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1 Executive Summary

A monitoring programme has been established by the Auckland Regional Council (ARC) for seven estuaries across the region. From north to south, these estuaries are Puhoi, Waiwera, Orewa, Okura and three arms of the Whitford embayment: Mangemangeroa, Turanga and Waikopua. The general purpose of this programme is to monitor the benthic ecology and sediment characteristics in these estuaries through time. Auckland UniServices has now been monitoring benthic intertidal macrofauna and several environmental parameters at ten sites within each of these estuaries for a period of up to 7 years. The central question addressed in the present report is: **Do these data provide a good baseline against which future impacts can be detected?**

In direct response, the answer is unequivocally ***yes***. These data do indeed provide the start of an excellent initial baseline against which future impacts can be detected. However, ongoing monitoring is absolutely essential for this programme in order to establish a sufficient baseline to incorporate explicit measurements of multi-year cycles, such as El Niño / La Nina weather patterns and inter-generational population dynamics. Longer time series of data are critical in order to distinguish human impacts from natural cycles occurring across these longer time scales. The relative consistency across shorter time scales (less than 5 years) observed in the baseline data obtained thus far is, however, an excellent start to developing longer-term models. These patterns of temporal consistency are demonstrated by:

- ❑ The magnitude of temporal variation was small and limited compared to spatial variation among sites and among estuaries.
- ❑ Communities at individual sites and individual estuaries have remained stable over the past 7 years of monitoring and are easily characterised in terms of dominant component fauna. No sites currently show any evidence of impacts expected from increased muddiness.
- ❑ Overall diversity (number of taxa) and the densities and size-frequencies of individual bivalve species (*Austrovenus*, *Macomona* and *Paphies*) have all remained stable over the course of the monitoring programme, at the scale of individual sites and whole estuaries.
- ❑ Measured environmental variables, especially ambient sediment texture and data from sediment traps, explain the most important gradients in biotic variation well, reinforcing the potential for causative links to be inferred under future impact scenarios.

Individual sties were characterised in terms of component fauna and a robust model was developed of benthic community structure in response to percentage mud in ambient sediments. This model allows sites to be monitored specifically for predicted changes in communities expected under longer-term sediment impacts. Event-driven sampling to date has indicated that rainfall (at current trigger levels) has no important biological effects on communities, so new, more extreme, rainfall triggers are appropriate. Recommendations are:

- ☐ Monitoring of biota and environmental variables from all estuaries should continue as before, but it is no longer necessary to sample after periods of rainfall as defined under the former sampling triggers. The relative temporal stability recorded to date provides a good initial baseline, but there is not yet enough temporal data to identify natural longer-term (multi-year) patterns (such as El Niño/La Niña cycles, etc.).
- ☐ Sampling should continue to be done once in each season after relatively 'dry' periods (according to previous definitions), but event-driven sampling should be done according to new, more extreme, rainfall triggers (to be determined in consultation with the ARC and available rainfall data).
- ☐ Sampling after rainfall should focus on the estuaries of special interest and where a greater number of environmental parameters can be measured on an ongoing basis. These include, presently, Orewa, Okura and Mangemangeroa. Separate rainfall triggers should be established for each of these estuaries, as even intense rainfall events in the Auckland region are commonly very patchy.
- ☐ These additional environmental measures should be compared and correlated at various temporal and spatial scales with sediment trap data, to develop calibration models and to assist in the development of causal links under ongoing monitoring. If possible, similar environmental measurement tools should be installed at all of the estuaries to provide the most robust possible causal inference base across the region.
- ☐ Under present budgetary restrictions, we recommend sampling after heavy rainfall (as defined under new triggers) up to three times in each of the three nominated estuaries, regardless of when these happen during the year.

2 Introduction

Sediment loads to estuaries at the fringes of the Auckland metropolitan area are predicted to increase as a result of rural, residential and urban development over the next few years. Of special concern is the expectation that changes in land-use resulting in increased sediment inputs from catchments will negatively affect the benthic fauna living in the estuaries and thus, the ecological functioning of the estuarine receiving environments.

A monitoring programme has been established by the Auckland Regional Council (ARC) for seven estuaries across the region. From north to south, these estuaries are Puhoi, Waiwera, Orewa, Okura and three arms of the Whitford embayment: Mangemangeroa, Turanga and Waikopua. The general purpose of this programme is to monitor the benthic ecology and sediment characteristics in these estuaries through time. More particularly, long-term monitoring is required through the anticipated periods of pre-development, development and post-development phases.

Both "press" and "pulse" types of impacts might occur from increased sedimentation in estuaries as a consequence of catchment development. Fairly rapid recovery might be expected from the "pulse" type of impacts caused by isolated events of fine terrestrial sediment deposition, because these environments are physically quite dynamic, due to freshwater inputs, tides and wind-driven waves (Norkko et al. 2002; Thrush et al. 2003a). Although colonisation is expected to be site-dependent (Norkko et al. 2002; Hewitt et al. 2003), many benthic species are mobile, with short generation times, so can re-colonise denuded sediments in energetic estuarine environments reasonably quickly (e.g., Hewitt et al. 2003; Lundquist et al. 2006). However, the potential longer-term system-level impacts of chronic increases in the frequency and intensity of fine sediment inputs may not allow rapid recovery. Overall changes in turbidity, increases in the proportion of fine muddy sediments in estuarine beds, and in-filling over time could all have irreversible negative "press" impacts on benthic ecosystem function (Thrush et al. 2004).

Monitoring of the benthic community in Okura estuary began in April 2000. Okura is of special concern to the ARC, as it is an estuary of high ecological value whose catchment is scheduled for development. In August 2002, four other estuaries were added to the monitoring programme (Puhoi, Waiwera, Orewa and Mangemangeroa) in order to place any potential changes through time at Okura within a broader regional context. It was important to include an estuary to the south of Okura (Mangemangeroa) to avoid pseudoreplication in the monitoring design. Notably, Mangemangeroa is also of interest in its own right to the ARC, as it is also scheduled for catchment development. Furthermore, it differs from the other northern estuaries by being more sheltered, lying further to the south within the Hauraki Gulf. Fur useful comparisons to be made, a greater number of reference estuaries of this nature were required, so in August 2004, Turanga and Waikopua (also from the Whitford embayment) were added into the regional monitoring programme. Ten sites along the length of each estuary have been monitored 4 times per year – twice in each of two seasons: once after rainfall and once after a relatively dry period.

In addition to monitoring the entire suite of benthic fauna (up to 153 taxa), we also considered that three species of bivalve: *Austrovenus stutchburyi* (cockles), *Macomona liliana* (wedge shells) and *Paphies australis* (pipi) deserve special attention. First, these species are some of the most conspicuous organisms in these estuarine habitats and in many cases they dominate the community in terms of proportional abundance and biomass. Second, as suspension-feeders or surface deposit-feeders, they may demonstrate special sensitivity to increased turbidity and fine sediment loads, which can have not only lethal effects due to smothering (Peterson 1985, Norkko et al. 2002), but also sub-lethal effects on feeding efficiency, condition and reproduction (Norkko et al. 2006). Third, their presence can increase diversity, acting as a hard substrate for other species to colonise (e.g., anemones, barnacles, limpets, etc.). Fourth, they are known to make very important contributions to ecosystem function in estuaries, due to their active filtering, redistribution of sediments, nutrient regeneration, bioturbation, and as prey to birds and fish (Cummings et al. 1997; Hines et al. 1997; Thrush et al. 2006). Abundances of these bivalves are therefore also quantified within each of three size-class categories, with a view to understanding some of the population dynamics for these species.

Should any short or long-term impacts on the estuarine fauna be detected (for whole communities or for these individual bivalve species), it will be important to link these specifically to sediment inputs and deposition, as far as possible. Therefore, a number of relevant environmental variables have also been measured in this monitoring programme along with the biota. These include the texture of ambient sediments, bed-height movement and sediment accumulating in sediment traps.

Auckland UniServices has now been monitoring these estuaries for a period of up to 7 years. The central question we wish to address in the present report is:

Do these data provide a good baseline against which future impacts can be detected?

If the existing data show extremely large temporal variation, then it may be difficult to detect changes over longer time periods. However, if existing temporal variation is relatively small and communities are fairly stable, then our power to detect important longer-term changes will be much stronger. Therefore, we aim to determine the relative stability of biotic communities (and populations of sentinel species, such as bivalves) through time in the absence of impacts (i.e., in the current pre-development phase) in order to assess our ability to detect longer-term "press" changes in the future.

This report provides a quantitative analysis of the monitoring data in order to answer the above question. To achieve this, a number of more specific fundamental questions needed to be addressed:

1. How variable are the communities at individual sites within each estuary through time?
2. How variable are the communities in each estuary (as a whole) through time?
3. How do measures of temporal variation in communities compare (in size) to measures of spatial variation among sites and among estuaries?

