



Effects of Suspended Sediment Levels on Suspension-Feeding Selfish in the Whitford Embayment

2001

TP159

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Effects of Suspended Sediment Levels on Suspension-feeding Shellfish in the Whitford Embayment

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NIWA Client Report: ARC01267

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1 Executive Summary

This study is part of a series undertaken by NIWA for the ARC to determine the risk that the urban development process poses to the receiving environment of the Whitford embayment. The focus of this study was to investigate and test the effect of suspended sediment concentrations on feeding, growth rates and condition of suspension-feeding shellfish living in the Whitford embayment.

The investigation used three techniques. Laboratory experiments of 9 - 14 days duration studied feeding rates and short-term condition of adult cockles (*Austrovenus stutchburyi*) and pipis (*Paphies australis*) exposed to a range of suspended sediment concentrations (up to 800 mg l⁻¹). Maximum concentrations used in the laboratory were similar to those recorded in the Whitford embayment. Short-term field experiments (1 tidal cycle) related the laboratory feeding rates to those likely to be observed in the field. A field transplant experiment related suspended sediment concentrations found at different sites in the Whitford embayment to: (a) changes in growth rates of juveniles of the wedge shell (*Macomona liliana*) and cockles, and (b) changes in condition of adult cockles and pipis.

Our results suggest that cockles, initially, benefit from extra food available in high suspended sediment concentrations, at least when the suspended sediments are not terrigenous clays recently arrived in the marine environment. High concentrations occurring more frequently than 25 % of the time reduced this benefit. Concentrations >400 mg l⁻¹, persisting for 14 days, adversely affected cockle condition.

Decreased condition of pipis at suspended sediment concentrations > 75 mg l⁻¹ for periods exceeding 13 days were observed in the laboratory. In the field, there was an indication that pipis also received some benefit from increased suspended sediment concentrations, however, high concentrations occurring more frequently than 25 % of the time decreased condition.

Suspended terrigenous clay affected cockles more than resuspended marine sediment. Feeding rates were lower in suspended clay, and negative effects on condition were also more immediate.

Field growth rates of juvenile cockles and *Macomona*, and condition and reproductive status adult pipis and cockles at some sites were adversely affected by suspended sediment concentrations presently occurring in the Whitford embayment. Four aspects of suspended sediment concentrations explained much of the variation observed between sites: (i) the length of time that elevated suspended sediment concentrations occurred; (ii) the median suspended sediment concentration; (iii) sediment settling fluxes; and (iv) the percent organic content of the settling sediment.

From this study, we have gained a realistic indication of how some common shellfish will respond to increases in suspended sediment. As the results are species specific, it is hard to extrapolate these findings to other animals living within the Whitford embayment. However, these results, combined with sensitivity analysis of other

species based on habitat surveys, should allow us to predict likely responses to the suspended sediment loads predicted by catchment and hydrodynamic modelling.

Overall, suspension-feeding bivalves respond to increases in suspended sediment concentrations in a measurable way. Thus, their use as a bio-indicator of suspended sediment change, both via field transplant experiments and by their inclusion in long-term monitoring programmes, is recommended.

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). They are also characterised by large fluctuations in the quantity and quality of suspended sediment in their waters (Navarro & Widdows, 1997). However, changes in land-use and modification of coastlines due to human development have increased rates of sedimentation and changed the 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 contain this expanding population, the Auckland region is undergoing continual urban and semi-rural development and expansion of the infrastructure that is necessary to support this development. The urban development process usually results in higher than usual amounts of sediment in runoff, which eventually ends up in the region's rivers, estuaries and coastal ecosystems. There is growing recognition that sediments 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.*, 2000).

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 the effect they may have on 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- this study.

The aim of this study was to investigate and test the relationships between the feeding, growth rates and condition of suspension feeding bivalves dwelling in the Whitford embayment at a range of suspended sediment concentrations. The results in this report will provide a better understanding of the effects of enhanced suspended

sediment levels on the feeding, condition and growth of suspension feeders and will aid in determining the long-term and broad-scale consequences of elevated suspended sediments.

The major questions asked by this study are:

- How do increased suspended sediment concentrations affect feeding of suspension feeding shellfish?
- Do these changes in feeding have any longer-term consequences on shellfish condition, growth and mortality?

2.1 Study rationale

Suspension feeders feed by removing particles from the water, thus, they are likely to be directly impacted by changes to suspended sediment. In estuaries and coastal embayments a significant proportion of the benthic macrofauna can be suspension feeders. Furthermore, as most of the shellfish consumed by people (oysters, mussels, cockles and pipis) are suspension feeders, they play a dominant role in the public perception of these environments. Thus, predicting any negative effects on such animals as a result of changes to suspended sediment loads is important.

Effects of elevated suspended sediment concentrations on suspension feeders will depend primarily on two factors; the size range and the food content of the suspended sediment. If changes occur above the size range that most suspension feeders feed on (usually > 20 µm), then effects will be minimal. If the food content of the suspended sediment is high, animals may be able to get more nutrition per unit time feeding. If the food content is low, animals will have to work harder to gain their food. The more energy that has to be expended to gain the same amount/quality of food, the less energy is available for growth and reproduction (Kjørboe *et al.*, 1980). As the energy expended on feeding increases, the animal loses condition and, finally, dies.

Concentrations of suspended sediment in estuarine environments are influenced by many interacting factors and are highly variable both spatially and temporally (Smaal & Haas, 1997). As a result, animals that live in these environments develop the ability to adapt to a dynamic environment. Due to this, studying the relationship between suspended sediment concentrations and feeding rates alone, especially over a short time period, will not necessarily indicate whether growth, reproduction or mortality will be affected. Assessing reproductive success is time consuming and difficult to determine within an experimental situation. However, studies of feeding rates, growth and mortality are feasible using field and laboratory based techniques. These techniques have their own strength and weaknesses, due to practical constraints, which compromise their realism.

- Experimental manipulation of precise suspended sediment levels for studying effects of feeding rates in the field is only possible for short time periods (usually over a day or less).

- Laboratory-based studies can run for longer periods (usually up to a month). This allows us to determine if feeding responses are consistent over the long-term and whether such responses have flow on effects to condition. However, natural rhythms and behaviour of the animals are affected, as tides are not replicated and animals are not kept in sediment. Food composition and general environmental factors are also different and all these could be expected to affect feeding rates, growth and health.
- Manipulative transplant experiments, where animals from one site are transplanted to a series of other sites experiencing different suspended sediment concentrations, provide a powerful technique. Such experiments can also be run long enough to determine effects on growth, mortality and longer-term condition. However, such studies rely on being able to find a sufficiently distinct gradient in suspended sediment concentration that is not confounded by gradients in other factors (e.g., temperature, pollution, salinity). Thus, interpreting cause and effect relationships requires good experimental design and knowledge of both the environmental characteristics of sites and the biology of the test species.

To overcome the advantages and disadvantages of each technique, we decided to adopt a three-way approach in our investigation. Laboratory experiments were designed to study feeding at controlled suspended sediment levels, as well as giving an indication of short-term changes in condition as a result of increased levels of turbidity. Short-term feeding experiments were then carried out in the field to determine whether the laboratory results were realistic. Finally, longer-term transplant experiments were designed to show the effects of a suspended sediment gradient, naturally occurring in the Whitford embayment, on growth and condition. The results from these three investigations could then all be pulled together to provide a realistic indication of the effects of increased suspended sediment levels on the health of suspension feeders commonly found in the Whitford embayment.

3 Methods

As discussed in the study rationale, differences in food content and size of particles in the suspended sediment will influence its effect on an animal. Increased suspended sediment concentrations in coastal waters due to urban development are likely to be a combination of two sources. The first is new terrigenous material entering the system in a storm. The second is marine sediment that, although it may have originally been terrigenous, is retained in the embayment and continually resuspended. Also, how an animal responds to changes in suspended sediment can depend not only on the type of sediment and the species of animal, but also on its age and reproductive state. Thus, experiments were carried out with different sediment types, different species, at different times of the year (this being a surrogate for reproductive state) and on different size classes (see Table 1).

