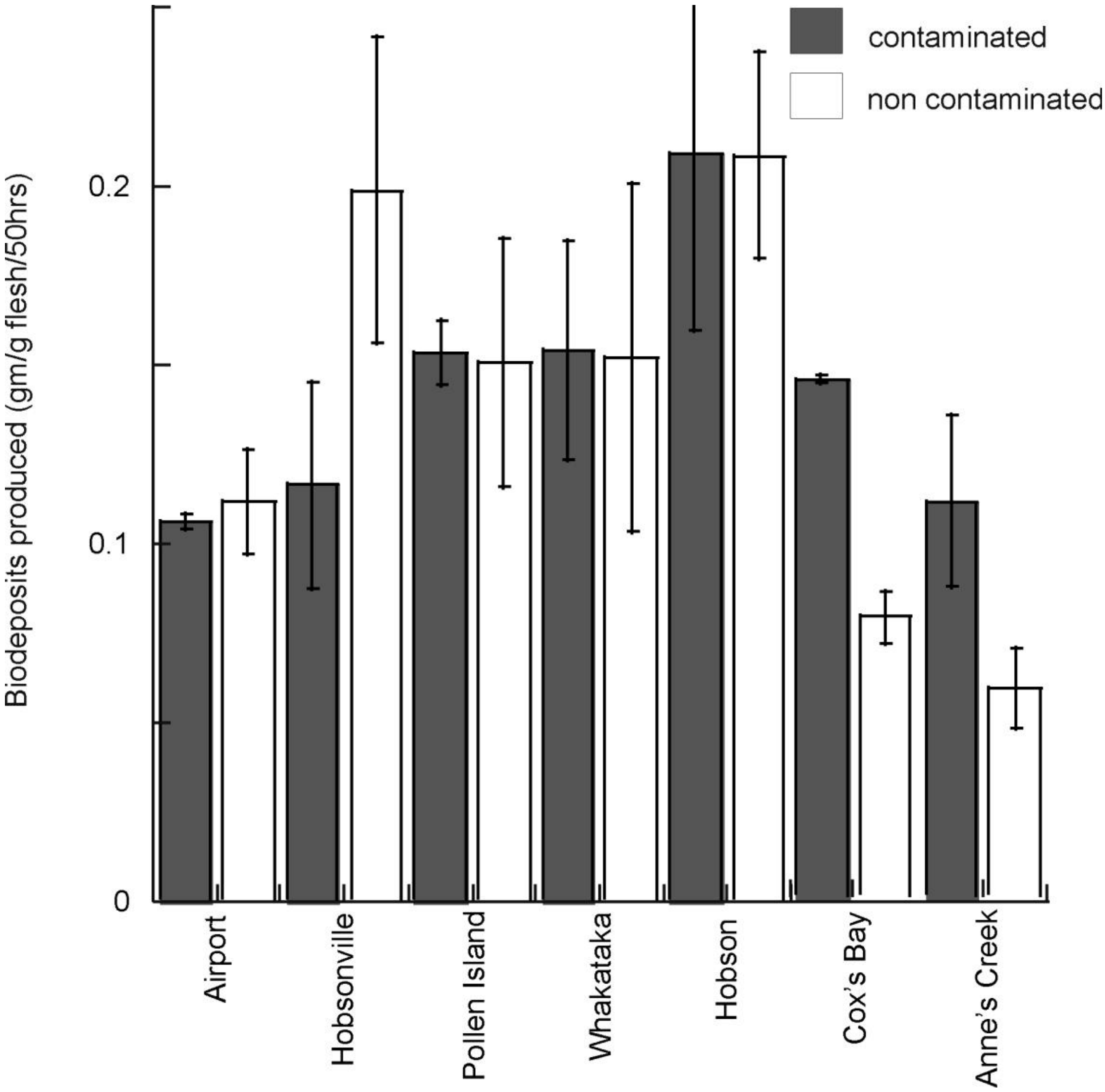
Figure 6:
The relationship between cockle density and feeding rates for: algae (o) or sediment (infilled circle).



4.6 Contaminant effects on biodeposit production rates

Biodeposit production rates of cockles did not show a response to site sediment contamination (Figure 7), nor was there a clear response to the type of sediment cockles were fed. Comparison at each site between cockles fed contaminated vs. non-contaminated sediment shows that the 2 least contaminated sites (Airport and Hobsonville) had higher biodeposit production when fed non-contaminated sediment, and the 2 most contaminated sites (Annes Creek and Cox's Bay) had higher biodeposit production when fed contaminated sediment.

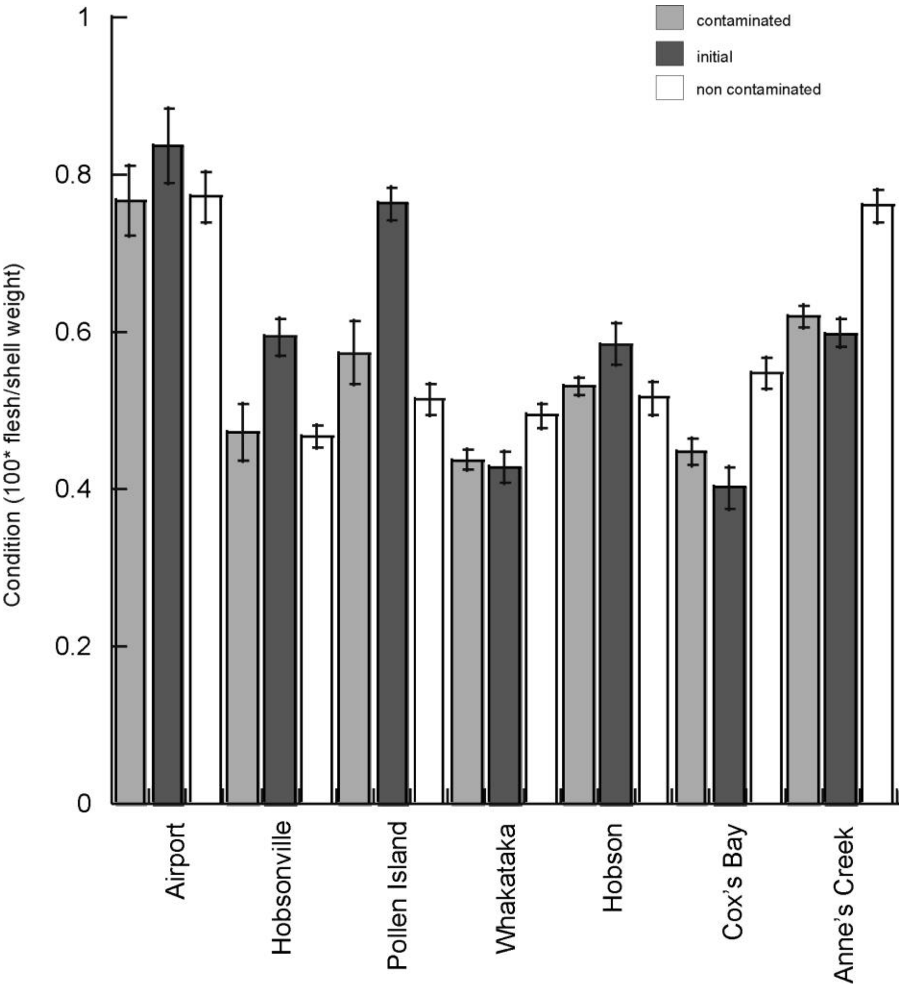
Figure 7:
Biodeposit production rates at each site when cockles are fed either contaminated or non-contaminated sediment.



4.7 Condition

Condition of cockles (measured as dry flesh weight to shell weight on 15 cockles) collected from the 7 sites showed no clear response to site sediment contamination. Generally, condition of the cockles after being fed sediment for 50hrs was lower than the condition found in the field (Figure 8). Interestingly, there was a strong negative relationship for cockles fed contaminated sediment between the change in condition and the degree of site contamination (Pearson R of -0.72, -0.80 and -0.74 for correlations with total zinc and copper concentrations and the overall TCCU index respectively). That is, cockles from more contaminated sites lost more condition when being fed contaminated sediment than cockles from less contaminated sites. This may have been related to the potentially poorer quality of the contaminated sediment, although we did not test food quality.

Figure 8
Cockle condition found at each site (initial) and after 50 hrs of being fed contaminated or non-contaminated sediment.



4.8 Summary

Our experiments show that when algae are available at high concentrations, cockles will actively feed and assimilate this food resource, thereby producing few biodeposits. In contrast, at high sediment concentrations, filtering activity is also very high, with concomittant high biodeposit production. This much greater feeding activity and lower biodeposit production associated with algae when compared to sediment indicates that cockles are able to differentiate between organic and inorganic material. This is not surprising, as marine bivalves are known to be able to differentiate feeding on the basis of food quality (Cucci et al. 1985; Safi et al. 2005). Also, Riisgård et al. (2003) found that *Cardium edule*, *Mytilus edulis* and *Mya arenaria* reduced their feeding in the absence of algal cells. This was also inferred from a study on the combined effects of anoxia and reduced food availability in the clam *Paphies australis* (Norkko et al. 2005).