4. Does temporal variation include either a significant seasonal or rainfall-driven component? How important are these?
5. What are the patterns of similarity among sites across the region if we integrate all of our current data through time?
6. How well do measured environmental variables explain variation in community structure across the region (i.e. do existing relationships indicate that causal links can be established in the future)?
7. What characterises individual sites and estuaries in terms of the dominant fauna found there?
8. Can we use existing spatial differences among sites to build a general regional model of how we would expect the benthic community at a given site to change with gradual long-term increases in the mud content of ambient sediments?
9. Which sites, if any, have demonstrated significant directional changes in community structure through time? Are these changes of a sufficient magnitude and in a direction that indicates sediment impacts?
10. At which sites are specific bivalve species (*Austrovenus*, *Macomona* and *Paphies*) consistently most abundant? How stable are these populations through time? What proportion of these populations are juveniles and is there any evidence of seasonal variation in their abundances?
11. What are the spatial patterns of diversity across the region? How stable is diversity (number of taxa) through time at individual sites and across whole estuaries?

By addressing each of these individual questions, in turn, we provide an answer to the central question, yielding a rigorous assessment of the quality and utility of this monitoring programme for detecting and characterising future impacts.

3 Methods

3.1 Estuaries and sites in the monitoring programme

The seven estuaries in the monitoring programme are (from north to south): Puhoi (P), Waiwera (W), Orewa (R), Okura (O), Mangemangeroa (M), Turanga (T) and Waikopua (K) (Fig. 1). Within each estuary, 10 sites were sampled (denoted as 1-10, with 1 being closest to and 10 being furthest from the mouth of the estuary). The specific locations of sites are given as GPS coordinates (Appendix 1) and are also shown as numbers on aerial photographs of each estuary (Appendix 2). These sites were chosen to cover existing environmental gradients from the mouth to the upper reaches of each estuary. Within the Whitford embayment, the sites were also chosen to cover zones previously identified as being most vulnerable to potential impacts from sediment inputs, or as areas of high biodiversity (Senior et al. 2003). Each site is fully identified by a single letter and number. For example, R3 corresponds to the 3rd site from the mouth of the Orewa estuary. Each site is located in the intertidal zone (ranging from -0.6 to 1.6 m tidal height relative to mean sea level) and measures 50 m (parallel to the waterline) x 25 m (perpendicular to the waterline). These sites are smaller than the 100 m x 100 m sites used in monitoring programmes in the Manukau, Waitemata and Mahurangi estuaries (Nicholls et al. 2002; Cummings et al. 2003; Funnell et al. 2003), because of the difference in estuary scale and available mud/sand flat.

3.2 Timing of sampling

The timing of sampling was designed to incorporate potential seasonal variation, and was also timed to occur when increases in sediment inputs from the surrounding catchment due to heavy rainfall (particularly with the advent of land-use changes and development) might be expected. Sampling was therefore event-driven and occurred twice (after rain, and after a dry period) within each of two discrete seasonal three-month blocks (winter/spring: August – October and summer/autumn: February – April), yielding four sampling times per year.

To identify an appropriate "trigger" for sampling after rainfall, seventeen years of data from the Leigh Marine Laboratory meteorological records were examined. It was found that a rainfall event of 15 mm in a 24-hour period could reliably be expected to occur at least twice in each of the seasons. Therefore, a "rainfall event" was defined as ≥ 15 mm of rainfall in a 24-hour period. In each season, sampling was done at each site across all of the estuaries 7-10 days after a rainfall event ("rain") and when such a rainfall event had not occurred in ≤ 10 days ("dry")[1]. Rainfall was initially gauged from the St Heliers weather station, which is central to all estuaries. From mid-2004, more

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[1] This use of this criterion to trigger sampling began in August 2002. A different sampling design was used prior to that time.

accurate measures of rainfall have been obtained from the records available for Mangemangeroa, Orewa and Okura sites in the Hydrotel online database[2]. At each sampling time, all 70 of the sites were sampled within a period of three to five days[3], as shown in Table 1 for the '05-'06 and '06-'07 sampling years.

Figure 1.

Map of the east coast of the Auckland Region, showing all seven estuaries sampled. Abbreviations used for the estuaries in reporting results are shown in brackets after each name.

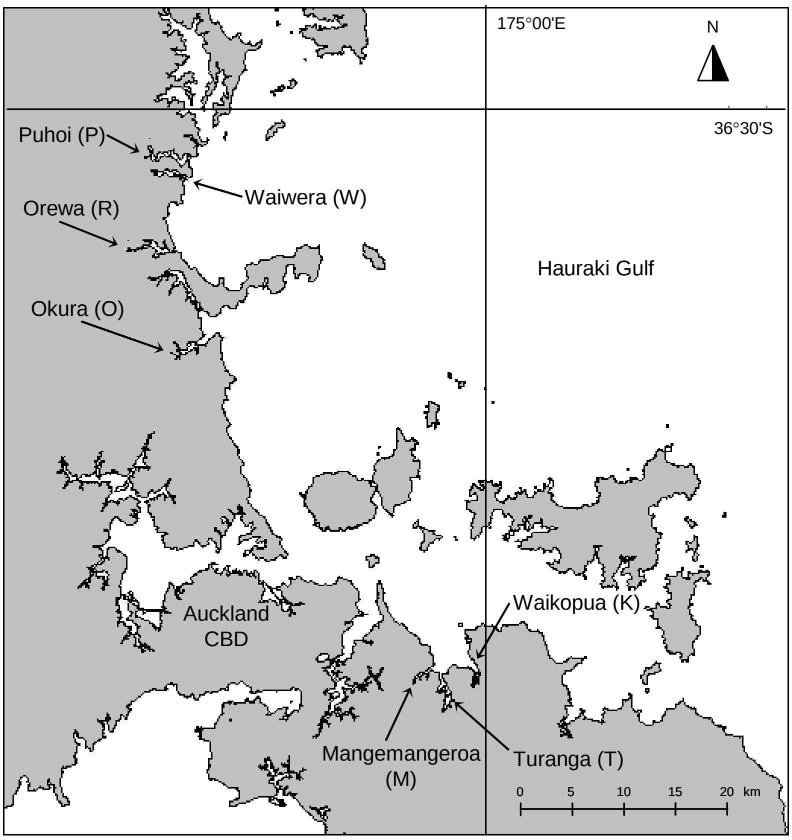

Table 1.

Dates of sampling for the '05-'06 and '06-'07 years of monitoring.

	Rain	Dry
Winter/Spring 2005	28-30 September	17-19 August
Summer/Autumn 2006	1-3 February	24-26 April
Winter/Spring 2006	18-20 September	7-9 August
Summer/Autumn 2007	5-7 April	14-16 February

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[2] http://maps.arc.govt.nz/website/maps/map_hydrotel.htm

[3] One exception to this historically was in August 2000, when sampling was done over a 7-day period.

In '01-'02, sampling was done 6 times per year: twice in each of three seasons. However, seasonal effects were found to be minimal compared to spatial variation within and among estuaries (e.g., Ford et al. 2003a). Thus, from August 2002 onwards, only two seasonal blocks were deemed necessary (as outlined above) and effort was instead directed towards sampling a greater number of estuaries (Ford et al. 2004; Ford and Anderson 2005).

A summary table showing the timeline for the monitoring programme, including all times of sampling and the points in time at which different estuaries were added, is provided in Appendix 3. From this, it will be noted that certain sites in Okura have been sampled 31 times since April 2000. The other estuaries of Puhoi, Waiwera, Orewa and Mangemangeroa have been monitored, along with Okura, since August 2002 (i.e., for the last 20 times of sampling). These, plus two additional arms of the Whitford embayment: Turanga and Waikopua, have all been monitored since August 2004 (i.e., for the last 12 times of sampling). This summary table is a useful reference when examining results, because it also identifies each time point of sampling in a series ("Time serial") from time 1 (August 2000) through to time 31 (April 2007). It also identifies the season and whether the time point corresponded to sampling after rain (R) or after a relatively dry period (D).

3.3 Sampling of fauna

At each site, the corner closest to the channel of an area measuring 50 m parallel to the shore (the x-axis) and 25 m perpendicular to the shore (the y-axis) was marked with a permanent cross at the origin (0, 0) (see Appendix 4). Six replicate faunal cores (130 mm in diameter x 150 mm deep) were obtained from random positions within each site. This was achieved by randomly generating pairs of values (x, y) in the range {0 to 50} for x and {0 to 25} for y, which indicated a precise position to place each of the cores (in meters in each of the x and y directions from the origin marker) within each site. Each core was sieved in the field using 0.5 mm mesh. Material retained on the sieve was brought back to the laboratory for sorting and identification. All organisms retained were preserved in 70% isopropyl alcohol with 0.01% rose bengal.