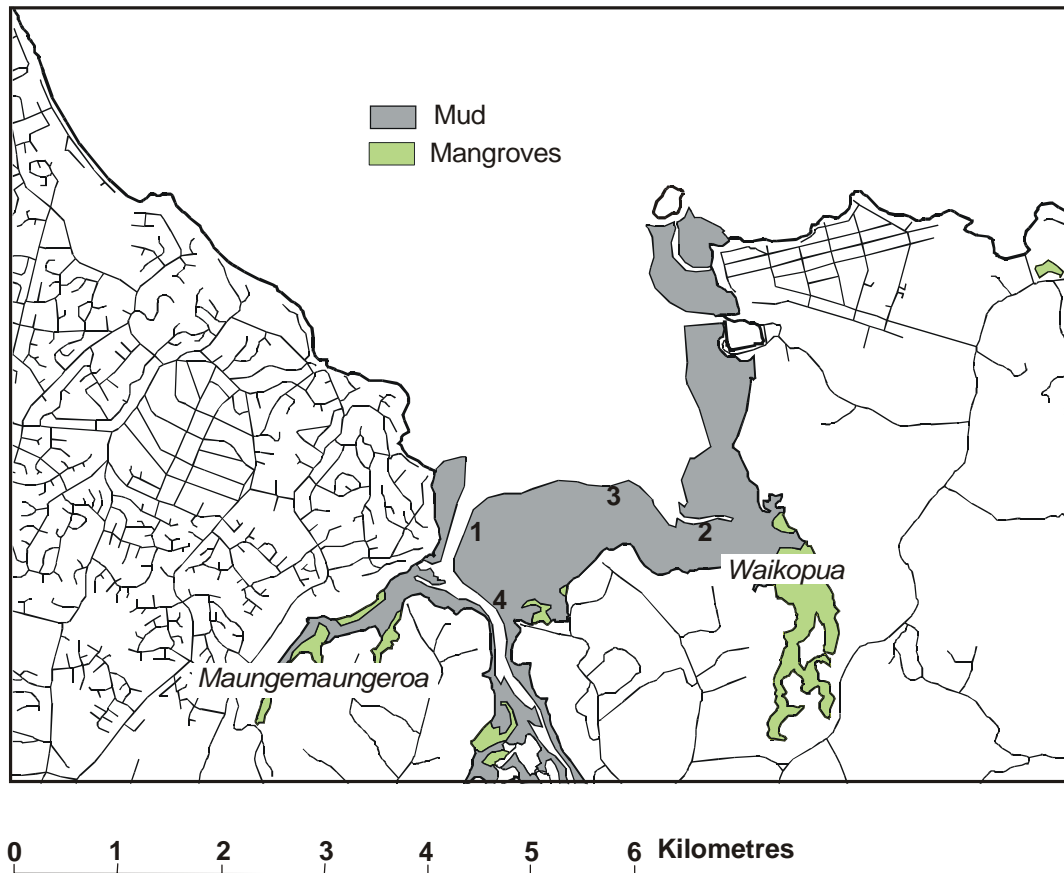
Table 1. Summary of the experimental set-ups used in each experiments.

	Laboratory feeding	Field feeding	Field transplant
Time of year / duration	December / 9 days February / 14 days March / 14 days	February / 1 day March / 1 day	March – June / 11 weeks
Suspended sediment type	marine and terrigenous clay	marine and terrigenous clay	naturally occurring
Suspended sediment range	0 – 800 mg l ⁻¹	0 – 800 mg l ⁻¹	0 – 900 mg l ⁻¹
# of treatments	6 – 9	9	8
# of replicates	December & February 4, March 1	1	see Table 2
Species and size class (mm)	Adult cockles December 20 - 25 February 30 - 35 Adult pipis All times 45 - 55	Adult cockles February 30 - 35 Adult pipis March 45 - 50	Adult cockles 20 - 25, 30 - 35 Juvenile cockles 10 - 15 Adult pipis 44 - 50, 58 - 63 <i>Macomona</i> 10 - 15

An initial summary of the extensive inter- and sub-tidal survey of the Whitford embayment, conducted by NIWA for the Manukau City Council in early summer, suggested that the dominant suspension feeder in the harbour was the cockle *Austrovenus stutchburyi*. Dense beds of adult pipi (*Paphies australis*) were also found, and juvenile pipis occur in many areas. Extensive numbers of juveniles of the wedge shell (*Macomona liliana*¹) were also widely distributed throughout the intertidal region. Only low numbers and small specimens of suspension-feeding species were observed subtidally. Thus, the animals chosen for this study were: (1) cockles, because of their abundance, hardiness and cultural significance; (2) pipis, because of their cultural significance, and likely sensitivity to increased suspended sediment loads (as indicated in FRST funded work carried out by NIWA in the programme 'Effects of Sediment on Estuarine and Coastal Ecosystems'); and (3) *Macomona*; because of their abundance, importance as a food source for birds and fish and their ability to affect macrofaunal species composition and diversity (e.g., Thrush et al., 1992, Thrush et al., 2000).

¹ While *Macomona* are normally deposit feeders, they also frequently suspension feed.

Figure 1. Map of Whitford embayment showing collection sites for the feeding experiments. Cockles were collected from sites 1 and 2, and pipis from site 3. The short-term field feeding experiments were carried out at site 4.



3.1 Laboratory and field feeding experiments

Laboratory experiments were conducted in December 2000 and February 2001 on cockles and pipis and in March 2001 on pipis only. Field experiments were conducted in February 2001 on cockles and in March 2001 on pipis. Cockles were collected from the Whitford embayment (Figure 1, sites 1 & 2), while pipis were either collected from the Whitford embayment (Figure 1, site 3) or from a sub estuary in Tauranga. Although beds of pipis had been observed during the Whitford habitat survey, fewer dense beds were found in December. To avoid our experiments having a detrimental effect on these populations, pipis used for the December and February laboratory experiments were collected from Tauranga. In order for us to be sure that the results for the Tauranga pipis were applicable to Whitford, pipis for the field experiment and for the March laboratory experiment were collected from Whitford.

As there was no information available about suspended sediment levels likely to be observed in the embayment as a result of development, we added a range of six

concentrations² (0, 25, 75, 200, 400, 800 mg l⁻¹). Most estuaries normally have suspended sediment concentrations between 20 – 100 mg l⁻¹, although, in periods of high sediment runoff this may increase to as much as 1000 mg l⁻¹ (Fahey & Coker 1992). The December and March laboratory experiments used marine sediment, while the February laboratory experiments and the field experiments used six marine sediment and three terrigenous clay treatments (hereafter referred to as clay). Monetary constraints precluded a complete range of clay treatments, so 50, 300 and 800 mg l⁻¹ were used. The emphasis was placed on using marine sediments rather than clay, as these were considered to be the more relevant when considering long-term and chronic change.

Marine sediment was collected, several times during the experiments, from the Whitford embayment (Figure 1, site 1). To obtain the sizes of particles likely to be resuspended during storm events, sediments were sieved through a 36 µm sieve. Clay was collected from earthworks at the Sandstone landfill site and mixed with freshwater to approximate natural run-off. Before this mixture was used in the experiments, we determined that the mix would not flocculate when added to seawater, or alter the seawater pH or salinity.

3.1.1 Laboratory Experimental Design and Analysis

Shellfish for the laboratory experiments were kept cool and damp during transport back to the NIWA Hamilton site, where they were gently cleaned. Animals were left to acclimatise for 24 hours in 1 µm filtered seawater in a temperature controlled room, at the approximate temperature observed at the collection sites (20°C) and a 16:8 hour light:dark cycle.

After 24 hours, animals were randomly placed in 20 litre buckets filled with 15 litres of seawater. Each bucket was continuously aerated to ensure it was well mixed and that the sediment remained in suspension. One bucket per treatment contained no animals and was used as a control for non-animal related sedimentation. Data from previous experiments was used to indicate the number of animals required to produce a measurable feeding rate over a 1 h period. Six cockles were used each time, whereas 5 pipis were used in December and 3 in both February and March. The flagellate *Isochrysis galbana* was chosen as a food item and was added to the buckets approximately every three hours during the light cycle, and then again before the dark cycle began. The total amount of food added per day (calculated from chlorophyll *a* concentrations) was based on natural levels observed in Mahurangi and Tauranga Harbours. Treatments were similarly maintained at a suspended concentration level, as determined by turbidity, by sediment additions every three hours (at the same time as the algae were added). Water was changed daily, with new water brought up to temperature before the change. At this time, dissolved oxygen and ammonia were measured to make sure that the experiments were not affecting these parameters.

² The addition of the algae increased the amount of suspended sediment in the water such that the zero added sediment treatment actually had a suspended sediment concentration of around 50 mg l⁻¹ and all the other treatment concentrations were similarly enhanced.

During each laboratory experiment, samples of water were taken at T1 (after adding sediment) and T2 (a set time later and before the next dose was added) for analysis of total particulate matter³ and organic particulate matter⁴. For the December experiments, which ran for nine days, these measurements were made on days 1, 2, 3, 6 and 8, and the T2 measure of suspended sediment made by estimation from turbidity. For the February experiment, measurements were made on days 1, 2, 5, 8 and 14. For the abbreviated March experiment, measurements were made once only, on day 8.

Feeding was measured as clearance rate per individual, which is defined as removal of suspended sediment over a known time period (T).

$$\text{Clearance rate (mg l}^{-1}\text{min}^{-1}) = (\text{TPM}_{T1} - \text{TPM}_{T2}) / (V \times T \times N)$$

where TPM = total particulate matter, V = volume of water in the bucket, T = time in minutes between T1 and T2, and N is the number of animals in the bucket. This rate was then adjusted for natural settlement of sediments out of suspension by subtracting the percentage decrease in suspended sediment concentration observed, for that sediment treatment and that time period, in the bucket without animals.

Animal health was determined, at the beginning and the end of the feeding experiments, using condition as a surrogate. The animals were shucked and ash weight 5 and shell dry weight were measured. The condition calculation used for the purpose of this report was:

$$\text{Condition (mg g}^{-1}) = (\text{flesh ash weight}) / (\text{shell dry weight})$$

This condition index provided consistent results and is commonly used in the literature. Using the ash weight ensures that sediment that had been ingested and was present in the stomach was not included as animal flesh weight. Longest shell dimension was also measured at the beginning and the end of each experiment. No shell growth was observed over the duration of each experiment.

Data from each time and each species were analysed separately to determine the effects of suspended sediment on daily and long-term clearance rates and on the condition of the animals. Initially, clearance rate data was plotted separately for each day and sediment type within each experiment to determine the form of the response curve. Analysis of covariance was conducted on data (after a natural log transformation to linearity) to allow us to determine whether the relationship of feeding rate to suspended sediment was similar on every day or whether it changed as the experiment progressed. As a significant difference ($P < 0.05$) was always observed, each day was then analysed separately. Similarly, for condition, plots were used to identify the form of the response curve for each sediment type within each experiment. In this case, the data used was a mean obtained for each bucket. Then a regression model was run to test for a significant relationship between suspended sediment concentrations and condition.