The results of our experiments across both years indicate that site sediment contamination is associated with reduced feeding rates in cockles, although the response is moderated by the composition of food. In addition, it appears likely that cockles from contaminated sites may consume a greater component of poor quality food in an effort to satisfy feeding requirements. This is indicated to some extent by the response to food-borne contamination, which showed that cockles from the most contaminated site displayed higher feeding rates when fed more contaminated sediments than cockles from less contaminated sites. Cockles from less contaminated sites may simply have shut down, awaiting a time when better quality food would be presented. Similarly, in the second years experiments, cockles from more contaminated sites appeared less resilient, i.e., they lost condition more quickly when being fed contaminated sediment than cockles from less contaminated sites.

Importantly, the negative effect of contaminants on feeding rates was stronger for small cockles, decreasing their generally higher feeding rates. Increased contamination also increased the negative relationship observed between feeding rate and cockle density in the laboratory. From the results of these experiments an equation relating cockle feeding rate to cockle size, density and contaminant levels was developed for use in the complex system model (Section 7). The model was derived using a multiple stepwise regression to determine a set of useful predictor variables, that were uncorrelated, from cockle size and density and sediment grain size, and contaminant information, using backwards elimination at $\alpha = 0.15$.

$$FR = 1122.5 - 187.4 \ln CD + 234.6 \ln SS - 7.7\, Cu$$

Where FR = removal of SS from water as $mg.L^{-1}.hr^{-1}.g^{-1}$

and CD = cockle density x average weight,

SS = suspended sediment concentrations ($mg.L^{-1}$)

Cu = concentration of copper at a site ($\mu g.g^{-1}$)

Filtering bivalves show considerable plasticity in their ability to take advantage of food sources available within the water column. Selective mechanisms exist both externally and internally (within the gut passage). It has been suggested that regulation of feeding rate to optimize energy balance may be a better strategy compared with regulation of digestion and assimilation, which uses significantly more energy (17% of total feeding cost) compared to the metabolic cost of mechanical pumping (<3% of total feeding cost) (Widdows and Hawkins 1989; Hawkins et al. 1998). Reduction in ingestion rate of contaminated food sources has been demonstrated in the suspension feeding clam *Potamocorbula amurensis* (Decho and Luoma, 1996). These authors also demonstrated that this species was capable of modifying its digestive processing of food particles to reduce exposure to high levels of metals during prolonged exposure. They found a significant decrease in the mean proportion of contaminated bacteria processed by glandular digestion in elevated Cr (III) concentrations. Digestion times were reduced and therefore the potential risk of contaminant accumulation reduced. However, a reduction in carbon assimilation was also observed. There is clearly a trade-off between gaining sufficient nutritional benefits from prolonged digestion and increased assimilation of contaminants.

The decreases in feeding rates we observed were more strongly correlated with the metal concentrations measured on the < 500µm fraction (total metals). The <63µm fraction of metals is more commonly considered to represent biologically available concentrations as it represents the size fraction that invertebrates are likely to feed on.

Furthermore, the weak acid-digestion extraction method (used to assess the <63μm metal fraction) is thought to be representative of digestive processes in an acidic gut system. However, the level of contaminants in the <63μm fraction of local sediments may not reflect the level of contaminants in the cockle food supply as a whole. Suspension feeders feed from the water column across a range of particle sizes (up to 180μm, although the most likely fraction may be the 2 – 20μm size. While the <63μm fraction is most likely to be resuspended, at sites with a low proportion of such sediments, feeding is more likely to occur on matter that is either sourced from elsewhere (as suspended material transported into the site) or is planktonic in nature. Thus, at sites with higher contamination in the <63μm than the <500μm fraction, but with a low proportion of fine sediment available within the site, suspension feeders may be feeding on a diet that is proportionally less site-related, and may well be less contaminated.

Interestingly, feeding rates on both the clean sediment and the site sediment showed strongest relationships with copper concentrations. This finding supports analysis of the ARC Regional Discharge Programme site data by Hewitt et al. (2009), which found abundance of cockles to be more strongly related to total copper concentrations than to zinc or lead.

5 Effects on contaminant levels

5.1 Introduction

We also wanted to determine whether uptake rates of contaminants by cockles differed depending on whether the cockles had been exposed to contamination for a long time and whether cockles discriminated against contaminated sediment when feeding. While the second question could be partially answered by the contaminant-biodeposit production rates experiment discussed in the previous section, further evidence could be gained from the levels of contaminants found in cockle tissue and biodeposits. Finally, we needed to know whether biodeposits settling rates were affected by contaminants as this would determine whether resuspension of sediment from sites within the model had to be adjusted for contaminant levels.

5.2 Methods

5.2.1 Levels of contaminants found in tissues

For each site, a random selection of cockles were taken immediately after collection in the field, and and after being fed contaminated or non-contaminated sediment for 50hrs. Cockles were depurated for 2 hrs then their flesh was removed, freeze dried and ground before being analysed for total copper, zinc and lead.

5.2.2 Levels of contaminants found in biodeposits

After biodeposits from the contaminant-biodeposit production rates experiments had been freeze dried and weighed a subsample was taken and ground for metal analysis. Both total and weak extraction methods for copper, zinc and lead were used.

5.2.3 Biodeposit settling rates

Small aliquots of biodeposits were introduced into a 1000ml measuring cylinder filled to the 1L mark. The time taken for the first and last biodeposit particle to drop 12cm was recorded. This procedure was repeated three times for each of the five sites. Data were averaged and rates (in mm/second) were calculated.

5.3 Uptake of contaminants from sediments- results

Cockle tissue had higher levels of contaminants this year than last copper 1.3 – 3 x, lead <1.8 x, zinc 1.1- 1.4 x (Table 3).

Table 3:

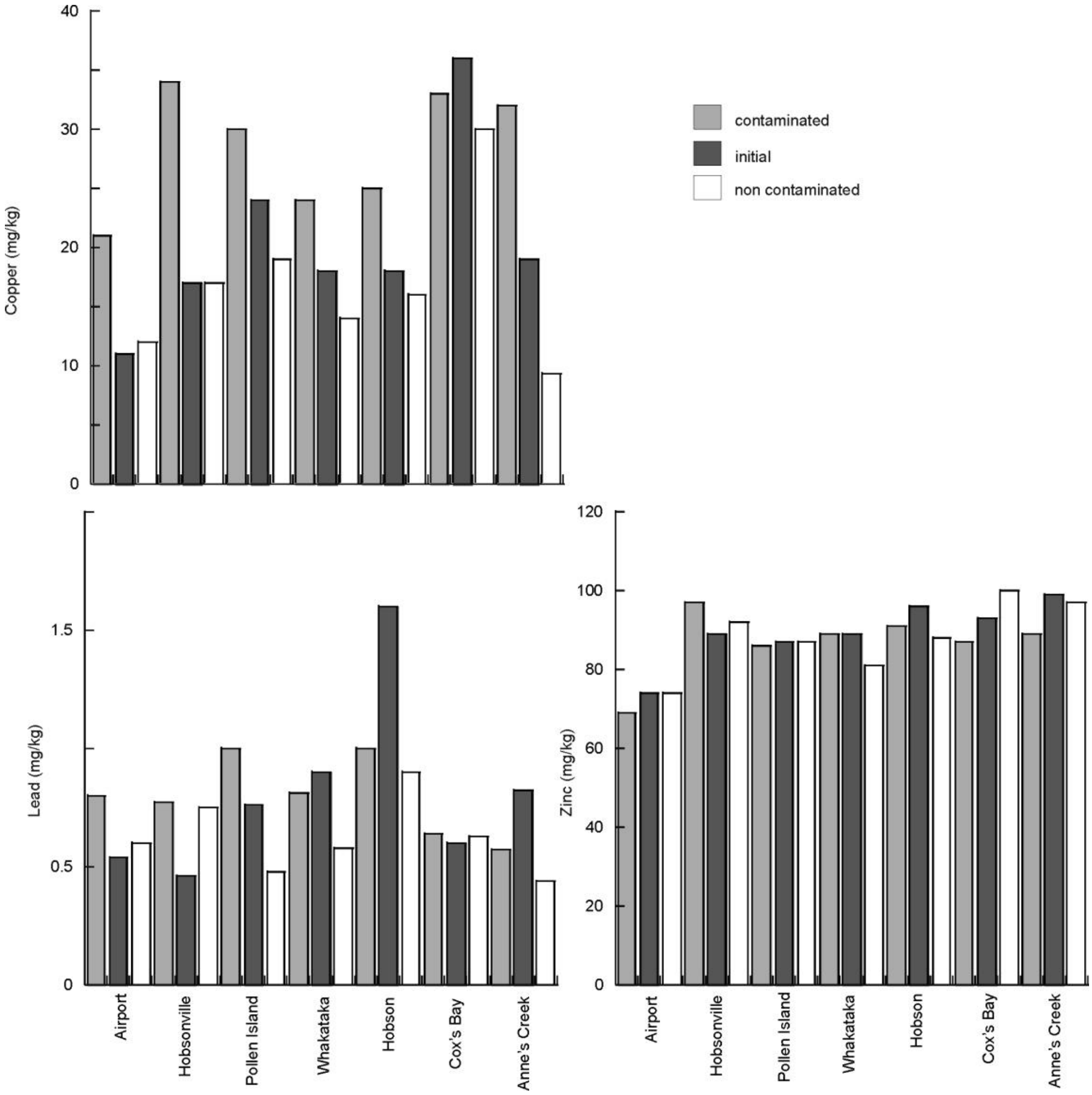
Levels of heavy metals (as total extracted mg/kg) found in cockle tissue in 2008 and 2009.