All organisms were identified to the lowest level of taxonomic resolution possible. This varied, depending on the particular group. For example, nemerteans were grouped at phylum level, while bivalves were identified to species. The list of taxa used here includes the list agreed upon for estuarine fauna as part of the ARC's benthic health modelling (Anderson et al. 2006), but also includes some taxa that are uniquely identified as part of this monitoring programme. A full list of the taxa identified as individual variables in this study is provided in Appendix 5. The level of taxonomic resolution has naturally increased slightly through time, as expertise in this area continues to develop. The biotic variables are, however, quite consistent for these data from August 2002 (time 12) onwards, so community-level analyses use data only from this time point onwards.

3.4 Sampling of ambient sediments

Ambient sediments were sampled adjacent to each faunal core (i.e., *n* = 6 per site). For this, a specially adapted 20 ml syringe was pushed into the sediment to a depth of approximately 2 cm and the sediments in this layer were withdrawn[4]. The six sediment cores from a single site were combined together into a single sample for analysis, yielding a wet weight of approximately 60 g.

To characterise the grain size fractions, samples were dried and treated with 9% hydrogen peroxide until fizzing ceased, to dissolve organic matter. Samples were then dried again and weighed to obtain a total dry weight. They were then deflocculated for at least 4 hours (using Calgon 5g per litre) and wet-sieved on a stack of sieves (500, 250, 125 and 63 μm). Each fraction (>500, 250-499, 125-249, 63-124 and <63 μm) was dried, weighed and calculated as a percentage of the total weight. The fraction less than 63 μm was calculated by subtraction of all other dry weights from the initial dry weight due to the inherent difficulties in settling and drying these fine sediments[5]. Due to changes in methodology for the sampling and grain-size analysis of sediments (see Appendix 6 for details), only data from August 2004 onwards are considered comparable through time and were used in subsequent analyses.

3.5 Sampling of sediment inputs

Sediment inputs were characterised by using a combination of a sediment trap and a depth-of-disturbance rod at each site. A sediment trap (37 mm diameter by 500 mm deep) was placed at the lowest point of each site so that the opening was 200-250 mm above the sediment surface (see Appendix 4). These traps collected sediment settling from the water column.

Sediment traps are deployed continuously at each site and are sampled approximately monthly. The amount of sediment collected in the traps over each period was standardised across all sites by being expressed as a rate in grams per cm^2 per day. However, at some sites (R1, R3 and W3), a shorter deployment period is necessary (e.g., a fortnight, or even less), because these sites have a greater turnover of sediments and, if left for a whole month, the traps would frequently overfill. Sediment collected from traps was filtered (mesh size ~ 2 μm), dried and weighed. These sediments were then sub-sampled, pre-treated for organics, deflocculated and wet-sieved as for ambient sediments to characterise their grain-size fractions.

Trapped sediment measures do not precisely quantify sediment deposition *per se* because they integrate deposition from the water column and resuspension of material from the bed. However, they do provide a useful measure that, although often partially correlated with ambient sediments, has proven more useful in explaining biotic assemblages than ambient sediment composition alone (Ford and Anderson 2005).

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[4] Prior to August 2004, ambient sediment samples were obtained using a 38 mm diameter corer to a depth of 15 cm and each replicate was analysed separately. A full explanation of the changes in methodology in the sampling and analysis of grain sizes of sediments is given in Appendix 6.

[5] Prior to August 2002, sediment grain size data were binned into slightly different grain-size categories (in μm), viz. < 65.5, 65.6-120.7, 120.7-258.9, 259.8-555.7, and >555.7 μm. See Appendix 6.

Nevertheless, if the aspect ratio (the ratio of the distance from the top of the trap to the surface of the sediment accumulated within it, versus the diameter of the trap, which is 37 mm) is less than 10:1 (i.e. if the distance is <370 mm), then there can be no assurance that substantial resuspension of sediments may not have occurred. Data from traps were excluded from subsequent analysis when aspect ratios were breached[6].

Depth-of-disturbance rods (Clifton 1969; Greenwood and Hale 1980) were adapted from previous designs (Anderson et al. 2002) due to safety concerns and problems of sample reclamation. Marker poles with sediment traps attached were used to gauge relative change in the height of the bed (Appendix 4). Measurements were taken between the top of the sediment trap holder and the ambient sediment surface at least once a month. The height of the top of the sediment trap holder above the sediment surface measured the net erosion or accretion at a site. When scour was present at the base of the marker poles the height of the top of the holder was estimated in relation to the ambient bed height at the pole independent of any scouring using a ruler.

3.6 Statistical and graphical methods

The statistical and graphical methods outlined below (§ 3.6.1 – 3.6.11) correspond directly to the questions numbered 1-11 in the introduction above. All multivariate analyses of community structure were done using the PRIMER v6 computer program (Clarke and Gorley 2006) with the PERMANOVA+ add-on package (Anderson and Gorley 2008). In addition, all multivariate analyses were done on the basis of Bray-Curtis dissimilarities calculated from square-root transformed abundances. All univariate analyses and plots were done using the R package for statistical computing (R Core Development Team 2007). For reference, a glossary of statistical terms is provided in Appendix 7.

3.6.1 Measuring and comparing the temporal variability of communities among sites within each estuary

To measure the temporal variation in community structure among sites, the abundances of individual taxa were averaged across the *n* = 6 cores for each site at each time point. For each estuary in turn, patterns of dissimilarity among the sites and through time were visualised using non-metric multi-dimensional scaling (MDS) of the site x time centroids. The temporal variability (dispersion) of each site was quantified as the average Bray-Curtis dissimilarity among time points. These dispersions were formally compared among the ten sites (separately within each estuary) using a permutation test of dispersion with 4999 permutations (PERMDISP, Anderson 2006). For Puhoi, Waiwera, Orewa, Okura and Mangemangeroa, there were 20 time points

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[6] Aspect ratios were only measured from December 2004 onwards. The relationship between aspect ratio and total sediment weight indicated that aspect ratios were breached when total sediment weight exceeded 190 g. Thus, data prior to December 2004 were also excluded from analysis if total sediment weight exceeded 190 g.

(from August 2002, or time 12 onwards), while for Turanga and Waikopua, there were 12 time points (from August 2004, or time 20 onwards, Appendix 3).

3.6.2 Measuring and comparing the temporal variability of communities among whole estuaries

A similar approach was used to measure and compare temporal variation in community structure at the larger scale of whole estuaries. First, the abundances of individual taxa were averaged across the n = 6 x 10 = 60 cores for each estuary at each time point. Patterns of dissimilarity among the estuaries and through time were visualised using non-metric multi-dimensional scaling (MDS) of the estuary x time centroids. The temporal variability (dispersion) of each estuary was quantified as the average Bray-Curtis dissimilarity among time points. These dispersions were formally compared among the seven estuaries using PERMDISP with 9999 permutations (Anderson 2006). This approach directly compared temporal variation in the community structure of whole estuaries. In addition, to compare the site-level temporal variation among estuaries, the average and standard error of temporal variation calculated from the 10 sites were plotted for each estuary.

3.6.3 Comparing the relative sizes of temporal and spatial variation in community structure

The relative importance of the factors of Estuary ("E", up to 7 levels), Site ("S(E)", 10 levels, nested in Estuary), Time ("T", up to 20 levels) and their interactions (E×T and S(E)×T) were examined and quantified by partitioning the total variation in the biotic data (averages of the n = 6 cores at the site level), using permutational multivariate analysis of variance (PERMANOVA, Anderson 2001; McArdle and Anderson 2001). Direct multivariate analogues to the usual ANOVA estimators of variance components (Searle et al. 2002; Anderson et al. 2005) were calculated for each term and expressed in terms of their square root, in order to place these onto the measurement scale of the dissimilarity measure for direct comparison.

To visualise patterns in the relative sizes of variation for the main effects, the average abundances of taxa were calculated (i) for each whole estuary, (ii) for each time point (from time 20 onwards) and (iii) for each site (numbered from 1-10, and being treated simply as rank distance from the mouth of the estuary). The Bray-Curtis dissimilarities among these main effect centroids (7 estuary points + 12 time points + 10 site points) were then calculated after square-root transformation, and plotted using non-metric MDS.

3.6.4 Determining the relative importance of seasonal and rainfall-driven effects

Effects of season and rainfall-driven sampling events were assessed by further partitioning the multivariate variation for the factor of Time into two specific 1df contrasts: winter/spring vs. summer/autumn (Season) and rain vs. dry (Rainfall). The power and utility of using contrasts for *a priori* hypotheses such as these is discussed, for example, by Quinn and Keough (2002). To accompany this, the 12 Time centroids (from time 20 onwards) were also examined alone in a separate MDS plot with labels corresponding to the season and rainfall-driven factors.