³ 25 – 100 ml was filtered onto ashed and pre-weighed GF/F 25 mm filters, which were then dried to a constant weight at 60 °C before reweighing.

⁴ The filters were then ashed at 400 °C for 5.5 h and the weight loss calculated, to determine the amount of organic particulate matter.

⁵ Ash weight is the difference between the dry weight and the weight remaining after ashing in a blast furnace at 400 °C for 5.5 h.

3.1.2 Field experimental design and analysis

Two field feeding experiments were conducted at site 4 (Figure 1) on both cockles (13 February) and pipis (27 March) collected from the Whitford embayment.

Animals were measured (longest shell dimension), then placed in sealed chambers (Figure 2) to which seawater with different marine sediment and clay loads was introduced via a header tank. A valve on the outflow pipe controlled the flow through the chamber. Flow was kept as close as possible to a predetermined flow rate. As it is impossible to have all chambers flowing at the exactly same rate, the actual volume that passed through each chamber over each hour was collected in a bucket, measured and used in the calculation of clearance rates. Eighteen chambers were used in the experiments, two for each sediment treatment. The two chambers with the same treatment were both fed from the same header tank, with the odd numbered chambers acting as a control and containing no animals. The suspended sediment concentrations used in the field experiments were as close as possible to those used in the laboratory experiments.

Figure 2. Setting up for a field experiment: chambers used in the field experiments, showing one header tank and collection bucket.



The experiment was split into seven runs of one-hour duration. To account for changes in food quality that would be normal over a tidal cycle, each run used seawater collected from a different stage of the tidal cycle. At the end of each experimental run, the water collected in the bucket below the chamber was mixed and sub-sampled for analysis of suspended sediment, as described for the laboratory experiments.

Clearance rates for each species and each sediment type were calculated separately for each run. Analysis of covariance was conducted on data (after a transformation to linearity) to allow us to determine whether the relationship of clearance rate to suspended sediments was similar every hour or whether it changed as the experiment progressed. As no significant changes to the relationship were observed over the tidal cycle or with time, an overall regression was fitted.

3.2 Field Transplant Experiment

On 27th March 2001, cockles, pipis and *Macomona* (see Table 2) were transplanted from a site within the embayment to nine sites that we “predicted” would experience different suspended sediment concentrations (Figure 3). This “predicted” gradient was based on changes in sediment grain size. Sites were all located at similar tidal heights and comprised of 4 cages, one of which was studied under a FRST research programme and will not be commented on here. All animals of a particular species and size class were collected from a single site, though different species and size classes were collected from different sites. Although we would have liked to include small juveniles (3 - 8 mm) of each species in this experiment, large numbers of these size classes had not been observed in the last month and contract time constraints did not allow us to wait until a new recruitment occurred.

Table 2. Field transplant experimental design.

	Cage #1	Cage #2	Cage #3
Cage ⁶ size (cm)	30 x 30 x 10 deep	30 x 30 x 10 deep	30 x 30 x 20 deep
Species (# animals)	Juvenile cockles (10), juvenile <i>Macomona</i> (10)	Large adult cockles (10), small adult cockles (10)	Large adult pipis (7), small adult pipis (10)
Time exposed before mean low tide (h)	1.5	1.5	0.5
Measurements made	Growth monthly	Growth and condition over 11 weeks	Growth and condition over 11 weeks

Before starting the experiment, sediment for filling the cages was sieved to remove all macrofauna. Cages were dug into the substrate and half to two thirds filled with sieved sediment (Figure 4). Pre-measured animals (longest shell dimension) were added to the cages, which were then pegged down and tied shut.

Sites were visited every 2 – 4 weeks over a three-month period, so that cages could be checked for biofouling and cleaned if necessary. During each monthly visit, DOBIE wave gauges were downloaded and the large sediment traps reset (see section 2.2.1 for explanation of these terms). Also at this time, the cages containing the juveniles were dug up and the animals counted and measured. All other cages were left, as it was expected that the only measurable growth over the period of a month would be observed in the smallest animals.

⁶ Cages were made of 4 mm plastic mesh.

Figure 3. Location of transplant sites. Adult pipis were collected from site 6, juvenile *Macomona* and juvenile and small adult cockles from near site 4 and large adult cockles from site 3.

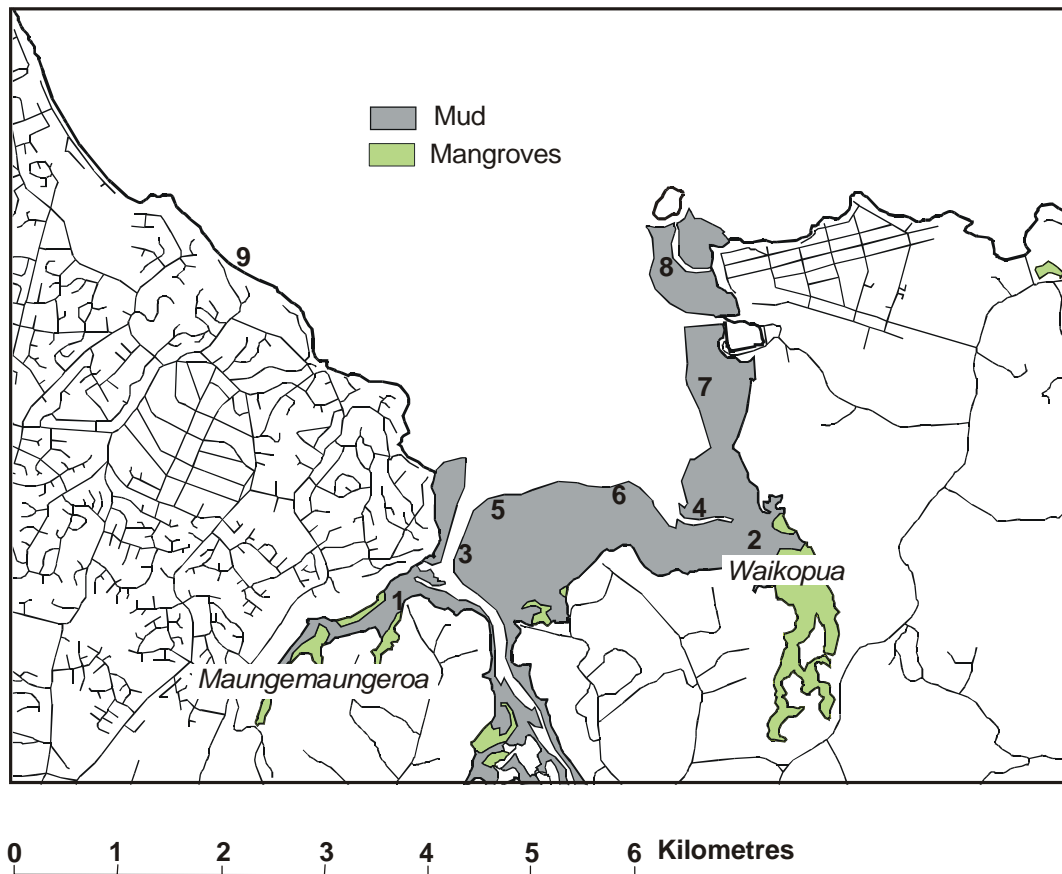


Figure 4. Transplant cages deployed at site 2, with a DOBIE in the top right corner.



In May, site 9 was decommissioned as the cages containing the juveniles and the pipis had disappeared. In June, 11 weeks after setting up, the entire experiment was terminated. All animals were brought back to the laboratory and their longest shell dimension measured. Adults were then shucked and weight measurements made on dry shells, dry flesh and ashed flesh, to determine condition.

3.2.1 Measuring the gradient

A number of methods were used to determine suspended sediment levels. Optical back scattering devices (OBS) connected to DOBIE wave gauges were initially installed at five sites (see Figure 4); later this was extended to all sites. Sites 1, 2 and 7 also had conductivity and temperature gauges. Large sediment traps were placed at all sites except site 1, as it was impossible to embed it far enough into the underlying bedrock. In calm water, these traps collect all sediment that settles out of the water column. However, when waves are present, resuspension of sediment from the trap can occur. To control for this, small sediment traps were set up to measure over one tidal cycle only in calm periods. Sediment from all small traps was analysed for organic content. On three occasions, water samples were taken, at three stages of the tide over each site, and analysed for suspended sediment and % organic content.

3.2.2 Analyses

Regression analysis was used to estimate the effect of suspended sediment concentrations on growth rates, mortality and condition. Juvenile growth rates were calculated on a monthly basis for each site and an average value over the 11 weeks used in the analysis. Adults were only measured at the beginning and end of the experiment. As adults of all species at all sites grew < 1 mm, their growth rates were not analysed. Condition of adults was measured in the same way as for the laboratory experiments, i.e., ash flesh weight (mg) divided by shell weight (g). A mean was calculated for each species/size class at each site and used in the regression analysis. During processing of the adults for condition, we noted that the majority of animals were preparing to spawn. An index of ripeness was calculated for each site by allotting a score to animals based on whether they showed no signs of gonad ripeness, were half-full or were completely full. Scores were then summed for each species/size class at each site, and this sum used in a regression analysis. Mortality over the 11 weeks for each species and size class was also included in the analysis. No data from site 9 were included.

After removing times when OBS's at different sites were not recording properly, OBS data from the last 3 weeks of the study were converted into concentrations of suspended sediment by calibration curves set up for each instrument prior to deployment. Maximum, upper quartile (75 percentile), median (50 percentile), lower quartile (25 percentile) and minimum values were calculated. At all sites, the lower 2 values were very similar. However, differences were observed in the maximum, upper quartile and median values so these were included as indicators of a gradient in suspended sediment concentrations in the regression analysis.