	Year	Copper	Lead	Zinc
Airport	2009	11	0.6	74
Pollen Island	2008	8.05	0.53	79
	2009	24	0.76	87
Hobsonville	2008	13	0.25	68
	2009	17	0.46	89
Whakataka	2008	10.8	1.5	71
	2009	18	0.9	89
Hobson	2008	12	1.035	69.5
	2009	18	1.6	96
Cox's Bay	2008	23.5	0.515	75
	2009	36	0.6	93
Anne's Creek	2009	19	0.8	99

Based on both years data, cockles accumulated more copper, than zinc or lead. Lead values in tissues were around 0.1 of the levels (total extracted) in the surrounding sediment. For zinc the average accumulation level (tissue concentration / sediment concentration) was 2.2, while for copper it was 5.4. However while cockles from more contaminated sites had higher levels of contaminants in their tissues, this was not a simple relationship; in fact the degree of accumulation was inversely related to contamination (Copper Spearmans ρ = -0.86, Lead Pearson R = -0.78, Zinc, Spearmans ρ = -0.99). That is, cockles from contaminated sites had accumulated fewer mg/kg of metals than would have been predicted by rates observed at non-contaminated sites.

Contaminant levels in cockle tissues showed relatively rapid changes with food source (Figure 9). Over the 50 hrs of the experiment cockles from contaminated sites became less contaminated when fed non-contaminated sediment, while cockles from non-contaminated sites became more contaminated when fed contaminated sediment.

Figure 9:
Contamination levels found in cockle tissues at the start of the experiment (initial) and after being fed contaminated or non-contaminated sediment for 50hrs.



5.4 Contaminant levels in biodeposits- results

Copper concentrations in biodeposits, from the cockles fed contaminated sediment, were not significantly different from the input sediment, however, lead and zinc concentrations were slightly elevated (29 vs 23.5 mg.kg-1 and 130 vs 105 mg.kg-1 in the biodeposit vs input sediment for lead and zinc respectively). This suggests that the sediment filtered out of the water column by cockles is a sediment fraction having heavy metals bound to it, and the copper is more frequently stored within the cockle tissue, while the other two metals are passed out in the biodeposits. The degree of elevation observed was not related to the contaminant level of the site that the cockles were originally collected from.

5.5 Biodeposit settling rates- results

Differences were observed between sites for the biodeposits produced immediately after collection. These differences are most likely to be driven by sediment particle size as no significant difference was observed between settling rates of biodeposits produced by the contaminated and non-contaminated sediment (Table 4).

Table 4:

Settling rates as time of minutes taken for the first and last biodeposit to travel 12 cm.

Site	Type	First	Last
Airport	Site	1.52	2.09
	Contaminated	2.69	3.88
	Non-contaminated	2.12	3.24
Hobsonville	Site	2.53	3.32
	Contaminated	2.62	4.32
	Non-contaminated	2.74	5.01
Pollen Island	Site	1.89	2.77
	Contaminated	3.16	5.18
	Non-contaminated	2.74	5.85
Whakataka	Site	2.67	3.84
	Contaminated	1.98	3.11
	Non-contaminated	2.67	4.08
Cox's Bay	Site	1.85	2.31
	Contaminated	1.06	1.76
	Non-contaminated	2.04	3.93
Hobson	Site	1.89	2.77
	Contaminated	1.79	1.72
	Non-contaminated	2.89	5.04
Anne's Creek	Site	0.83	1.35
	Contaminated	1.91	2.96
	Non-contaminated	1.40	2.71

5.6 Summary

Based on both years data, cockles accumulated mainly copper, with some zinc and little lead. Contaminant levels in cockle tissues showed relatively rapid changes (significant changes over 50 hrs) with food source. The degree of accumulation was inversely related to contamination, with cockles from contaminated sites accumulating less metals than those from non-contaminated sites. However, this is most likely to be associated with the decreased feeding rates observed for cockles from these sites, rather than an ability to discriminate when feeding.

The lack of any observed difference in settling rates of biodeposits based on contamination will make modelling of the effect of cockles on resuspension easier.

Model predictions will be able to be based solely on site particle size and not have to include changes associated with interactions between biodeposit production, contamination and ability for resuspension.

6 Contamination effects on cockle movement and sediment resuspension

6.1 Introduction

Cockle movement may have implications for the degree of contamination observed in surficial sediment, as they constantly mix the top 2 – 4 cm of sediment. While this may be insignificant compared to the degree of mixing occurring within this zone by physical forces (waves and currents), at present there are few estimates of cockle movement rates on which to base this assumption.

Dependent on the rate of mixing by cockles, the surface sediment may be made more fluid and thus more susceptible to resuspension by waves and currents. The rate of mixing is likely to be affected by density in a number of ways: (i) above a certain density, increasing densities of cockles increases the number of times a feeding cockle is forced below the sediment as other sub-surface cockles try to obtain a feeding position; (ii) increasing densities may decrease the amount of horizontal movement by non-feeding cockles on the sediment surface (Whitlatch et al. 1997, Cummings et al. 2007)). Cockle density can also interact with hydrodynamics, with low densities of cockles increasing surface roughness and thus the amount of turbulent flow produced by currents available to resuspend sediment and very high densities armouring the surface against resuspension by both currents and waves.

Cockle densities have been predicted to decrease with increasing contamination by copper (Hewitt et al. 2009), moreover it is possible that there be may be sublethal responses to low levels of copper and the ability of the cockle to move may be decreased. This section therefore explores the potential effect of storm-water contamination and cockle densities on cockle movement and resuspension of sediment.

Three studies were conducted:

- A field experiment, conducted in 2008, measuring cockle horizontal movement and suspended sediment concentrations against a gradient in storm-water contamination and cockle density.
- A laboratory experiment, conducted in 2008, measuring cockle vertical and horizontal movement and suspended sediment concentrations against a gradient in storm-water contamination, investigating the effect of different sediment types. The repetition between this study and the field study would increase our confidence that other naturally occurring gradients were not affecting the results of the first study.
- A second laboratory experiment, conducted in 2009, investigated the potential for cockle size and density, as well as the level of heavy metal contamination, to influence cockle movement.

6.2 Methods

6.2.1 Field measurements

Five intertidal sandy sites from Waitemata (Pollen Island, Hobsonville, Cox's Bay, Hobson and Whakataka) were used as study locations for a field experiment conducted between February to March 2008. At each of the sites, 6 x 1.44 m^2 plots were set up, along a transect, spaced approximately 12 m apart. In the central 0.64 m^2 (0.8m x 0.8m) of each plot, cockles were removed by hand and a 100 mm high mesh wall (10 mm aperture), 50 mm above/below the sediment surface) inserted into the sediment >20 days before the start of the experiment, to prevent re-entry of large cockles into the plots.

At all sites, after 20 days[1], each plot was randomly assigned to one of 6 cockle density treatments (0, 6, 13, 19, 25 and 38 corresponding to 0, 96, 208, 304, 400 and 608 individuals.m^{-2} respectively) that reflected the range naturally occurring within the Waitemata. The central 0.8m x 0.8m of each plot was divided into 16 square cells (0.2m x 0.2m). Cockles collected around the site were colour coded depending on which cell they were placed and the mesh surrounding each plot removed. DOBIE–OBS wave pressure gauges were deployed next to each plot (approx 0.4m away), to estimate water depth, wave height and the concentration of suspended sediment in the water column 5cm above the sediment surface. Prior to use the DOBIEs were calibrated using sediment similar in character to that of the study sites. DOBIEs sampled at 10 Hz, recording one burst of 1024 points every 10m minutes over the last 12 hrs of the experiment. An Acoustic Doppler Velocimeter (ADV) was deployed on the alongshore edge of each site (20m away) to measure the speed and direction of currents. It was run at 4 Hz frequency, recording one burst of 40 data points every 10 minutes. At each site, the ADV orientation was recorded using a handheld compass to allow calculation of direction and speed.