3.6.5 Patterns of similarity among sites from different estuaries across the region, integrated through time

Averages in the abundances of taxa were obtained for each site within each estuary from time 20 (August 2004) onwards. These are centroids from 72 cores (6 cores per site x 12 time points), obtained for each of the 70 sites across the region. A non-metric MDS plot of these centroids provided a visual representation of patterns of similarity in community structure across all of the sites in the region, integrated through time.

3.6.6 Explaining spatial variation in community structure across the region with measured environmental variables

There were 12 environmental variables measured in this study and integrated (averaged) over time from August 2004 onwards for use in subsequent analysis. The list and description of these variables is provided in Table 2. Environmental variables were first examined for approximate normality and to identify any outliers using draftsman plots. Individual variables were transformed, if necessary (see Table 4 in §4.6 for details).

Table 2.

Environmental variables measured and included in analyses.

Group	Variable name	Description
Ambient sediments	mud	Percent (by weight) of ambient sediment < 63 μm (mud)
	fine.s	Percent (by weight) of ambient sediment 63-124.9 μm (fine sand)
	med.s	Percent (by weight) of ambient sediment 125-249.9 μm (medium sand)
	coarse.s	Percent (by weight) of ambient sediment 250-499.9 μm (coarse sand)
	shell	Percent (by weight) of ambient sediment > 499.9 μm (shell hash)
	a%org	Organic content of ambient sediment (percentage by weight)
Trapped sediments	tsed	Rate of sediment accumulation in traps ($g.cm^{-2}.day^{-1}$)
	t%org	Organic content of trapped sediment (percentage by weight)
	tmud	Rate of accumulation of mud (< 63 μm) in traps ($g.cm^{-2}.day^{-1}$)
	t%mud	Percent (by weight) of trapped sediment < 63 μm
Bed measures	bh	Rate of change in bed height ($mm.day^{-1}$)
	th	Tidal height (m) compared to mean sea level (Auckland datum 1946)

The relationship between the environmental variables and the biotic data (also averaged for each site from time 20 onwards) was examined using a distance-based linear model (DISTLM, Legendre and Anderson 1999; McArdle and Anderson 2001) on the Bray-Curtis dissimilarity matrix of square-root transformed abundances. The model was fitted first using a forward selection on the R^2 criterion simply to determine how much of the biotic variability could be explained overall. However, R^2 simply increases with increases in the number of predictor variables, and it is desirable to obtain a more parsimonious model which also takes into account the correlation structure among the environmental variables. This was done by selecting the best out of all possible models using a direct multivariate analogue to Akaike's "An Information Criterion" (AIC, Akaike 1973). AIC balances the increase in R^2 with a penalty for the number of parameters used in the model (e.g., Seber and Lee 2003). To visualise the resulting model, distance-based redundancy analysis (dbRDA, McArdle and Anderson 2001) was used, where the ordination axes are linear combinations of the environmental variables that maximally explain biotic variation.

3.6.7 Characterising sites in terms of the dominant fauna

Temporal variability was found to be small in magnitude (see results) and community structure was quite stable at individual sites through time. Thus, characterising each site in terms of dominant fauna, as a baseline for future reference, is appropriate. The proportional abundances of individual taxa were calculated for each of the sites after summing abundances through time. The top ten species in terms of proportional abundance were noted, along with the average and range in the number of species and the average and range in total abundance of the organisms found through time at each site. The proportions of total abundance accounted for by the 5 and 10 most abundant taxa were also determined to indicate community evenness at each site.

3.6.8 Modeling expected changes in community structure with increasing mud content of ambient sediments

A strong relationship was found between community structure and the percentage of mud (< 63 μm) in ambient sediment (see § 4.6). Thrush et al. (2003b) have modeled the responses of several species of macrofauna to sediment mud content across estuarine and tidal creek habitats in the Auckland region. Here, canonical analysis of principal coordinates (CAP, Anderson and Robinson 2003, Anderson and Willis 2003) was used to model the community along a gradient in the percentage mud of ambient sediments across the region. The model built was *spatial*, and used averages in both faunal abundances and percentage mud from time 20 onwards at each of the 70 sites, thus integrating temporal variation.

To make specific predictions regarding expected changes in component fauna with chronic longer-term ("press") increases in sediment mud content at any given site, the 20 most abundant taxa in the dataset (i.e., having the largest total average abundance at the site level, summed across all sites) were also modeled individually along the mud gradient. Admittedly, sediment mud content may not be the only factor influencing the abundance of an individual species, but it may well limit the maximum abundance attainable by a given species within a given environment (Thrush et al.

2003b). The maximum can be fairly volatile, however, as a test statistic. A model built on the 95th percentile is less sensitive to outliers. Thus, quantile regression of the 95th percentile of the distribution was used to model the abundances of dominant species (or taxa) along the regional gradient in percentage mud (Koenker 2005), using the R package "quantreg" (Koenker 2007). Distributions of abundances of species along gradients are also known generally to be highly non-linear (e.g., ter Braak 1985; Zhu et al. 2005; Yee 2006), so quantile regression spline models were fit rather than linear models (e.g., Leathwick et al. 2005). The appropriate polynomial (or df) required for the spline to provide an adequately-shaped fit was determined visually in scatterplots for each species, using the minimum df possible. The value at which the predicted density achieved a maximum along the gradient was identified and taken as an estimated optimum percentage mud for that species. This allowed specific predictions for the community in response to changes in mud content in terms of the numerically dominant species across the region. To ground-truth the model, results were compared with the proportional abundances of taxa occurring at a series of representative sites along the existing spatially derived mud gradient.

3.6.9 Identifying sites having significant directional changes through time and which show evidence of sediment impacts

A significant relationship between the (linear) time trajectory ("Time serial") and faunal community structure at a given site would indicate that fauna are changing through time in a *directional* (as opposed to a random or non-directional) manner. The relationship between community structure and time was tested separately at each of the 70 sites using DISTLM, with 9999 permutations for each test. However, there is clearly a potential problem here because, naturally, the more tests that are done, the greater the chance of falsely rejecting the null hypothesis. Indeed, if one were to use a significance level (criterion for rejection) of $\alpha = 0.05$ for every test, then one would expect to reject the null hypothesis (i.e. to obtain a p-value less than 0.05) in at least 1 out of 20 tests just by chance. By doing 70 tests (one for each site), the overall (family-wise) error rate considerably exceeds the desired level of 0.05. Fortunately, by using the permutation distributions that are available for each of the individual tests, it is possible to correct for increased error rates due to multiple testing, and adjust the significance levels for each test to achieve an exact family-wise error rate of 0.05 overall (Manly et al. 1986; Westfall and Young 1993; Manly 2007; Ford et al. 2007). This was the approach taken here, using a specially-written computer programme written in FORTRAN by M. J. Anderson (FWER.exe).

It is recognised that a linear model may not be optimal, even for the Bray-Curtis measure. However, by treating time only as a rank integer value (rather than attempting to model actual time in months), the approach used here is extremely general, and does provide a screen that will identify important directional changes for individual sites.

The detection of significant directional change through time is perhaps a necessary but certainly not a sufficient condition to infer the presence of an impact at a site. It is also necessary to ask: (i) is the ***size*** of the temporal change of sufficient magnitude to consider it unusual (given the temporal variation exhibited by sites of that type in general across the region)? and (ii) is the ***direction*** of the change consistent with what is predicted for the community with increases in fine sediment inputs?

Each of the sites that were identified as changing directionally with time were examined more closely in order to assess the size and direction of the change. First, an individual MDS plot was done of the community at that site through time, to show its temporal trajectory. Second, the site's trajectory was mapped (projected) onto the canonical axis of the mud gradient model to see whether its temporal change coincided with predicted changes that would occur from increased muddiness. This canonical axis for the site along the mud gradient was plotted through time and examined for trends.

3.6.10 Describing temporal and spatial patterns in abundances of bivalves

All analyses and plots were done separately for each of the three bivalve species of interest: *Austrovenus*, *Macomona* and *Paphies*. Total densities at the estuary level were examined by plotting the sum of bivalve abundances (measured from 6 cores x 10 sites = 60 cores and expressed as a density per square metre) through time. Information regarding relative abundances of different size classes was retained and displayed in all time series plots. Data were transformed using log(x+1), and tests for overall trends through time were done using simple linear regressions. Okura cockle density appeared to be non-linear so a generalised additive model (GAM) was fit, and the inflection point of the resultant model was used to split the time series into two parts for piece-wise linear trend fitting. Seasonal effects were examined using a paired design. The difference in average density between the winter/spring and summer/autumn seasons was calculated for each year. A classical *t*-test was used to test the null hypothesis that the average seasonal difference was equal to zero, and a 95% confidence interval was constructed to quantify the size of any significant seasonal effects. Spatial comparisons in overall densities among estuaries (using the time points as replicates) were done using ANOVA, with *P*-values obtained using 9999 permutations.