The amount of sediment found in the large sediment traps was highly variable but generally increased with increased wave energy. Suspended sediment concentrations in the water samples showed clear differences over the tidal cycle with higher values occurring on the incoming tide on all 3 sampling occasions. Data from the water samples was therefore treated in 2 ways: firstly, the value for the incoming tide; and secondly, an average was calculated over the tidal cycle. Salinity data from the water samples was also included, although very little in the way of a gradient was observed (the change of < 4 ppm over all sites was much less than the change over a tidal cycle at a site). All these physical variables were averaged over the 3 sampling periods.

Because we had only 8 sites for analysis, we could not include all the physical variables as explanatory variables in the regression analysis. To help select the physical variables most likely to be important, correlations (both Pearsons r and Spearman's ρ) were run between the physical and the biological data. As a result, four physical variables representing different aspects of suspended sediment concentrations were chosen for use in the regression analysis: the upper quartile and median suspended sediment concentrations from the OBS; the sediment settling flux over a tidal cycle from the small sediment traps; and the % organic content found in the sediment collected by the small sediment traps.

All these variables were used in a multiple regression framework to determine those variables that best predicted differences in the biological data between sites. Non-

linearity in response was investigated by including log and exponential transformations and polynomial terms (up to 2nd degree) in the regression models. Backwards selection with an exit value of 0.15 was used to determine the best fit. The stability of the reduced model, to the order of exit of variables, was tested. The final models discussed in this report are those which have the best fit and are most stable.

4 Results: suspended sediment effects on feeding and short-term condition

Experimental suspended sediment concentrations varied, both from those originally intended and between experiments, as it was difficult to maintain exact concentrations over the duration of the experiments. For all experiments, organic suspended sediment concentrations were highly correlated with total suspended sediment concentrations, hence more suspended sediment potentially equalled more food. However, the marine sediment had significantly higher organic content than did the clay ($p = 0.0267$). Relationships involving organic suspended sediment concentrations and interactions between total and organic suspended sediment concentrations as factors affecting both clearance rate and condition, were investigated. However, all results presented are in terms of effects of total suspended sediment concentrations, as the strength of the correlation between total and organic suspended sediment concentrations resulted in total suspended sediment concentrations being a sufficient predictor.

4.1 Cockles

Clearance rates in the December experiment were highest for day 1 and 2 at most suspended sediment concentrations (Figure 5). Clearance rates increased only slightly with increasing suspended sediment concentrations on most days. On two of the five days, clearance rates at the highest suspended sediment concentrations were lower than the preceding level. This result suggests that the cockles would have difficulties coping with suspended sediment concentrations higher than 400 mg l^{-1} over long periods. Further weight is added to this observation by considering the change in cockle condition over the duration of the experiment (9 days). An increase in condition was observed up to suspended sediment concentrations of 450 mg l^{-1} (Figure 6), after which condition decreased. However, this decrease in condition did not result in a lower condition than that observed in the zero-sediment added treatment (i.e., the lowest suspended sediment concentration plotted on Figure 6).

In February, cockle clearance rates at the zero-sediment added treatment were similar to that observed in December (mean = $1.3 \text{ cf. } 1.1 \text{ mg l}^{-1} \text{ min}^{-1}$), although the average size of the cockles was larger (mean = $32 \text{ cf. } 22 \text{ mm}$) and the condition was slightly higher (mean = $18.5 \text{ cf. } 16.8 \text{ mg flesh g}^{-1} \text{ shell}$). On all but the last day, a significant increase in clearance rate with increased suspended sediment concentration was found. By day 14, clearance rates at all suspended sediment concentrations were similar (Figure 7). Clearance rates in the clay treatments were usually lower than that observed for the marine sediments and a decrease over time was apparent. For the 100 and 450 mg l^{-1} clay treatments, the amount of suspended sediment removed by the cockles was less than the marine sediment treatments on all but the last day.

Again cockle condition initially increased with increasing suspended sediment concentrations (Figure 8), this time up to $\sim 350 \text{ mg l}^{-1}$, above which it decreased. At concentrations of 100 and 400 mg l^{-1} there was no difference in condition between cockles living in marine sediment or clay, but the cockle condition in the 700 mg l^{-1} clay treatment was the lowest observed. By the end of this experiment, the condition of the cockles at $> 400 \text{ mg l}^{-1}$ was similar to or less than cockles in the zero-sediment added treatment. We do not know the exact point at which this decrease started, but, considering the shape of fitted curve, it is likely to be about 300 mg l^{-1} (Figure 8).

Figure 5. Daily clearance rate for cockles over a range of suspended sediment concentrations during the December experiments.

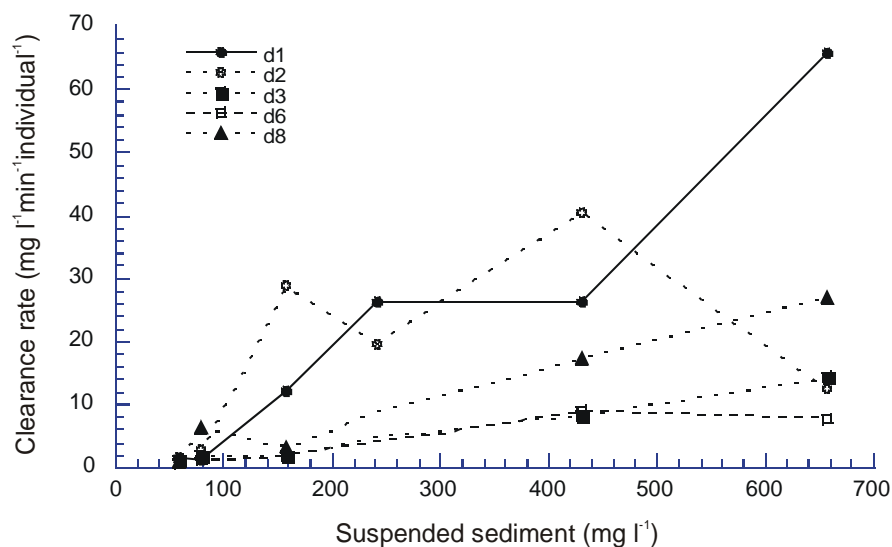


Figure 6. Relationship between cockle condition and suspended sediment concentrations observed in December. Means and standard error bars are shown. Control (zero-sediment added treatment) is the lowest suspended sediment concentration shown on the graph (see footnote 2).

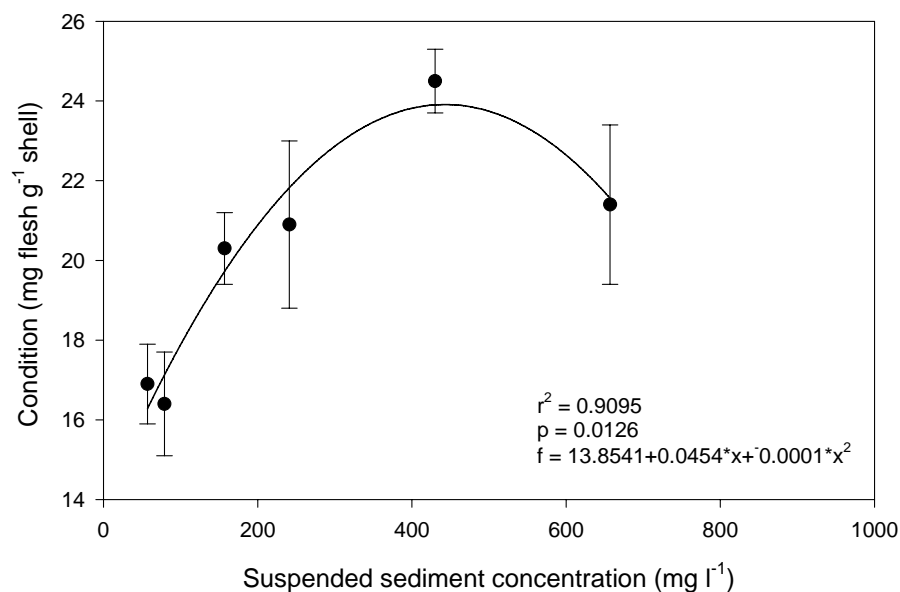


Figure 7. Daily clearance rate for cockles over a range of suspended sediment concentrations during the February experiments using (a) marine sediment and (b) clay.