After 24 hrs, the entire area was excavated, cell by cell, and, for each cell, the cell position and the number of the cockles of different colours recorded. The perimeter around each plot was also sampled for cockles that may have moved between 0-0.3 m and 0.3-0.6 m out from the edge of the plot. The average and the total distance moved were calculated based on changes in cell position over the 24hr period.

6.2.2 Laboratory experiment (2008) – contamination, sediment type, cockle movement and resuspension of sediment

Cockles and sediment for this experiment came from the same sites used for the field measurements (Hobsonville, Pollen Island, Cox's Bay, Hobson and Whakataka). A sixth site was included to extend the gradient (the highly contaminated Whau site to which cockles had been transplanted a month previously from Hobson Bay). Three sediment treatments were constructed that covered the natural range of sediment

[1] Note the measurements were conducted over a time of no rainfall and low wind. A rainfall/wind event did occur while working through the sites and measurements 3 days post this time to allow background conditions to revert to similar for sampling at the first 3 sites.

types inhabitated by cockles in the Waitemata, sand-mud through to sand with shell hash (Appendix 10.1), with a fourth treatment being unaltered site sediment. A range of contamination levels were included by using sediment from each site as a base, while the sediment types to be added were collected from unpolluted sources and stored in 1°C filtered seawater prior to use.

Aquaria (180mm x 180mm x 180mm) were filled with the different sediment mixs to a depth of 60mm. 0.9L of clean seawater was added to each aquaria and allowed to settle for one hour prior to the addition of cockles. For each site, 5 similar sized cockles were randomly allocated to each of three replicates of the four treatments. A control with no added cockles was included to determine the level of resuspension in the absence of cockles.

Suspended sediment concentrations were analysed as an indicator of resuspension at the end of the 24 hour monitoring period. 40 ml water samples were collected from each replicate and analysed using a Hach 2100AN turbidimeter, measuring turbidity in nephelometric turbidity units (NTU). The movement of cockles within the sediment environment was assessed using two approaches.

- Average horizontal movement: The surface of each aquaria was divided into a central zone (18cm x 18cm), and a first, second and outer perimeter (all 2cm wide). At the start of the experiment, five cockles were placed into the central zone. At the end of the 24 hr, all cockles were excavated and their position recorded. Individuals still in the inner zone scored 0 (Figure 3, white), those in the first perimeter scored 1, those in the second perimeter scored 2 and those in the outer perimeter scored 3. The average movement scores were calculated for each treatment, with the score able to range from 0 (no movement, all individuals within the central zone) to 15 (maximum movement, all cockles within the outer perimeter.
- Percent surface area covered by track marks: After 24 hours, the percentage cover of cockle track marks on the surface of the sediment of each aquaria was visually estimated. This measurement, while mainly measuring horzontal movement, does include a vertical component.

6.2.3 Laboratory experiment 2009, contamination and cockle density and size effects on movement

This experiment used cockles from the four size/density plots described in section 4.2.3 that had been established at 7 sites: the sites used in 2008 field experiment and two sites from Manukau (Airport and Anne's Creek). However, lack of large sized cockles at Airport, Hobsonville and Hobson constrained the size comparisons across all sites.

After one month, a quantity of ambient sediment from near the plots and five replicate 100 mm diameter cores from each treatment were brought back to the laboratory. Whole cores, rather than individual cockles, were collected, as video evidence from the previous experiment showed that cockle movement was affected by localized sediment disruptions. Thus, removal of the natural community could result in conservative estimates of cockle movement. Secondly, when cockles are removed from the sediment, they have to rebury before moving and this has the potential to affect their movement behaviour.

At the laboratory, the ambient sediment was sieved over a 2 mm mesh and placed into 300 x 300 mm square aquaria to a depth of approx 50 mm (see Appendix 10.2). Larger aquaria were used compared to the previous experiment as results from that experiment suggested movement may have been constrained by the aquarium size (see section 6.4.1). In each aquarium, a hole was excavated in the ambient sediment and one of the cores inserted. The containers were then filled with 5L of seawater. Air-stones were inserted into each container to gently circulate the overlying water and prevent anoxia. Temperature was maintained at 22°C.

After 36 hours, percentage surface area covered by and a mean movement score was calculated for each aquarium as described in section 6.4.2, for each aquarium that contained at least 2 cockles.

6.3 Field measurements

Cockle movement and sediment resuspension must be viewed not only against the density of cockles but against the wave and current conditions present at the sites. Over the time period of the study, water currents differed between sites (see Appendix 10.3) with Pollen Island and Hobsonville having the strongest flow on both the flooding and ebbing tide, while Hobson and Whakataka sites had lower flows. Technical problems with the ADV prevented data from being recorded at Cox's Bay. At Pollen Island and Hobson Bay the current flooded and ebbed in near opposing directions, however, at the other two sites ebb and flood currents were near perpendicular to each other. Wave energy over the experiment was minimal at Hobson, Whakataka and Cox's Bay, higher at Pollen Island and highest at Hobsonville (Appendix 10.3).

6.3.1 Cockle Movement

Differences were observed between the amount of movement observed at the different sites (Table 5), with Pollen Island and Hobsonville having the lowest percentages of cockles not moving. However, Pollen Island had a high percentage of cockles moving only 20cm. Hobsonville had the highest percentage of cockles moving into the outside area, suggesting that overall movement rates were highest here. Methodological problems at Hobson meant that the data from this site are not given in Table 4.1.

Multiple Stepwise Regression was used to determine a set of useful predictor variables, that were uncorrelated, from the sediment grain size and contaminant information, using backwards elimination at $\alpha = 0.15$. Total distance moved was well predicted (R^2 0.81) by mud content, which had a negative effect, and density, which had a positive effect. Average distance moved was also well predicted (R^2 0.88), in this case by silt content and WCCU (both negative effects).

Table 5:
Mean percent of cockles moving 0 to 4 cells (80cm) and into the outside area, together with the average and total distance (m) moved by cockles at each site. The % area potentially disturbed, assuming a 2cm sized cockle, in the plots with cockle densities of 67 and 420m^2, is also given.

Site	M0	M1	M2	M3	M4	Outside	Average	Total	%area
Pollen Island	54.1	35.6	3.7	0.3	0.7	5.6	0.121	87.3	16 - 79
Hobsonville	53.8	17.3	3.9	1.1	0.7	23.2	0.178	124.0	24 - 175
Whakataka	81.2	13.5	1.6	1.3	0.0	2.3	0.053	40.3	3 - 75
Cox's Bay	71.1	19.3	0.8	0.9	0.9	7.8	0.087	30.0	10 - 78

6.3.2 Sediment resuspension

Calculation of resuspension was complicated by failures with the data collection of some OBSs and boat damage (Townsend et al. 2008). However, data were collected at both low and high densities for the majority of sites. The concentration of suspended sediment on the 2nd high tide was averaged for each available plot (mean) and $\log_{10}$ transformed.

Again multiple stepwise regression was used to determine a set of useful predictor variables, this time also including wave and current information (Appendix 10.3). In the final model of average log suspended sediment concentration (R^2 0.66), increasing total distance moved increased the suspended sediment concentrations (slope estimate = +0.0035, p = 0.037), average current speed increased suspended sediment concentrations (slope estimate = +3.88, p = 0.009) and increased significant wave height decreased suspended sediment concentrations (slope estimate = -0.057, p = 0.017). The negative impact of wave height was unexpected and likely indicates a complex interaction between current speed, water depth and wind direction.

6.4 Laboratory experiment (2008) – contamination, sediment type, cockle movement and resuspension of sediment

6.4.1 Movement

The percent surface area covered by track marks varied from 0 to 85% across all treatments and was generally related to the average movement score (Pearsons R = 0.58, p <0.0001).

Comparing the numbers of cockles found in the different movement zones with those expected under random movement, showed that the inner zone and the outer perimeter were over represented (Table 6). That is, a large proportion of cockles did not move. Moreover when cockles did move, they usually moved the greatest distance possible, suggesting that movement was constrained by the aquarium size and that average and total movement scores calculated for this study probably underestimate movement.

Table 6:

Average percent of cockles found in different zones (actual), those expected if movement was random, adjusted by the area of the zone. Each successive perimeter is 2 cm wide.