3.6.11 Describing temporal and spatial patterns in diversity

The total number of taxa recorded at each estuary (from 6 cores x 10 sites = 60 cores) was determined at each time point and plotted through time to look for trends and/or seasonality. Spatial comparisons in overall diversity among estuaries (using the time points as replicates) were done using ANOVA, with *P*-values obtained using 9999 permutations. The total number of taxa recorded at each site (from 6 cores) was also plotted through time for each of the ten sites from each estuary. Results were expressed in terms of the averages and ranges in diversity values through time, as described in § 3.6.7.

4 Results

4.1 Temporal variation among sites within each estuary

4.1.1 Puhoi

In the Puhoi estuary, benthic communities from individual sites were identifiable as clusters of points having similar symbols on the MDS plot (Fig. 2). The temporal variation of any individual site is measured and can be seen visually in two ways in this figure: (i) from the relative spread (dispersion) of time points for each site in the MDS plot and (ii) from the bar graph showing the average Bray-Curtis (BC) dissimilarity among time points for each site. There were significant differences in dispersion (temporal variability) among sites (PERMDISP, $F_{9,190} = 12.73$, $P = 0.0002$). Sites P1, P4, P5 and P6 had the lowest average inter-point dispersions through time and the tightest clusters on the plot. Almost all of the sites showed average BC dissimilarities through time of around 40% or less, except for site P9 and site P10, in the upper reaches of the estuary.

The largest dispersion was shown by site P9 and this was mostly due to two outliers: time 16 (at the top of the MDS plot) and time 18 (in the middle of the cluster for site P1, Fig. 2). Examination of the original data for these individual time points showed an unusually large number of small (< 4mm) cockles (*Austrovenus stutchburyi*) was recorded at time 18, but the community was in other ways similar to what had been recorded at other times for site P9. For time 16, the cores contained relatively few species compared to other times for that site.

For site P10, the greater average dispersion was also apparently caused by two outliers: time 13 and time 19, which are seen in the middle of the cluster for site P1 in the MDS plot (Fig. 2). Examination of original data revealed larger-than-usual abundances of pipi (*Paphies australis*) and of the amphipod *Waitangi brevirostris* at those two times.

Since the communities through time at a single site generally appear as reasonably tight clusters on the MDS plot, it is also possible to infer relationships among whole sites in terms of community structure. For example, the communities at site P1 and site P4 (on the right-had side of the diagram) are distinct, but are more similar to one another than to other sites (Fig. 2). Moving to the left, we see site P6 and site P7 in the centre of the plot, which overlap to some extent. To the left, site P5 is relatively distinct, but sites P2, P3, P8 and P9 are quite similar to one another and overlap to a large extent.

4.1.2 Waiwera

As for Puhoi, individual sites in Waiwera are clearly identifiable as clusters of points through time on the MDS plot (Fig. 3). Perhaps the most prominent feature seen here is the considerably greater temporal variability (relative dispersion) apparent for site W4 compared to all of the other sites. Not surprisingly, significant differences among the sites in terms of their temporal variability in community structure was detected by PERMDISP ($F_{9,190}$ = 15.31, P = 0.0002). Sites W1, W2 and W10 showed a moderate amount of temporal variation (40-44% average BC dissimilarity), while the rest of the sites in the estuary (W3, W5, W6, W7, W8 and W9) showed very little change in community structure through time (27-38% BC dissimilarity). There were no obvious outliers for any of the sites.

A gradient in community structure among the sites is also apparent in the plot from left to right (Fig. 3): beginning with sites W1, W2, W4 and W10, moving through to sites W5, W7 and W9, then through to site W6, on to site W8, then site W3. This gradient clearly does not correspond directly to distance from the mouth of the estuary, but it does relate to the environmental characteristics measured for these sites (see § 4.6 below). For example, sites W1, W2, W4 and W10 are among the muddiest sites sampled within this estuary.

4.1.3 Orewa

Individual clusters were also apparent for sites at Orewa through time (Fig. 4). Although significant differences in temporal variation among the sites were detected, these differences were not quite of the same magnitude as was found for Puhoi and Waiwera (PERMDISP, $F_{9,190}$ = 8.15, P = 0.0002). Almost all of the sites had average BC dissimilarities in community structure through time which was near to or less than 40%. The exception was site R3, whose larger average dispersion (44%) was clearly seen as a split into two clusters in the MDS plot. This split occurred at time 19 (Mar 2004), when the position of site R3 was, in fact, physically moved (Ford and Anderson 2005). This was forced by a natural alteration in the physical position of the channel in the estuary. The change in community structure caused by this shift in position (~ 70 m away) was detected by control charts and discussed in Ford and Anderson (2005, referred to as site "RC" therein), but it is interesting to see now that the community, at the newly defined site of R3 has remained stable since that time.

Site R8 appeared as an outlier at time 16, when it was more closely associated with the community found at site R4 (Fig. 4). Upon closer inspection, time 16 lacked any bivalves of the species *Macomona liliana*, which at other times was prominent in the community sampled at site R8.

The gradient in community structure is, in this estuary, more closely linked with the distance from the mouth of the estuary (Fig. 4). Sites R1, R3 and R4 are on the right, then sites R2, R5 and R7 in the middle, followed by sites R6, R8, R9 and R10.

4.1.4 Okura

For Okura estuary (Fig. 5), the individual sites were clearly identifiable on the plot as individual clusters, with much less overlap in their positions than was seen for the three more northern estuaries. There is also strong similarity in community structure among certain sites: for example, sites O1, O4 and O6 form a sub-group in the lower right portion of the MDS plot (Fig. 5). Although there was significant variability in temporal dispersions detected among these sites (PERMDISP, $F_{9,190}$ = 8.15, P = 0.0002), all of the sites had average BC dissimilarities through time of less than 40% (26-38%, Fig. 5). In other words, the similarity in community structure within any of these sites between any two time points over the past five years (since time 12, Aug 2002) is at least 60%, based on the BC measure. This further attests to their relative stability over time.

Site 7, time 12 appeared as an outlier, occurring in the middle of the cluster for site 6 (Fig. 5). Compared to samples obtained at other times from that site, it had large numbers of *Nucula hartvigiana*, *Aonides oxycephala* and *Aquilaspio aucklandica*. No other outliers were apparent.

4.1.5 Mangemangeroa

The estuary which overall showed the smallest variability through time within individual sites was Mangemangeroa. Like Okura, despite significant differences in dispersions (PERMDISP, $F_{9,190}$ = 11.05, P = 0.0002), all of them were well under 40% in average temporal BC dissimilarities (25-35%, Fig. 6). Site clusters were readily identifiable on the MDS plot and the gradient in community structure from the mouth to the upper reaches of the estuary was also very clear (from right to left, Fig. 6). Site 4, time 31 appeared as an outlier. Closer examination revealed unusually large numbers of *Aquilaspio aucklandica* and barnacles at that time compared to samples at other times from that site, but no other notable differences.

4.1.6 Turanga

There is relatively small temporal variation (28-42% average BC dissimilarity through time) and clusters corresponding to individual sites are apparent in the MDS plot for Turanga estuary (Fig. 7). There were no apparent outliers, and no significant differences in temporal variation among the ten sites in this estuary (PERMDISP, $F_{9,190}$ = 1.82, P = 0.1954). As for Mangemangeroa, the gradient in community structure from the mouth of the estuary to its upper reaches is clear and strong. The groups of sites showing affinities in community structure in the plot are: {T1, T2, T3}, {T4, T5}, {T6, T7}, {T8} and {T9, T10}.

4.1.7 Waikopua

For Waikopua estuary, differences in temporal variation among the sites were apparent in the MDS plot and were statistically significant (PERMDISP, $F_{9,190}$ = 26.88, P =

0.0002) the greatest temporal variation was observed at sites K1, K9 and K10 (Fig. 8). In addition, there were distinct breaks in the MDS plot, indicating clear differences in community structure between: (i) site K1 and the rest and (ii) sites {K8, K9, K10} and the rest. Sites K2, K3, K4, K5, K6 and K7 formed a tight cluster and showed very little temporal variation (< 30% average BC dissimilarity through time, Fig. 8). None of the sites showed any clear outliers.

Figure 2.

MDS plot for Puhoi estuary, based on abundances of 153 taxa at each site (averages from *n* = 6 cores) at each of 20 time points from time 12 (August 2002) onwards. Numbers indicate the time points of sampling according to "Time serial" values given in Appendix 3.