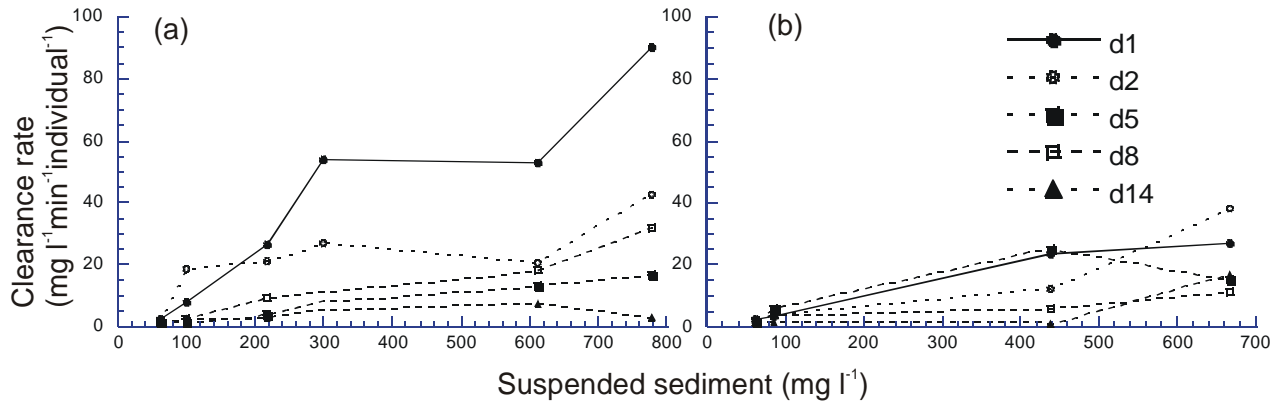
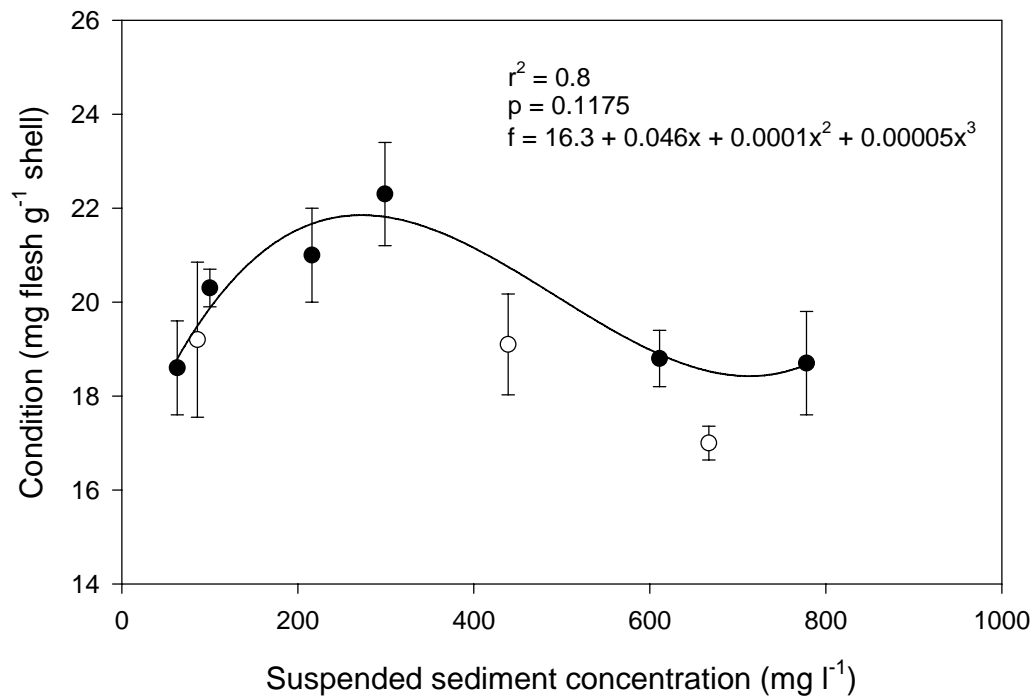


Figure 8. Relationship between cockle condition and suspended sediment concentrations observed in February. Marine sediment = ●, clay = ○. Means and standard error bars are shown.



4.2 Pipsis

Clearance rates in December in the zero-sediment added treatment were similar to those of the cockles (mean = 1.1 mg l⁻¹min⁻¹) even though the pipsis had a higher mass of tissue (mean = 0.5 cf. 0.13 g). Generally, a significant increase in clearance rate with increasing suspended sediment concentrations was found (Figure 9), although on two of the five days, clearance rates at the highest suspended sediment concentrations were lower than the preceding level (and no significant trend was found). Although lower condition was found in all sediment added treatments compared to the controls (Figure 10), this was not significant ($p = 0.124$, 1 way ANOVA).

Figure 9. Daily clearance rate for pipsis over a range of suspended sediment concentrations during the December experiments.

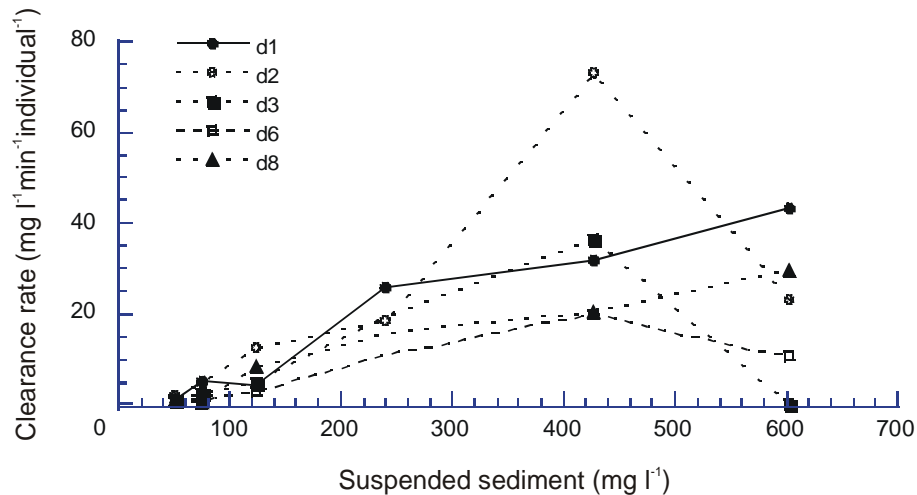
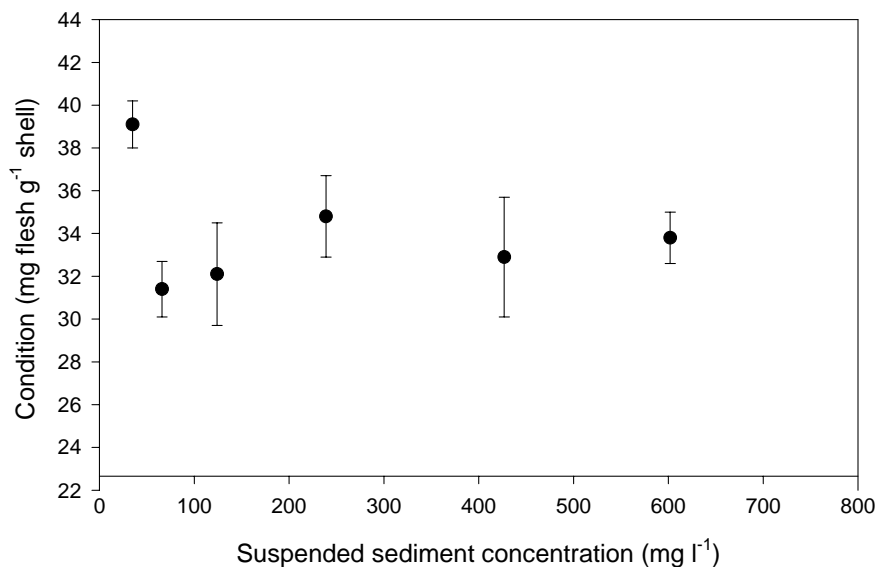


Figure 10. Relationship between pipi condition and suspended sediment concentrations observed in December. Means and standard error bars are shown.



The pipis used in February were similar in size to those used in December (mean = 53 cf. 50 mm) and had similar clearance rates in the zero sediment added treatments (mean = 1.3 cf. 1.1 mg l⁻¹min⁻¹). Relationships between clearance rates and marine suspended sediment concentrations were variable, with increases in clearance rates with suspended sediment concentrations observed on day 5 and day 8 (Figure 11a). A logarithmic decrease in condition with increased suspended sediment concentrations was also observed (Figure 12). Pipis were more able to feed in the clay treatments, with a marked increase in clearance rate with increased suspended sediment concentrations (Figure 11b). However this was only significant on day 2, and was not reflected in higher condition at the end of the experiment (Figure 12).

Figure 11. Daily clearance rate for pipis over a range of suspended sediment concentrations during the February experiments using (a) marine sediment and (b) clay.