Distance zone	Actual %	Expected %	Difference %
Inner zone 18cm x 18cm	33.61	11.11	22.5
1st perimeter	11.67	19.75	-8.1
2nd perimeter	11.11	29.63	-18.5
Outer perimeter	43.61	39.51	4.1

The lowest level of movement was for cockles from Whau, the most contaminated site, where on average 4 out of the 5 cockles did not move from the central area. The average movement score was well predicted (R^2 0.95) by a negative relationship with both WCCU (slope estimate = -2.45, p = 0.0060) and the ambient density of cockles at a site (slope estimate = -0.008, p = 0.0125). The average percentage of surface area covered by tracks was slightly less well predicted (R^2 0.87) by a negative relationship with both WCCU (slope estimate = -10.7, p = 0.031) and the ambient density of cockles at a site (slope estimate = -0.041, p = 0.0399).

6.4.2 Differences in movement associated with sediment type

There was no consistent effect of sediment type on the average movement index (Figure 10) or the percentage area covered by tracks, even when site sediment type was included as a predictor. This is probably due to the variable nature of the ambient sediment included in each treatment mixture type. Across all sites, however, reburial was significantly lower in the mud treatments (Figure 11). This relationship was least obvious at sites Whau and Whakataka, the two muddiest sites. Cockles in mud treatments may have exhibited a greater level of movement to avoid sinking into the soft sediment, below the range of their feeding siphon. However, there may be a threshold in mud content above which cockles can not avoid sinking.

6.4.3 Effects on resuspension of sediment

Across all sites, the presence of cockles reduced the amount of suspended material (Figure 12). For ambient sediment, the data indicated that although cockles generate re-suspension during movement, in the absence of hydrodynamic forces their capacity to filter the water column and remove suspended particulates, is the overriding and net effect.

Figure 10:

The average Movement Index for each site in the four sediment treatment categories. Error bars are 95% confidence intervals.

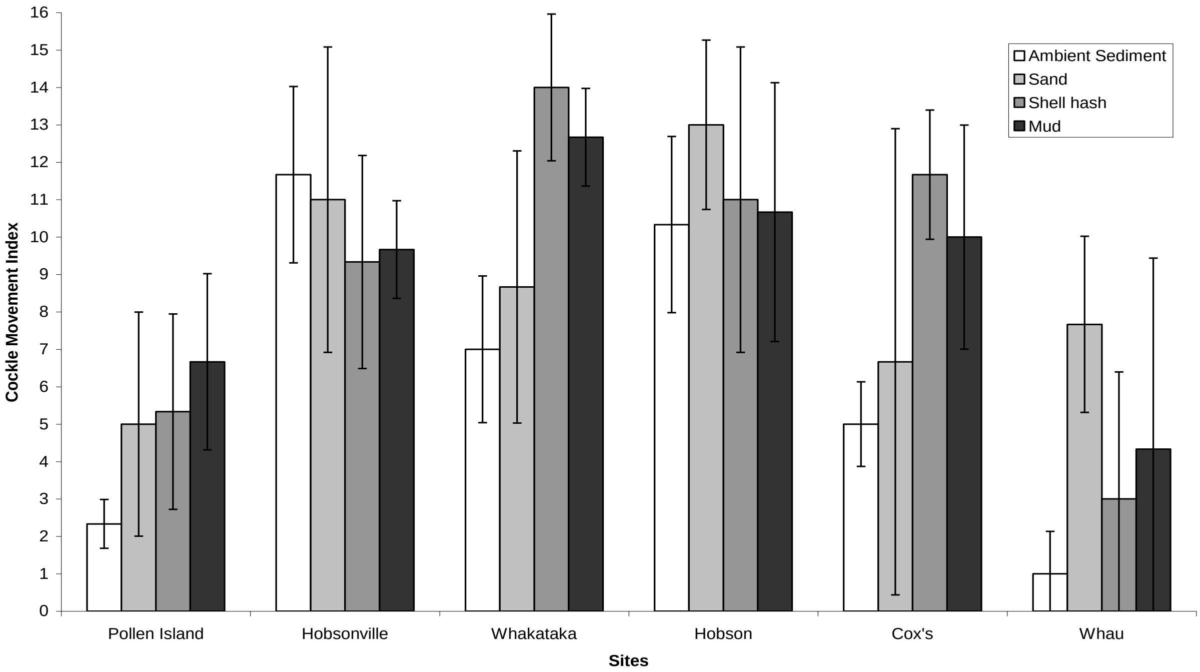


Figure 11:

The mean number of cockles still at the sediment surface after the 24 hour monitoring period, averaged across sites for the different sediment treatments. Error bars are 95% confidence intervals.

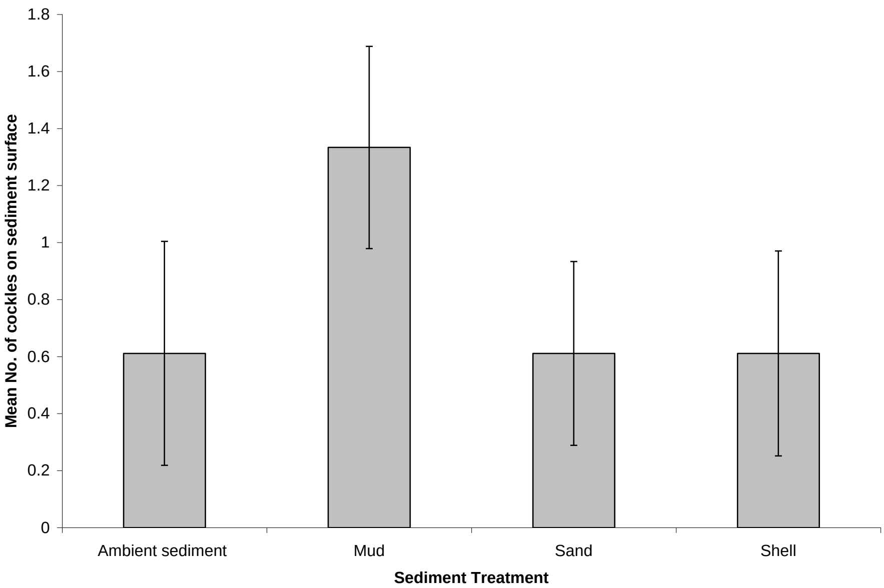
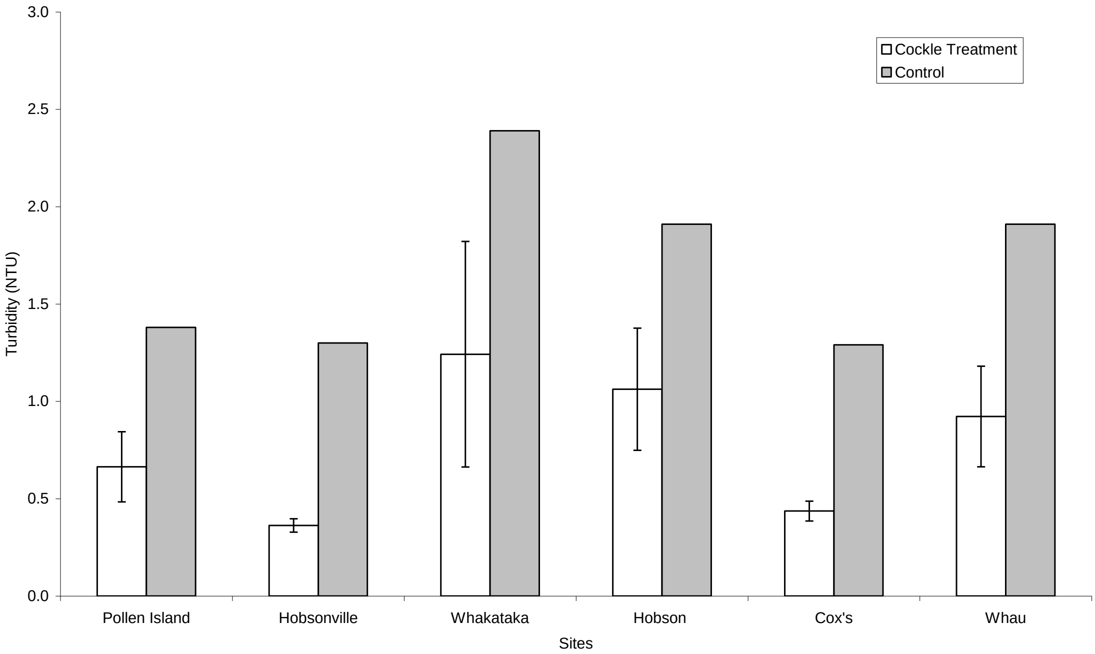


Figure 12:

The turbidity levels after the 24 hour monitoring period at each site for ambient sediment with (n=3) cockles. Error bars are 95% confidence intervals.