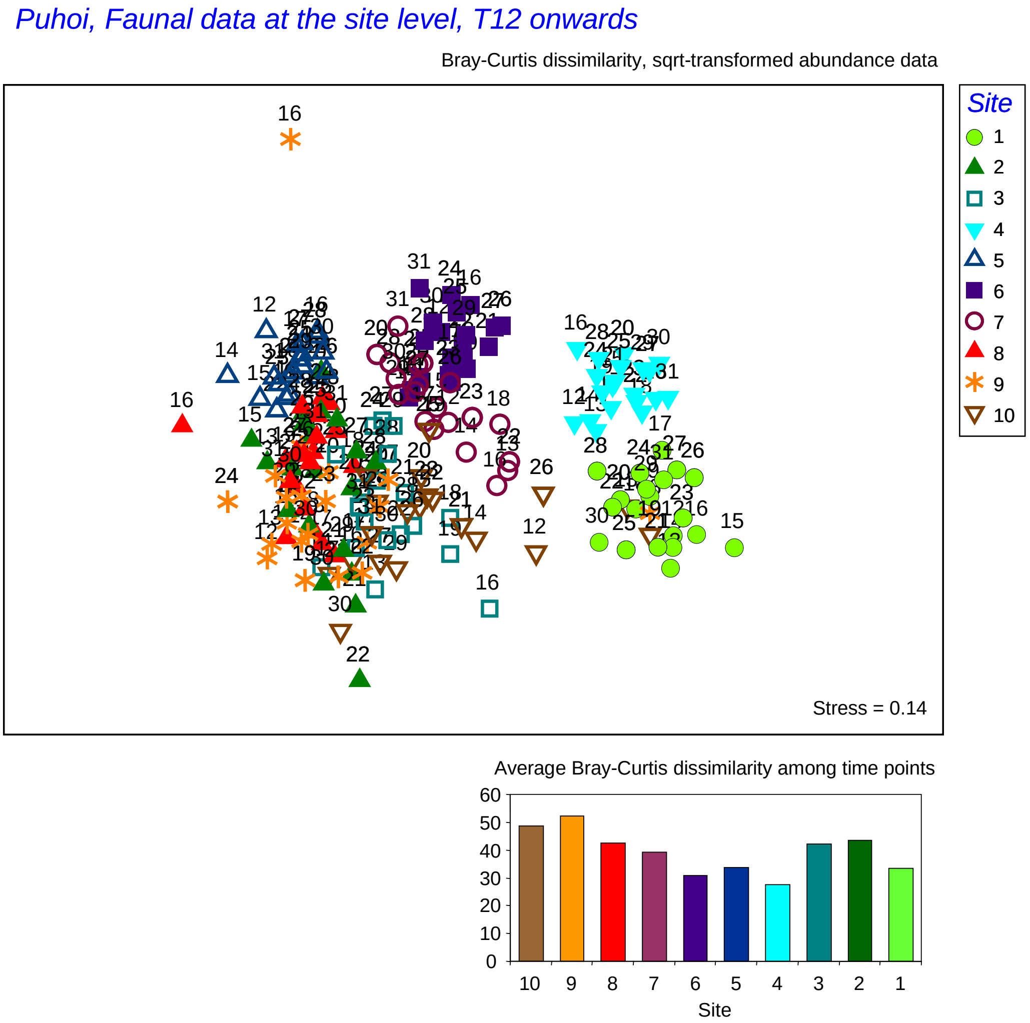


Figure 3.

MDS plot for Waiwera estuary, based on abundances of 153 taxa at each site (averages from n = 6 cores) at each of 20 time points from time 12 (August 2002) onwards. Numbers indicate the time points of sampling according to "Time serial" values given in Appendix 3.

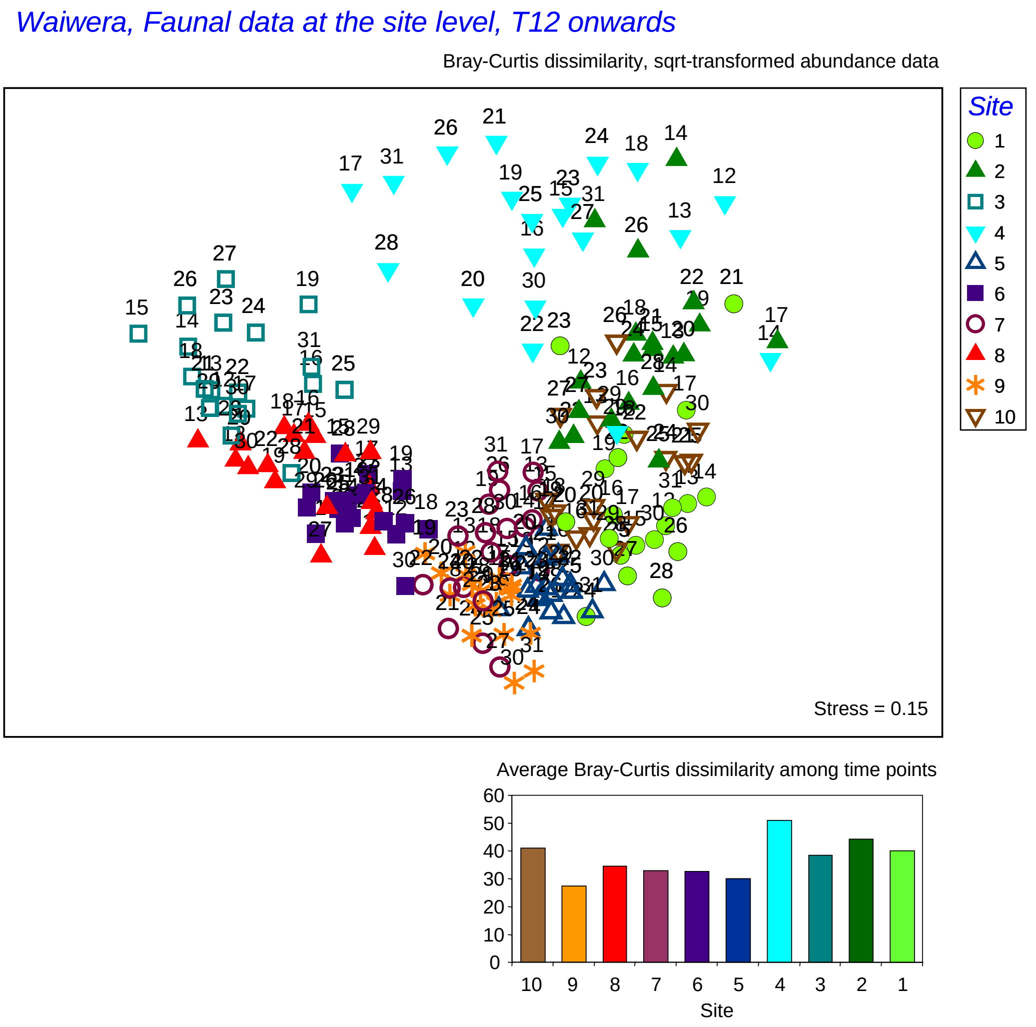


Figure 4.
MDS plot for Orewa estuary, based on abundances of 153 taxa at each site (averages from *n* = 6 cores) at each of 20 time points from time 12 (August 2002) onwards. Numbers indicate the time points of sampling according to "Time serial" values given in Appendix 3.