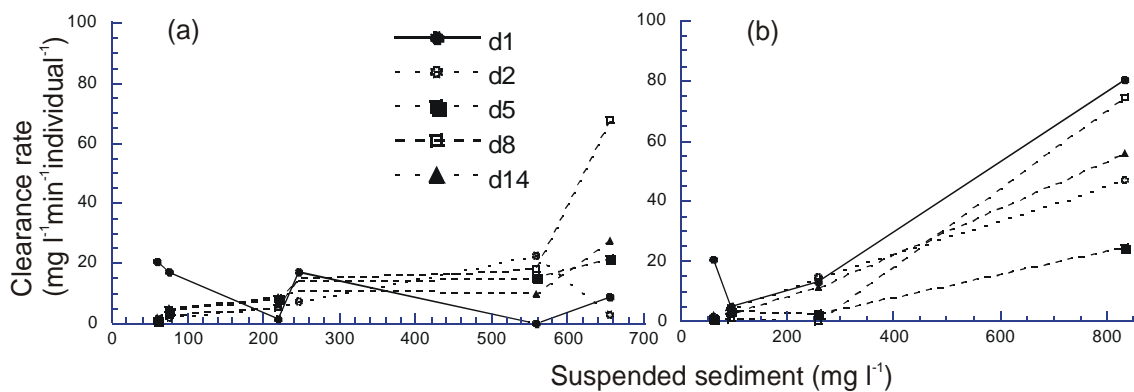
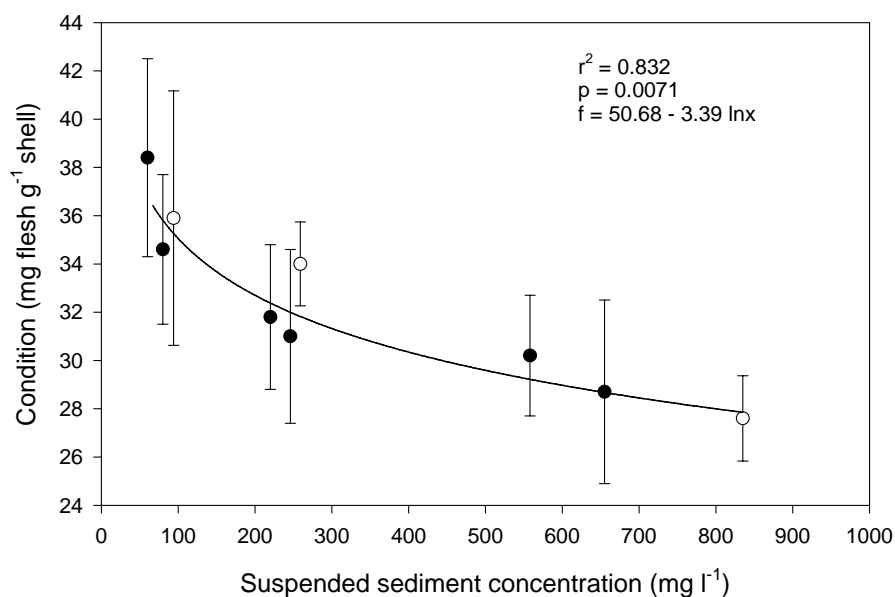
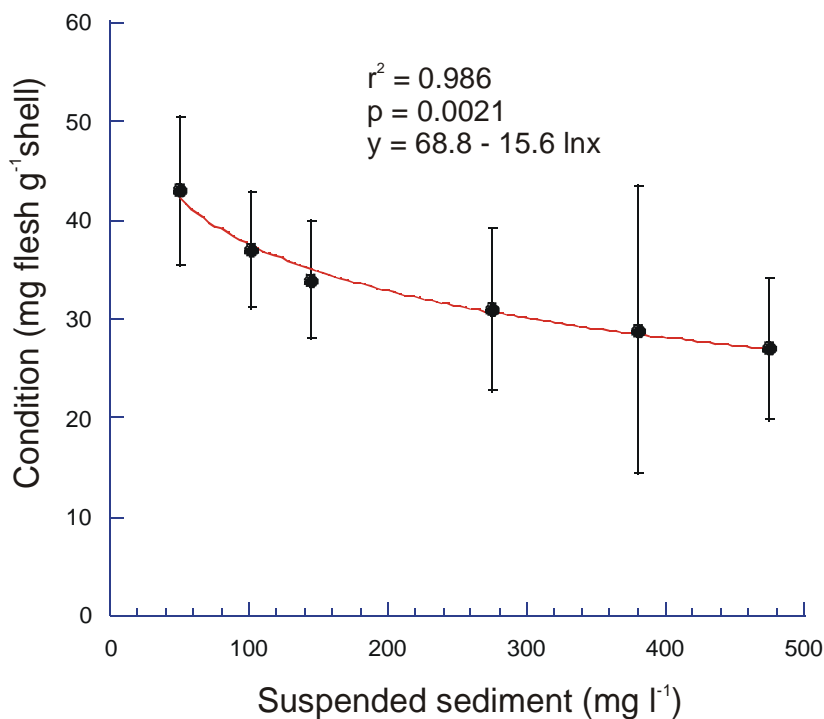


Figure 12. Relationship between pipi condition and suspended sediment concentrations observed in February. Marine sediment = ●, clay = ○. Mean and standard errors bars are shown.



The pipis collected from Whitford and used in the March laboratory experiment were slightly smaller in size to those used in December (mean = 47 cf. 50 mm) and the clearance rates in the zero sediment added treatments were much lower (mean = 0.5 cf. 1.1 mg l⁻¹min⁻¹). Relationships with marine suspended sediment concentrations (from measurements made on one day only) showed a slight trend of increased clearance rate with a flattening off at ~ 350 mg l⁻¹. Similar to the pipis used in the February experiment, a logarithmic decrease in condition with increased suspended sediment concentrations was observed (Figure 13).

Figure 13. Relationship between mean pipi condition and marine suspended sediment concentrations for the March experiment. Means and standard error bars (calculated from 3 individual pipis in one replicate bucket) are shown.

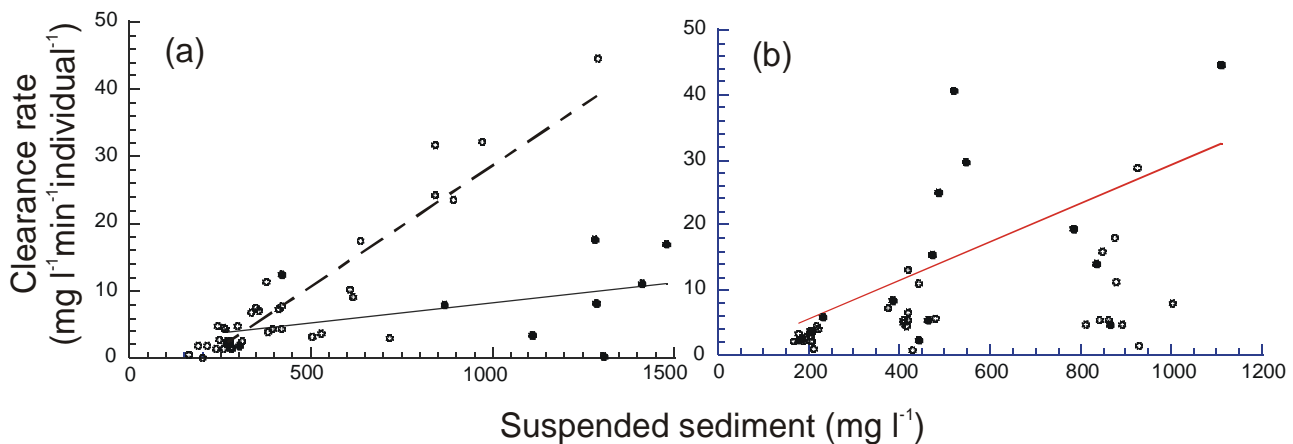


5 Results: How do laboratory and field feeding results compare?

5.1 Cockles

Clearance rates observed in the zero-sediment added treatments in the field experiment were similar to those found in the laboratory (mean = 1.1 cf. 1.3). A positive linear relationship between clearance rates and marine suspended sediment concentrations was consistent at all stages of the tidal cycle (Figure 14a). The clearance rates of the cockles in the clay treatments showed a weak significant increase with suspended sediment concentrations.

Figure 14. Field clearance rates over a tidal cycle of (a) cockles at various concentrations of marine sediment (—, $r^2 = 0.81$, $y = -7.6 + 0.36x$) and clay (—, $r^2 = 0.23$, $y = 2.25 + 0.006x$) and (b) pipis at various concentrations of marine sediment (no significant relationship) and clay (—, $r^2 = 0.36$, $y = -0.3 + 0.3x$). Marine sediments = \circ ; clay = \bullet .



5.2 Pipis

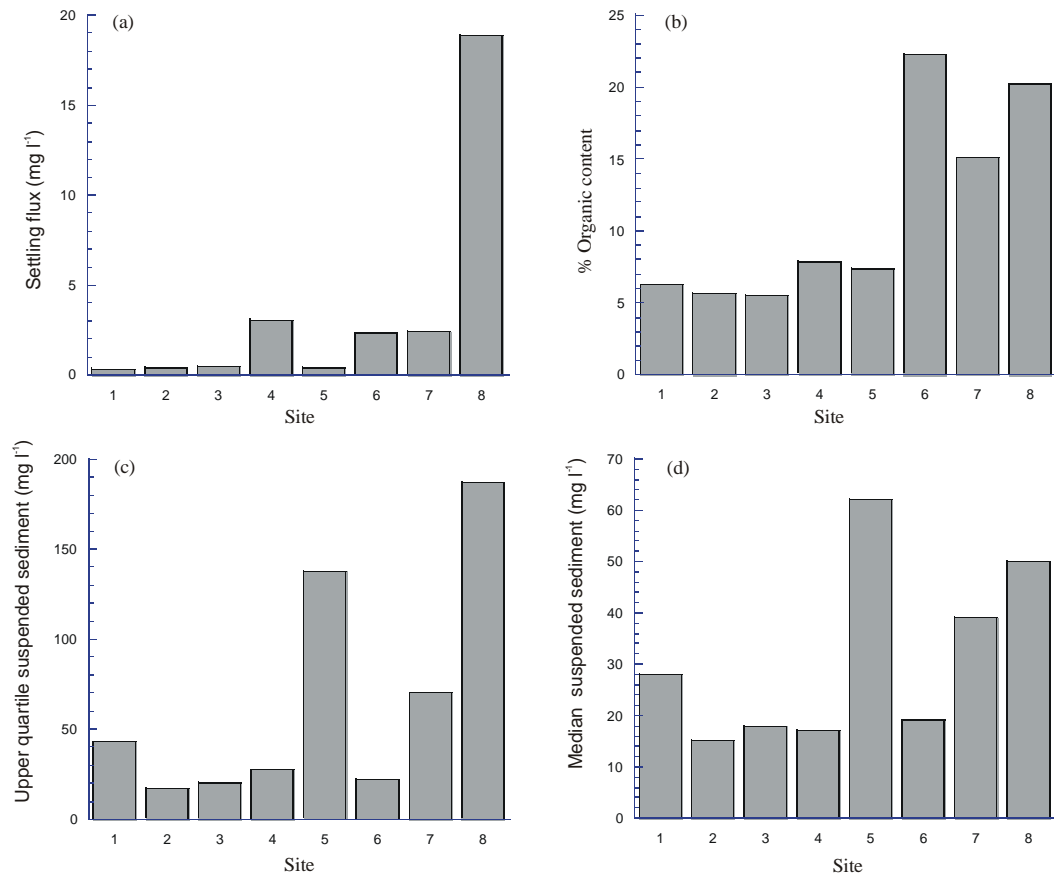
Clearance rates (mean = 2.5 mg l⁻¹ min⁻¹) observed in the zero sediment added treatments in the field experiment were much higher than those found in the laboratory for Tauranga pipis in February and Whitford pipis in March (means = 1.3 and 0.5, respectively). Presumably the lower results in the laboratory are a result of disturbance and being fed a single algal species. However, the relationships of clearance rates with suspended sediment concentrations were similar to the laboratory results. Clearance rate generally increased with suspended sediment concentrations, and although this was variable, there was not a significant effect of time throughout the day (Figure 14b). Greater variability in the response of clearance rate to suspended

sediment concentrations was observed at high suspended sediment concentrations. Clearance rates in the clay treatments increased more with increased suspended sediment concentrations than in the marine sediment treatments.