6.5 Laboratory experiment (2009)- contamination and cockle density and size effects on movement

The size of cockles contained in the cores brought back to the laboratory were relatively consistent across sites for each of the size class. For S1 treatments (15-20 mm), mean cockle size fell within the designated range (Table 7); although Cox's Bay was at the higher end. For S2 treatments (25-30 mm), a scarcity of larger individuals meant that the mean cockle sizes were lower than intended (Table 7).

Densities were relatively consistent across the sites for different treatments. For D1 treatments (low density) a density of 2 cockles per collected cores was typical; which equated to 255 cockles per m^2. Mean cockle densities for D2 treatments were typically between 8 and 10 (1000-1300 cockles per m^2). Two exceptions to this were at Pollen Island for the S1 size and at Anne's Creek for the S2 size, which both had higher mean densities than other sites and the greatest overlap between the D1 and D2 treatments.

Table 7:

Mean size of cockles (longest shell dimension) used in the small (S1) and large (S2) sized treatments, for both densities, measured on completion of the movement evaluation

Site	S1 low density		S1 high density		S2 low density		S2 high density	
	Size	95% CI	Size	95% CI	Size	95% CI	Size	95% CI
Airport	18.58	0.96	17.88	0.32	x	x	x	x
Whakataka	17.07	0.59	17.41	0.37	24.04	2.85	25.84	0.47
Hobsonville	18.84	1.69	18.89	0.50	x	x	x	x
Pollen Island	18.78	0.79	19.84	0.37	24.53	1.48	24.75	0.45
Hobson Bay	18.25	1.13	17.26	0.82	x	x	x	x
Cox's Bay	20.41	0.80	20.26	0.57	24.86	0.70	24.82	0.35
Anne's Creek	19.70	0.87	19.62	0.62	22.82	1.10	24.83	0.92

The majority of cockles (61%) did not move, or only moved a marginal amount, over the course of the experiment, across all treatments. Of the cockles which moved., 12% were found in the first perimeter, 9% in the second perimeter and 18% in the outer perimeter. However, the proportion of individuals in the outer perimeter, once adjusted by area, was not significantly different from that expected by random movement, suggesting that the aquarium size in this study was not constraining cockle movement.

6.5.1 Percent of surface covered by tracks

Across all sites and treatment replicates, the percentage of the sediment surface area containing cockle track marks ranged from 0% to 90%. At both high and low densities, average cover of tracks was higher in the treatments with larger cockles for most sites. Pollen Island was the exception for this at low densities and Cox's Bay for high densities.

The percent surface area covered by tracks was well predicted (R^2 0.72) by the ambient site density (slope estimate = -0.024, p = 0.0010), density in the treatment (slope estimate = +3.57, $p < 0.0001$), average size of the cockles (slope estimate = +2.11, p = 0.0129) and WCCU (slope estimate = -6.65, p = 0.0432). Consistent with the previous laboratory experiment, ambient site density had a negative effect on how much movement occurred despite the cockle being transplanted into different density plots prior to the laboratory experiment. The effect of WCCU was stronger in this experiment than in the previous laboratory experiment, possibly because of the underestimation of movement that occurred in that experiment. Not surprisingly the treatment density and the average size of the cockles increased the surface area covered by tracks.

6.5.2 Average movement score

Changes in cockle size had a greater impact on the average movement score in the lower density treatment (D1). Most S1D1 site treatments (Figures 13) scored considerably lower than their equivalent S2D1, with the exception of Cox's Bay. Fewer differences were apparent between the size classes in the high density treatment, with comparable movement score for most sites (Figures 13 and 14).

Figure 13:

Differences in the average movement score across sites for the D1 and D2 treatments of the small cockle size class (S1). Error bars – 95% confidence intervals.

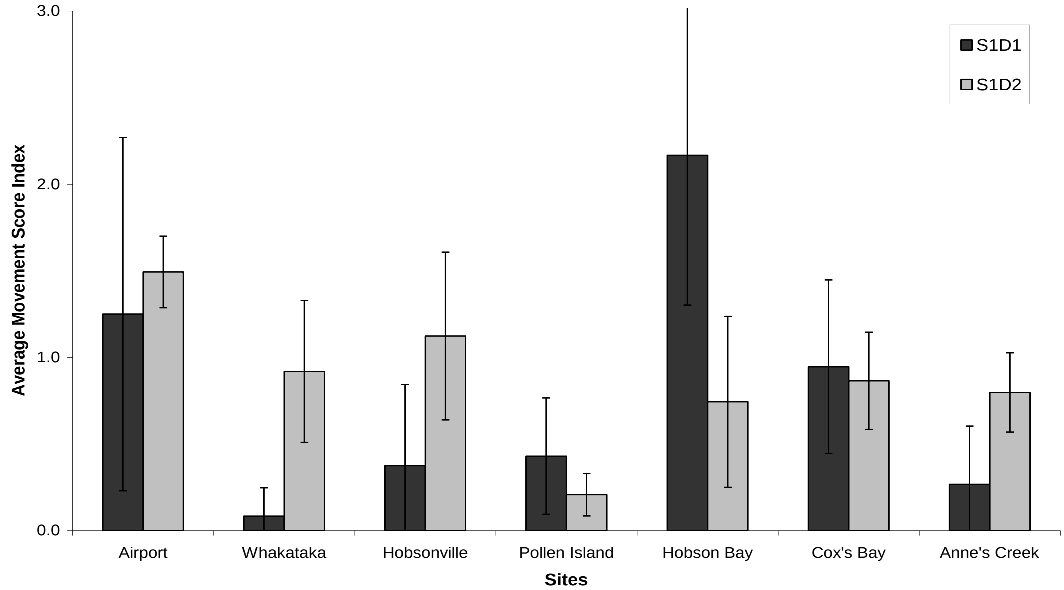
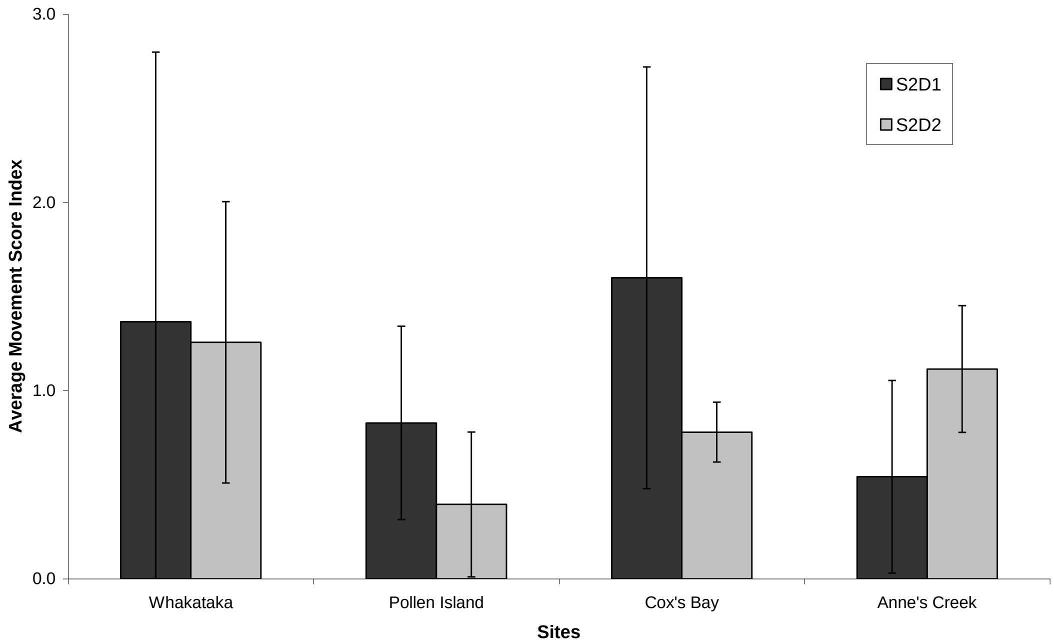


Figure 14:

Differences in the average movement score across sites for the D1 and D2 treatments of the large cockle size class (S2). Error bars – 95% confidence intervals.



The movement score was able to be predicted (R^2 0.55) by the ambient site density (slope estimate = -0.001, p = 0.0057), density in the treatment (slope estimate = -0.050, p < 0.1432), TCCU (slope estimate = -1.04, p = 0.0840) and an interaction between TCCU and average size of cockles (slope estimate = +0.0439, p = 0.1070). This interaction suggests that larger sized cockles in contaminated areas will be better able to move than smaller cockles.

6.6 Summary

Field measures of net average horizontal distances moved by cockles, over 2 tidal cycles, ranged from as little as 5cm to as much as 18cm. These net, and thus conservative, estimates when multiplied by cockle densities resulted in distances moved of between 30m to 124m. When these estimates are converted to percentage of the surface area able to be disturbed by cockles within the range of densities commonly found in the Waitemata, at low densities as little as 3% may be disturbed, but at high densities the whole surface area may be disturbed more than once over two tides. These high values suggest that cockles will play an important role in mixing the top 2 – 3 cm of sediment.