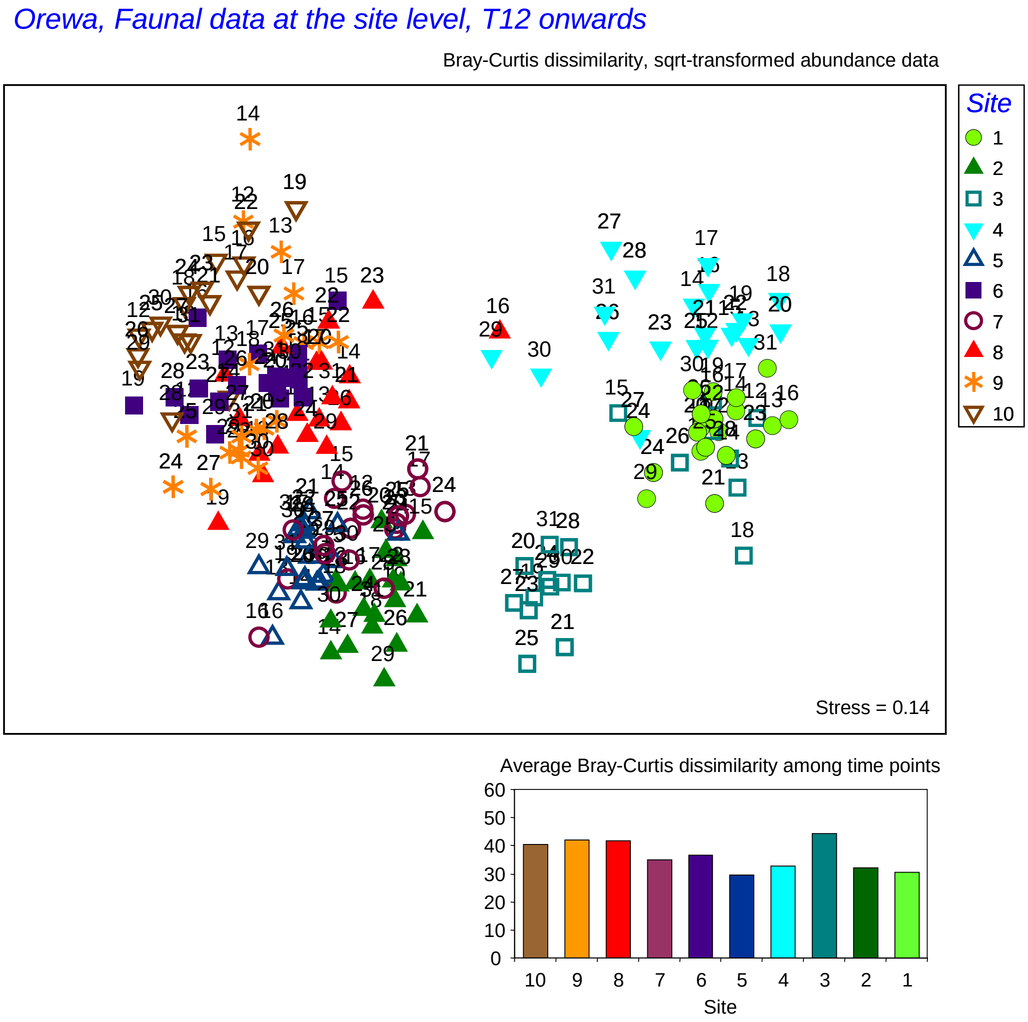


Figure 5.

MDS plot for Okura estuary, based on abundances of 153 taxa at each site (averages from *n* = 6 cores) at each of 20 time points from time 12 (August 2002) onwards. Numbers indicate the time points of sampling according to "Time serial" values given in Appendix 3.

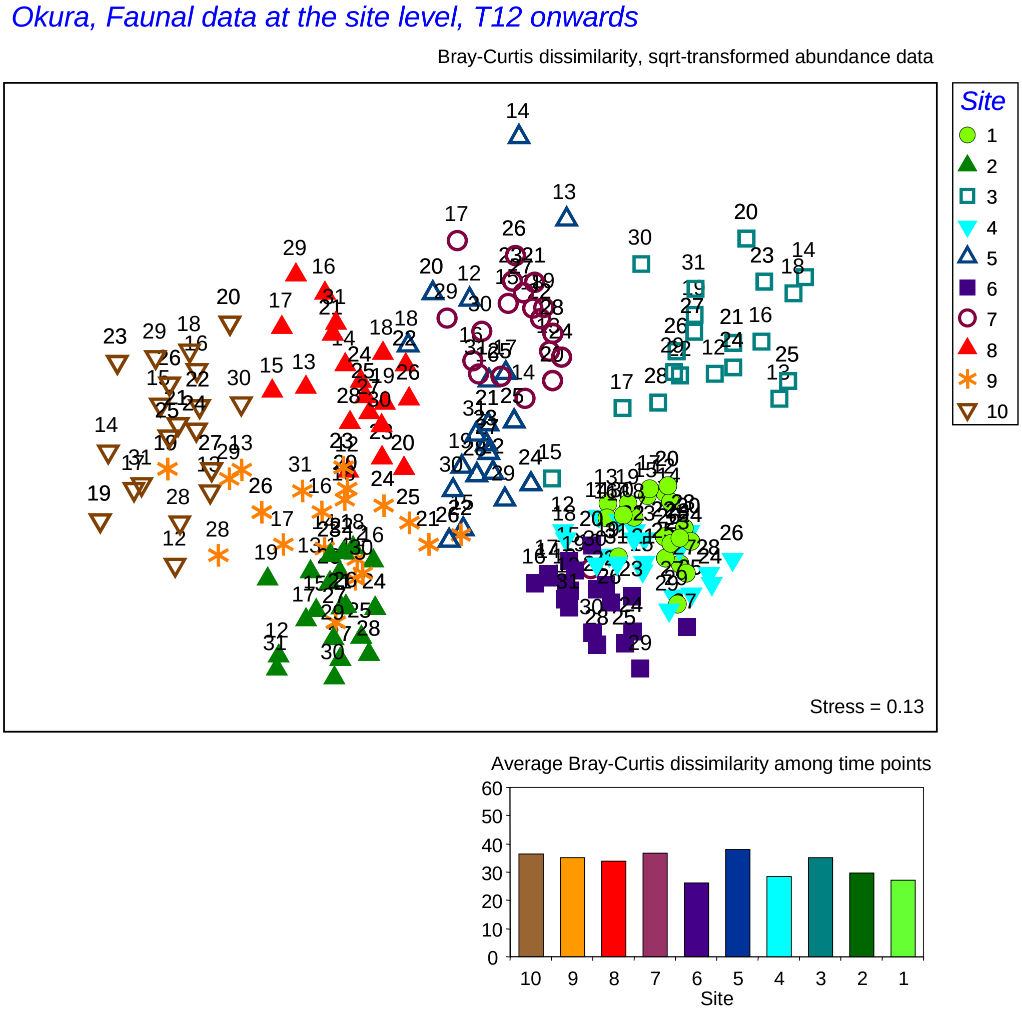


Figure 6.

MDS plot for Mangemangeroa estuary, based on abundances of 153 taxa at each site (averages from n = 6 cores) at each of 20 time points from time 12 (August 2002) onwards. Numbers indicate the time points of sampling according to "Time serial" values given in Appendix 3.

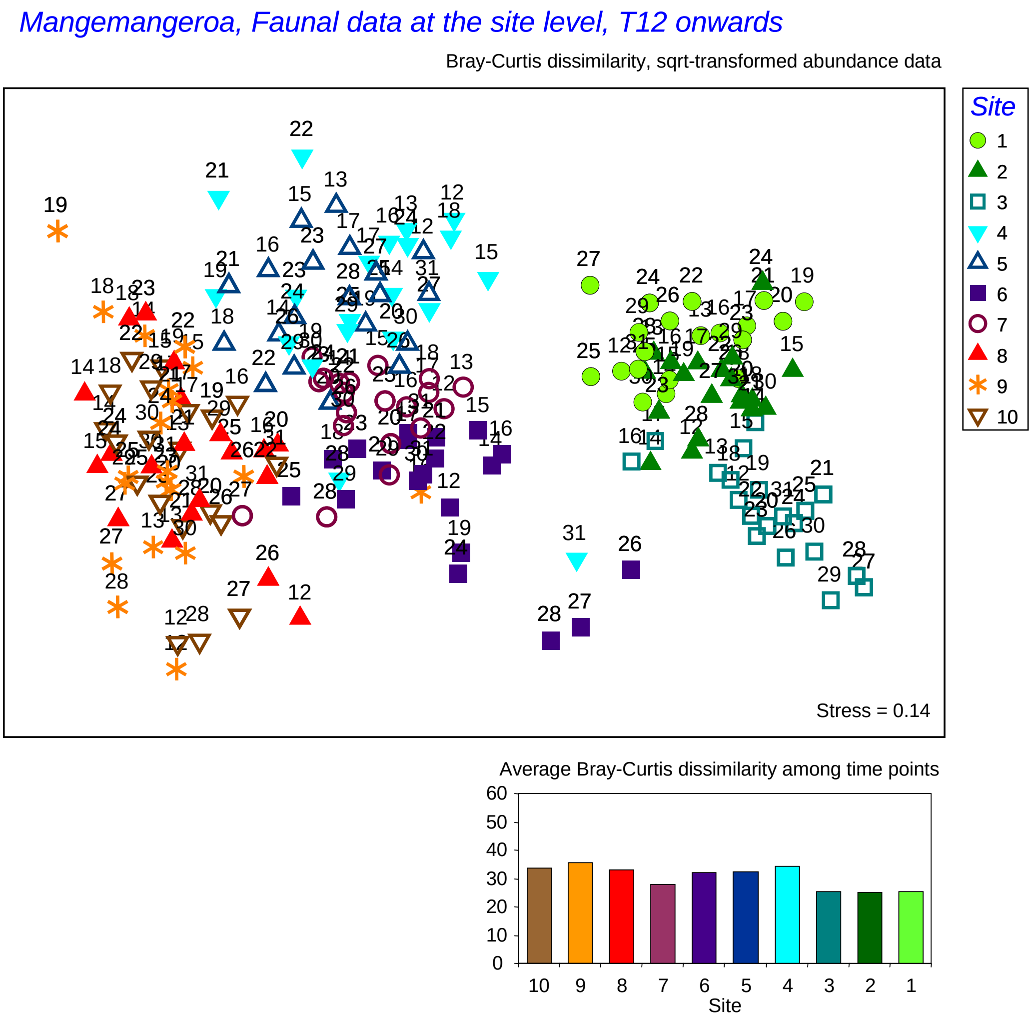


Figure 7.