6 Results: suspended sediment effects on growth rates and longer-term condition

Sites chosen for the transplant experiment varied in position, from the mouth of Maungemaungeroa to the south eastern edge of the embayment (Figure 3). Differences in concentrations of suspended sediment in the water column were observed between sites for the amount and % organic content of sediment settling fluxes over a tidal cycle (Figure 15a & b). Differences in suspended sediment concentrations over a 3 week period at the sites are demonstrated by the differences between the upper quartile and median suspended sediment concentrations (Figure 15c vs d). Sites divided into those where suspended sediment concentrations were most affected by input from the sub-estuaries (sites 1 - 4) and those where wave-driven resuspension events affected concentrations (sites 5 - 8) (see Figure 3). Differences were also observed between the amount of organics in the suspended sediments with sites 6 - 8 having higher % organic content than the other sites (Figure 15b).

Figure 15. Variation in variables found to be important in the regression models relating suspended sediment characteristics to juvenile growth rate and adult condition, (a) amount and (b) % organic content of sediment settling flux measured over a tidal cycle, (c) upper quartile and (d) median suspended sediment concentration measured over a 3 week period.



Growth rates of juveniles were similar between species with both cockles and *Macomona* growing ~ 0.5 mm/mo. However, differences were apparent between sites with cockles growing fastest at sites 5 and 8 and least at site 4, and *Macomona* growing fastest at site 7 and not at all at site 5 (Figure 16). Neither salinity nor temperature was important in explaining these differences. Instead, for *Macomona*, growth rate increased with increasing settling flux and decreased with increasing median suspended sediment concentrations (Table 3). A complex interaction with % organic content was suggested, with growth rate initially increasing with % organic content, then decreasing as % organic content continued to increase. This required a 2nd degree polynomial term to be included in the model (see Table 3). For cockles, growth rates were positively related to the median suspended sediment concentrations observed. Again, a complex interaction with % organic content was suggested. A major difference between the two species at this age seems to be that *Macomona* do not like increased levels of suspended sediment concentrations for long periods of time.

Figure 16. Monthly growth rates of juvenile (a) cockles and (b) *Macomona* in the transplant experiment. Means and standard error bars are shown.

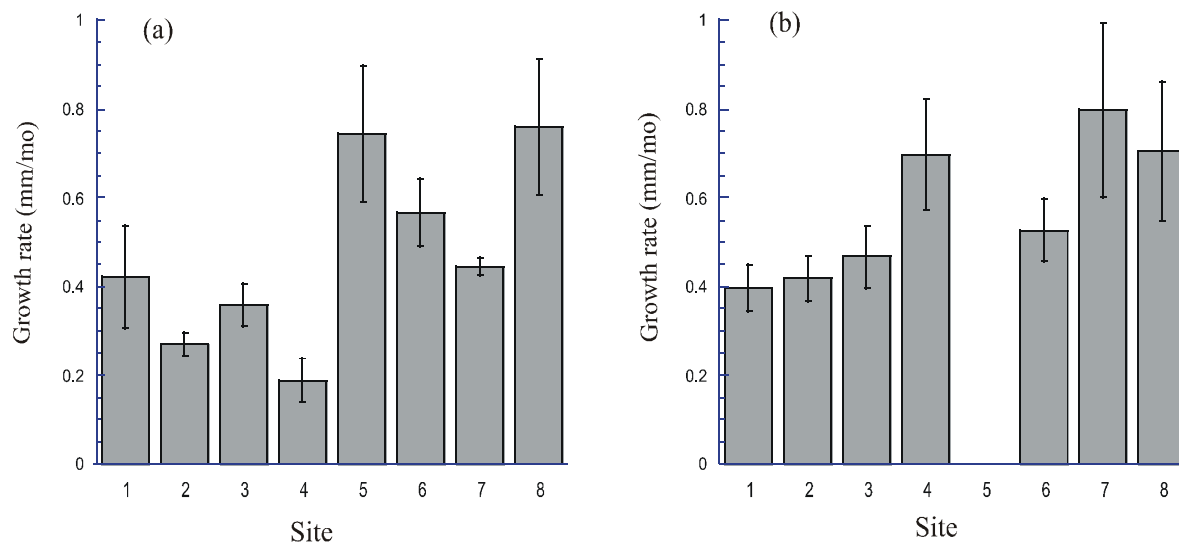


Table 3. Factors useful in predicting differences in growth rates of juveniles. + = increases growth rates, - = decreases growth rates. SSC = suspended sediment concentrations. % organic content² is the 2nd degree polynomial term used in the model (see text). Parameter estimates and p values are given in Appendix 1.1

Species	Cockles	<i>Macomona</i>
Model p - value	0.0002	0.0067
% explained by model	98	98
Median SSC	+	-
Sediment settling flux	-	+
% organic content	-	+
% organic content ²	+	-

Significant juvenile mortality occurred at some sites (Table 4). However, none of the mortalities could be explained by any of our measured environmental gradients.

Table 4. Mortality at the sites over the experiment, expressed as % deaths over 11 weeks.

Site	Juvenile <i>Macomona</i>	Juvenile cockles	Small adult cockles	Large adult cockles	Small adult pipis	Large adult pipis
1	30	10	10	30	0	10
2	20	0	0	0	0	20
3	20	30	0	10	0	30
4	90	20	30	10	0	0
5	100	10	0	0	0	0
6	30	80	0	0	0	10
7	30	0	40	0	0	10
8	20	20	0	0	0	10

Condition of both size classes of cockles and pipis varied between sites (Figure 17). Generally, our physical gradients were useful in explaining this variability, although, again, neither temperature nor salinity was important. Condition of small and large adult cockles and large adult pipis increased with increases in the median suspended sediment concentrations and the settling flux, but decreased with the upper quartile of suspended sediment concentration (Table 5). Differences between the effect of the median and upper quartile of suspended sediment concentrations are useful for indicating whether an effect is related to duration and/or frequency of high concentrations. When concentrations are high for brief periods, both the median and upper quartile will be low. When high concentrations persist for > 25 % of the time (in this case for over 5 days), whether this time is contiguous or not, the upper quartile will be elevated although the median will remain low. Thus, although condition of cockles and large pipis increased with increased suspended sediment concentrations, if these levels persist, adverse effects will be produced. Condition of small adult pipis was only influenced by the median suspended sediment concentrations. However, the percent of variability we could explain was lowest for this species, suggesting that there were other factors involved.

Figure 17. Condition of (a) large adult cockles, (b) small adult cockles, (c) large adult pipis and (d) small adult pipis found at the sites by the end of the transplant experiment. Means and standard error bars are shown.