In the field, average distance moved was negatively affected by silt content of the sediment and contaminant levels (as represented by WCCU). This negative effect of contaminants on average movement was also observed in both laboratory experiments (represented by WCCU in the first experiment and TCCU in the second). In the laboratory experiments the percent surface area covered by tracks was also negatively affected by contaminant levels (WCCU in both cases). Interestingly, for the second laboratory experiment, similarly good predictions of percent surface area covered by tracks could be obtained by replacing WCCU with TCCU and an interaction term with the amount of sediment mud content, suggesting that it may not be the extraction methodology that is important here but the sediment particle size to which the contaminants are bound.

The field experiment also suggested that density of cockles had an effect on movement, with cockles in very dense beds having lower rates of movements (as per Whitlatch et al. (1997) and Cummings et al. (2007)). The first and second laboratory experiments suggested that this resulted in a preconditioning of the cockles that continued for some time. Differential movement depending on size of cockles was observed to be site-dependent and the predictive models developed suggested that an interaction with contaminant level may occur with larger sized cockles in contaminated areas better able to move than smaller cockles.

While the field experiment suggested that mud (or silt) content of the sediment adversely affected the ability of cockles to move, the laboratory experiment that tried to tease apart this effect found no consistent effect of sediment type on the average movement or the percentage surface area covered by tracks. This experiment did find, however, that reburial was significantly lower in the mud treatments.

From the results of these experiments an equation relating sediment reworking by cockles (derived from movement and size) to cockle density, sediment type and contaminant levels was developed for use in the complex system model (Section 7).

The model was derived using a multiple stepwise regression to determine a set of useful predictor variables, that were uncorrelated, from cockle size and density and sediment grain size, and contaminant information, using backwards elimination at α = 0.15. The equation decided upon for use in the complex model was a function of cockle density alone as cockle density, in the model, was itself a function of sediment mud content and total copper concentrations in the sediment. These indirect effects of mud and copper on sediment reworking by cockles were very much larger than the direct effects of mud and copper on the ability of cockles to move. Thus, the simpler equation merely relating to density was used.

$SR = (0.0086\ e^{-0.5b} - 0.00043349)/3600$

Where SR = sediment reworking by an individual in $m^3/(m^2*sec)$

$b = ((N-1273)/520.8861)^2$

$N = density/m^2$

The field experiment measured an effect of cockle movement on suspended sediment, suggesting that cockle movement affects resuspension of sediment to a measurable degree. However, the laboratory experiment suggested that movement interacts with currents and/or waves such that without their presence the over-riding effect of the presence of cockles is their feeding removing sediment from the water column.

7 Complex System Modeling

7.1 The conceptual model

The starting point for any model is the conceptualisation of connections and possible interactions. For the interactions between contaminants and cockles and potential environmental effects, this can be most simply expressed as 4 different compartments: sedimentation, resuspension, sediment mixing and burial and cockle densities (Figure 15).

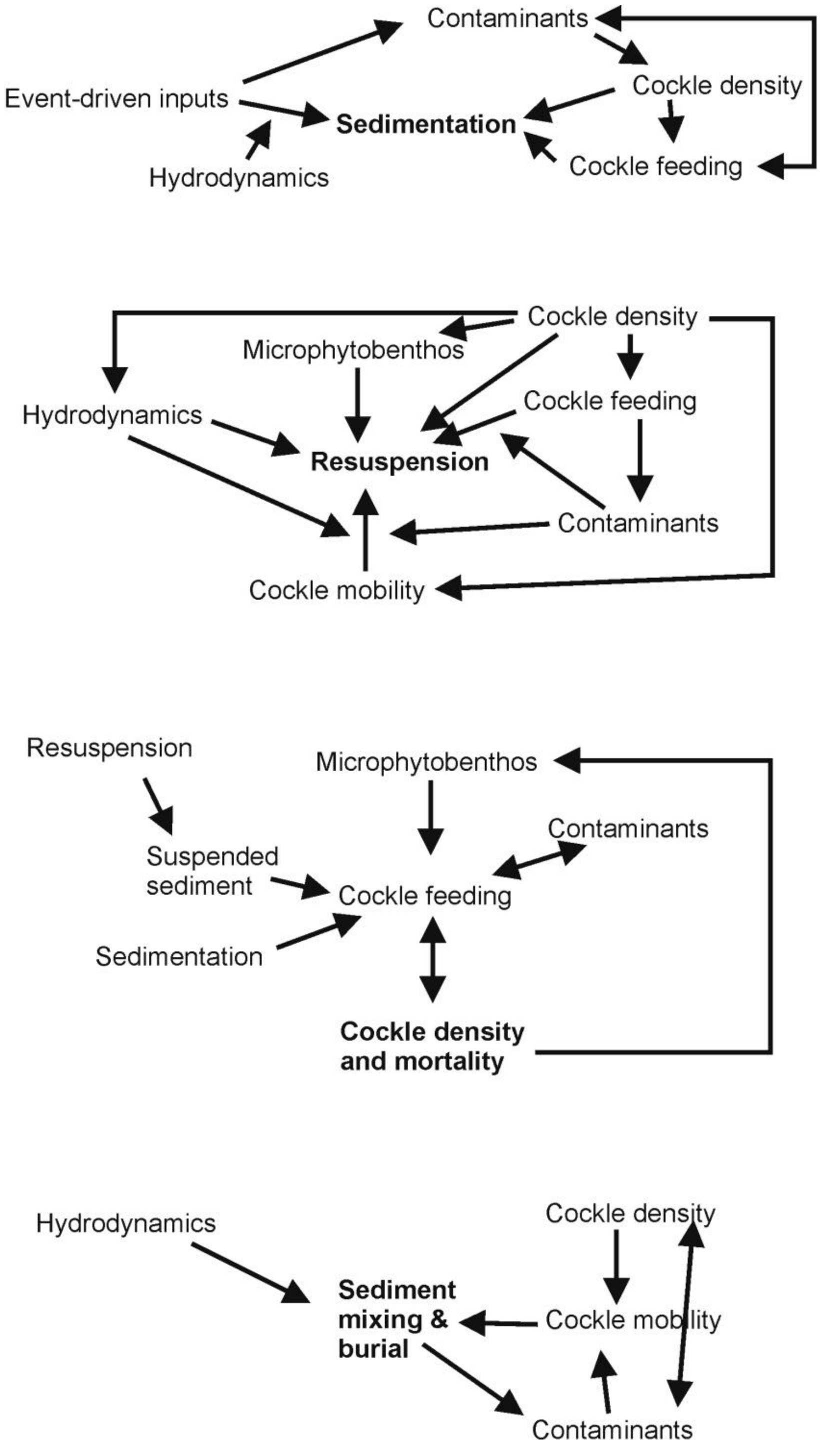
The results from the experiments discussed in sections 4 – 6 are then used to provide the parameters for the complex system model (see Table 8). The model provides a way to link all the parameters together, to explore how interactions may occur and assess relative importance, and to determine the most likely way that these relationships will play out under varying hydrodynamic conditions. It also allows the results of the experiments to be integrated with models predicting contaminant and sediment dispersal and accumulation in the upper and central Waitemata areas.

Table 8:

Information on the connections used in the conceptual model and where the input parameters used in the model will be obtained from. Input paramters derived from this project are given in bold.

Connection	Effect	Derived from
Event-driven inputs	Increases sedimentation and contamination	Waitemata contaminant models
Hydrodynamics	Variable effect on sedimentation	Hydrodynamic theory
Hydrodynamics	Variable effect on resuspension	Hydrodynamic theory
Hydrodynamics	Variable effect on sediment mixing	Hydrodynamic theory
Contaminants	Decreases cockle density	Regional Discharges Project data Hewitt et al. 2009in press
	Decreases cockle feeding	**Section 4.6 this report**
	Decreases cockle movement	**Section 6 this report**
Cockle feeding	Increases sedimentation	**Section 4 this report**
	Decreases contamination in water column, increases contamination on seafloor	**Section 4 & 5 this report**
	Affects resuspension though provision of biodeposits	Simpson 2009
	Affects cockle density and mortality	No information, a range of values will be tested
Cockle density	Affects cockle mobility	**Section 6 this report**
	Affects cockle feeding	**Section 4 this report**
	Increases microphytobenthos	Thrush et al. 2006, Hewitt pers comm., Lohrer et al. 2004
	Affects hydrodynamics	Hydrodynamic theory

Figure 15:
Conceptualisation of the links between hydrodynamics, sediment and contaminant inputs, dispersal and accumulation and cockle dynamics.



Model outputs are initially a time series of changes in sediment type and contamination, at different depths of sediment, and cockle density, all at varying locations across the Waitemata. The outputs from multiple conditions can be analysed to determine:

- Increases in contamination and movement of contaminated sediment down through the sediment (sediment binding) as a result of cockle feeding.
- Changes to sediment binding that occur as cockle densities and feeding rates are impacted by increased contamination.
- Spatial changes to dispersal of contaminated sediment driven by cockle feeding;
- Relative importance of different processes e.g., importance to resuspension and dispersal of contaminated sediment by waves and currents versus cockle movement.
- Changes in all the above relative to differing hydrodynamic conditions and natural sediment accumulation rates (as predicted by the various Waitemata contaminant dispersal models that do not include enhanced deposition by cockle feeding).

These results will be summarised in next year's report when the implications of declining cockle density to ecosystem goods and services will be presented.

7.2 Model methodology

The basis for the complex system model used was developed under the FRST programme "Effects-based management of contaminants". The model was initially developed to study the behaviour of fine-coarse sandy mixtures in the inner shelf (water depth around 20 m) and has been here largely modified to account for the presence of mud-sand mixtures, tidal variations and the feedbacks between cockle density, sediment and contaminant dynamics.

The model solves the advection equation and a corresponding discretized form of bed level changes that ensures sediment continuity. The model domain consists of a three-dimensional grid with periodic boundary conditions in the horizontal. Each cell is characterized by a specific value for grain size composition. For numerical convenience, a mixture of two sediment sizes (cohesive and noncohesive, also defined in the text as "fine" and "coarse") is considered and the contaminants are assumed to be part of the cohesive material. For all the simulations presented, the size of each cell is 5 m in each horizontal direction and 0.0125 m in the vertical (a small vertical size is required to fully capture the dynamics related to vertical sediment reworking by cockles). The bed elevation at each horizontal location is defined by the vertical position of the highest cell containing sediment and the percentage of that cell that is filled. Model results do not depend on the actual size of the cells or the time step (assuming the time step is small enough to avoid numerical instabilities). We have here used a time step of 200 seconds and simulations are run for 30 years. Throughout the simulations we always assume a constant mean sea level and a semi-diaurnal sinusoidal tide. With respect to wave height we do not directly account for processes related to shoaling and breaking. Wave height varies tidally to account for fetch effects so that larger waves occur at high tide.

The sediment flux of each grain size, fine and coarse, is evaluated separately and the fluxes are added to give the total sediment flux. The concept of an active layer has been implemented to ensure sediment continuity (Appendix 10.4). The model currently includes the possibility of superimposing a background sediment concentration and/or the effect of specific accretionary events.

Quantitative evaluation of erosion requires evaluating bed shear stresses for the cohesive and noncohesive regime which is initially evaluated assuming an abiotic bed. This value is then modified to account for the influence of cockle density on the critical bed shear stress and sediment transport rates adapting the approach presented in Paarlberg et al. (2005) to the case of cockles. This approach implies that the density of cockles could potentially provide a destabilizing effect (more cockles disturb more sediment), although this effect could be balanced and even overwhelmed by the filtering effect of cockles and by the Chlorophyll a content, a proxy for microphyte content and so certainly a driver of biostabilization effects. These biophysical effects are included in the numerical simulations by assuming a linear relationship between cockle density and Chlorophyll a content (which in turn directly affects the threshold for sediment motion). The density of cockles, coupled to the physical mixing provided by migrating bedforms, is also a direct driver of changes in the vertical mixing of sediments and the model uses the equation relating sediment reworking to cockle density derived in Section 6.8. Any consolidation effect is, at this stage, neglected. Vertical mixing of sediment (and contaminants) is driven by cockles reworking the sediment and bedform migration. This directly affects the surface bed composition (and degree of contamination) which in turn affects the density of cockles (Thrush et al. 2005, Hewitt et al. 2009). The density of cockles also affects the removal of suspended sediment (and contaminants) from the water column (clearance rate) using the equation derived in Section 4.6, which includes the effect of suspended sediment concentrations and copper concentrations in the sediment.

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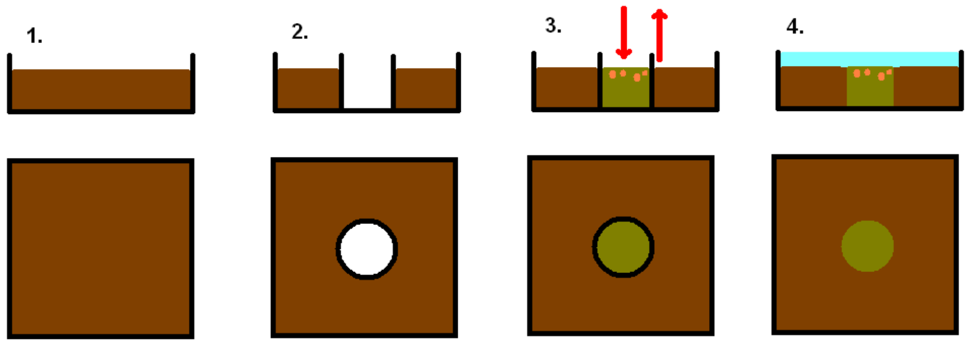
10 Appendices

10.1 Ratios of the different sediment types used in the construction of different sediment treatments for the laboratory experiment.

Treatments	Site Sediment	Sand Addition	Shell Hash Addition	Sandy Mud Addition
Ambient Sediment	7	0	0	0
Sand	4	3	0	0
Shell Hash	3	2	2	0
Mud	4	2	0	1

10.2 Schematic of the sequential process used to translocate cores of sediment into the aquaria.

1.) Ambient sediment sieved and introduced to containers. 2.) Empty 10 cm diameter core tube inserted into the centre of each container and the ambient sediment removed. 3.) Intact sediment core collected from a site/treatment inserted into the excavated central space, core tube then removed. 4.) Aquaria filled with 5 L of seawater.



10.3 Peak water current speed (m/s) at each site and current direction together with the mean significant wave height (cm) during the time of sampling.

		Flood		Ebb	
Site	Wave height	Speed	Direction	Speed	Direction
Pollen Island	5.53	0.2	45º	0.16	210º
Hobsonville	9.23	0.1	180º	0.125	290º
Hobson	1.51	0.075	50º	0.09	210º
Whakataka	1.54	0.06	180º	0.075	135º
Cox's Bay	1.58				

10.4 Sediment flux and the active layer

The grain size composition within this layer limits the entrainment of each size fraction. For example, the flux of fine sediment leaving the bed is the flux that would be entrained from an all-fine bed multiplied by the percentage of fine sediment in the active layer. The composition of the active layer changes as sediment is deposited and entrained, and as the elevation of the base of the active layer changes. Thus, at each time step and at each vertical column of cells, we need to distinguish between the thickness of the sediment layer interacting with the flow and the depth below which no flow-sediment interaction occurs. Different estimates have been proposed and active layer thickness can range between millimeters and a few centimeters. Given the uncertainty of the value of the active layer thickness and the need for a consistent model for simulations that involve planar beds and small bedforms, we have here opted for the simplest possible model (constant thickness of the active layer on the order of 0.1 m) and included an analysis of the model to variations in the value. It is worth indicating that the active layer thickness can be (and usually is) different from the vertical extent reworked by the cockles.

Sediment transport is a key component of the numerical model as it is the balance between sediment advected into and out of a cell and the locally generated sediment flux that ultimately provides a measure of local deposition/erosion. Predicting suspended sediment transport on abiotic beds is difficult because of the numerous nonlinear physical processes inolved in shaping the interaction between near-bed flow velocities and sediment. This is further complicated by the presence of cohesive and noncohesive sediments that behave differently in response to hydrodynamic forcing. For example, for noncohesive material bedload transport could be relevant while for suspension is the only mode of transport for cohesive sediment. Moreover, noncohesive sediments (e.g., sand) have a larger settling speed and adjust nearly instantaneously to hydrodynamic changes so that an equilibrium approach to evaluating transport fluxes can be used. In contrast, transport fluxes of cohesive sediments (e.g., mud) can only be evaluated solving the advection/diffusion equation. Mixing the two approaches raises difficulties and no "standard" formulation is available. Here we follow and integrate the approach of Chesher and Ockenden (1997) as recently adapted by Waeles et al. (2007) for a simulation of estuarine morphodynamics. We assume that cohesive and noncohesive sediments can be transported independently in the water column and the advection-diffusion equation is solved for each fraction separately. Erosion fluxes for each sediment fraction depend on the mud content of the active layer and therefore on the bed composition at the beginnning of the simulation and on the sequence of erosion/accretion events. If the sediment mixture at a specific location contains less than 20% of cohesive sediment, erosion of both fractions is evaluated with a noncohesive approach (Waeles et al. 2007).