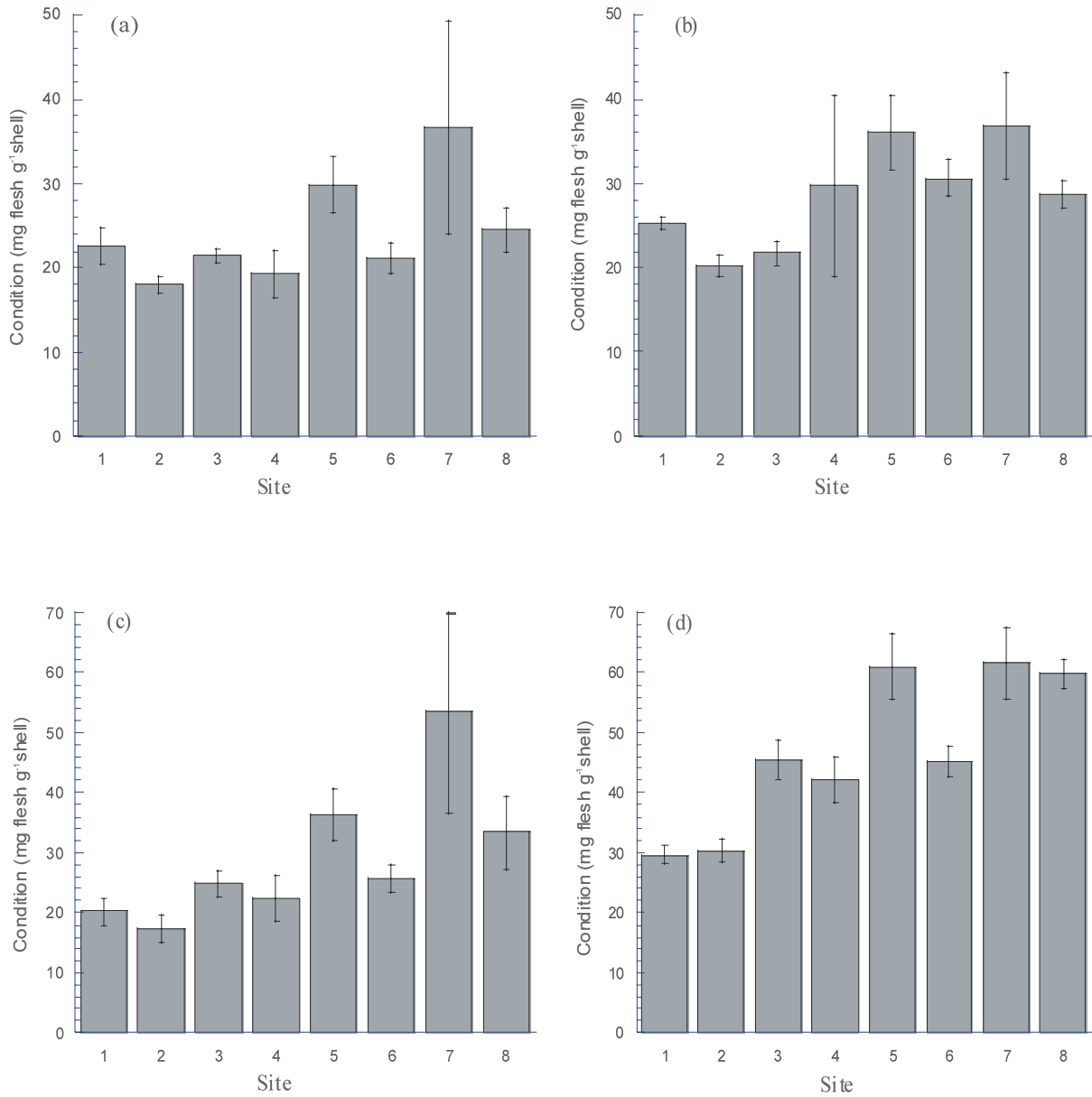


Table 5. Factors useful in predicting differences in adult condition. + = increases growth rates, - = decreases growth rates. SSC = suspended sediment concentrations. Parameter estimates and p values are given in Appendix 1.2.

Species	Small adult cockles	Large adult cockles	Small adult pipis	Large adult pipis
Model p - value	0.0380	0.0304	0.0279	0.0562
% explained by model	82	95	59	81
Median SSC	+	+	+	+
Sediment settling flux	+	+		+
Upper Quartile SSC	-	-		-

Differences in reproductive state of the animals were found between sites. More of the pipis were closer to spawning at sites 3 and 5. More large adult cockles were close to spawning at site 2 (the site furthest up the Waikopua sub-estuary) and most small adult cockles were close to spawning at sites 6 and 8. Regression analysis for the small adult pipis suggested that the same factors that were affecting condition were also affecting their reproductive state. However, for large pipis, salinity was also important and increasing median suspended sediment concentrations became an adverse factor. For adult cockles, none of our variables were useful in predicting reproductive state.

Table 6. Factors useful in predicting differences in adult reproductive state. + = increases growth rates, - = decreases growth rates. SSC = suspended sediment concentrations. Parameter estimates and p values are given in Appendix 1.3.

Species	Small adult cockles	Large adult cockles	Small adult pipis	Large adult Pipis
Model p - value			0.0996	0.0121
% explained by model	nil	nil	73	92
Median SSC			+	-
Sediment settling flux			+	+
Upper quartile SSC			-	+
Salinity				+

7 Summary

This report investigates effects of increased suspended sediment levels on the feeding behaviour, condition and growth of the cockle *Austrovenus stutchburyi*, the pipi *Paphies australis* and the juvenile wedge shell *Macomona liliana*, suspension-feeders commonly found in the Whitford embayment. The investigation used three techniques covering different aspects.

1. Laboratory experiments generally found significant positive effects on clearance rates, though these did not always translate into increased condition and growth. Condition of pipis responded negatively to the addition of sediment, whereas condition of cockles initially responded favourably to the addition of sediment. The effect of sediment type was also species specific. Ranges of concentrations used in the laboratory were similar to those observed in the Whitford embayment during the transplant experiment.
2. Similar effects on feeding rates found in the short-term field feeding experiments suggested that our laboratory results were realistic.
3. Field transplant experiments along a predicted suspended sediment gradient in the Whitford embayment found that four variables could explain much of the observed variation in growth and condition. The length of time that elevated suspended sediment concentrations occurred (represented by the upper quartile and the median concentrations) was important, as were settling fluxes and the percent organic content of the sediment. When the catchment and hydrodynamic models of the Whitford embayment are available, they can be used to investigate the frequency of high suspended sediment concentration events. Once we have this information, we can begin to predict the long-term consequences on growth and condition.

From these three investigations, we can gain a realistic indication of the effects of increased suspended sediment levels on the health of suspension feeders.

Adult cockles and pipis both exhibited the ability to continue feeding in high levels of suspended sediment over the short-term (≤ 1 week). Clearance rates in the field feeding experiment increased with increasing suspended sediment even up to 700 mg l⁻¹. However, by the end of the laboratory experiments, these relationships were not significant.

Condition of cockles and pipis can be adversely affected by high suspended sediment concentrations occurring for long time periods. Results from the field transplant suggest that condition of adults was positively related to median suspended sediment concentrations, probably due to an initial benefit of additional food. However, a negative effect of high concentrations for periods of > 5 days was indicated by the negative relationship with the upper quartile of the suspended sediment concentrations. The laboratory results support and refine these results, suggesting that > 400 mg l⁻¹ for 14 days will decrease adult cockle condition. How much condition decreases will depend on how long the suspended sediment concentrations stay high.

The effect on the condition of pipis was more negative, with decreases in condition in all sediment treatments when concentrations $> 80 \text{ mg l}^{-1}$ persisted for 14 days.

Growth rates of juveniles and adult reproductive status can be adversely affected by high suspended sediment concentrations. Juvenile *Macomona* were more sensitive to high suspended sediment concentrations than were cockles. They responded negatively to high suspended sediment loads occurring for more than 5 days in a month, whereas this did not affect the cockles. Rather, for cockles, an increased growth rate with increased median suspended sediment concentration was observed. Adverse effects of suspended sediment concentrations on reproductive state were detected for adult pipis and large adult cockles but not for small adult cockles. Size-dependent variations in response may well reflect ontogenic shifts in reproductive status. Adverse effects do not necessarily indicate that high suspended sediment concentrations will lead to decreased recruitment as recruits may be supplied from outside the Whitford embayment.

Suspended terrigenous clay affected cockles more than resuspended marine sediment. Cockle clearance rates for clay were lower than for marine sediments and negative effects on condition were more immediate, as the lower food quality did not confer so much of a benefit. Pipis were better able to feed, with higher clearance rates observed in the clay treatments than in the marine sediment. However, pipis exposed to clay sediment did not have higher condition than those exposed to marine sediment.

There are few studies on the effects of changes in suspended sediment concentrations on feeding and health of New Zealand shellfish that are not commercially farmed or harvested. However, the New Zealand horse mussel, *Atrina zelandica*, was found to respond adversely to both purely inorganic suspended sediment concentrations $> 100 \text{ mg l}^{-1}$ in laboratory and naturally organic suspended sediment concentrations in field feeding studies (Ellis *et al.*, in prep, Hewitt *et al.*, in prep). NIWA has previously investigated effects of settlement fluxes on *Atrina* in Mahurangi Harbour (Thrush *et al.*, 1998, Ellis *et al.*, 1999) for the ARC, where a significant effect on condition was observed. Although results from these reports and this present work suggest species-specific responses, the conclusion overall is that suspension-feeding bivalves do respond to increases in suspended sediment concentrations in a measurable way. Thus, their use as a bio-indicator of suspended sediment change, both via field transplant experiments and by their inclusion in long-term monitoring programmes, is recommended.

In summary, the results from this study, combined with sensitivity analysis of species described in Norkko *et al.* (2001), should allow us to predict likely responses to the suspended sediment loads predicted by catchment and hydrodynamic modelling.

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9 Appendix 1

9.1 Model regression results for the field transplant experiment

1.1 Juvenile *Macomona* growth rates

Upper quartile SSC ⁷	-0.005025	0.0023
Settling flux	0.046941	0.0038
% organic content	0.199428	0.0047
(% organic content) ²	-0.007072	0.0051

Juvenile cockle growth rates

Median SSC	0.011318	0.0001
% organic content	-0.094222	0.0023
(% organic content) ²	0.003872	0.0015

1.2 Small adult cockle condition

Upper quartile SSC	-1.014062	0.0217
Median SSC	2.959486	0.0174
Settling flux	4.380529	0.0249

Large adult cockle condition

Upper quartile SSC	-0.578545	0.0333
Median SSC	1.813050	0.0202
Settling flux	2.353614	0.0495

Small adult pipi condition

Median SSC	0.563533	0.0279
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Large adult pipi condition

Upper quartile SSC	-1.223129	0.0438
Median SSC	3.673665	0.0310
Settling flux	5.418684	0.0504

1.3 Small adult pipi ripeness

⁷ SSC = suspended sediment concentrations

Upper quartile SSC	-0.671252	0.0802
Median SSC	1.760198	0.0843
Settling flux	3.726280	0.0498
Large adult pipi ripeness		
Salinity	2.344288	0.0048
Median SSC	-0.090321	0.0924
Settling flux	0.315772	0.0355