MDS plot for Turanga estuary, based on abundances of 153 taxa at each site (averages from $n = 6$ cores) at each of 20 time points from time 20 (August 2004) onwards. Numbers indicate the time points of sampling according to "Time serial" values given in Appendix 3.

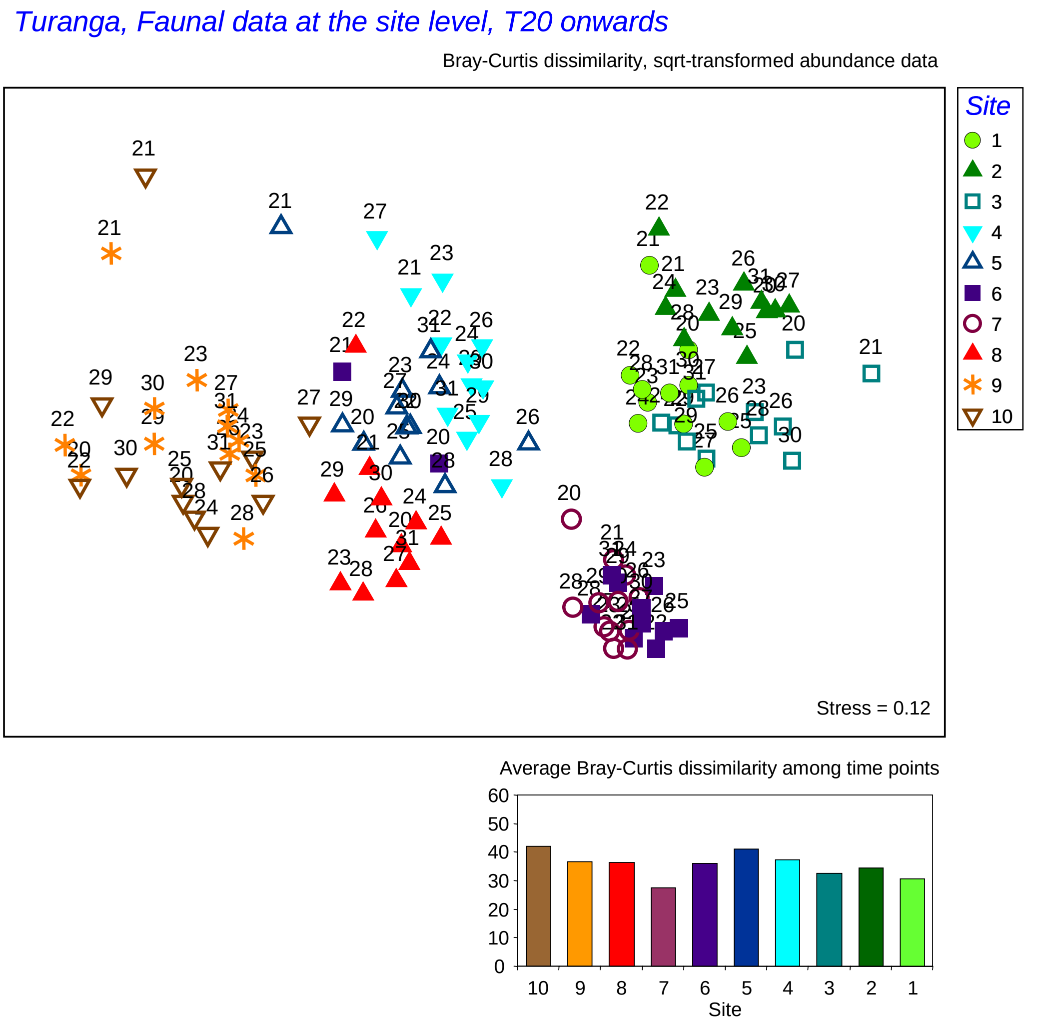
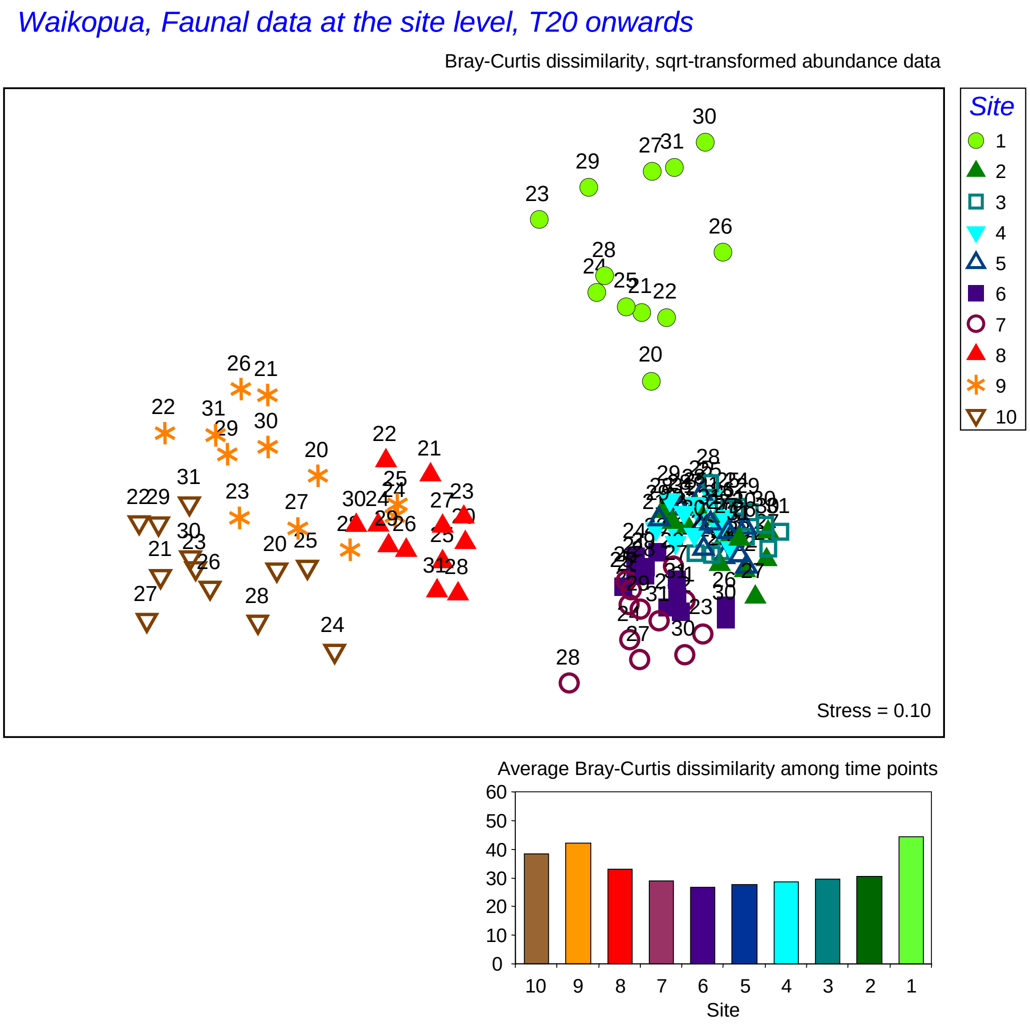


Figure 8.

MDS plot for Waikopua estuary, based on abundances of 153 taxa at each site (averages from *n* = 6 cores) at each of 20 time points from time 20 (August 2004) onwards. Numbers indicate the time points of sampling according to "Time serial" values given in Appendix 3.



4.2 Temporal variation among estuaries

When faunal data were integrated (averaged) across all of the sites within an estuary at each time point, clear differences among communities at the different estuaries were revealed (Fig. 9). The individual estuaries formed distinct clusters on the ordination plot and time points were seen as relatively small changes within each cluster. A clear pattern in the relationship among the estuaries in terms of their overall community structure was also apparent, with the northern estuaries (Puhoi, Waiwera and Orewa) on the left, Okura in the middle and the southern estuaries (Mangemangeroa, Turanga and Waikopua) located on the right. Interestingly, the three branches of the Whitford embayment (M, T, K) were all quite distinct from one another and from Okura. The three northern estuaries (P, W, R) showed a comparatively greater degree of similarity with one another. When the three northern estuaries were considered on their own in a separate MDS plot, however, clear distinctions between them were also readily apparent (Fig. 9). These finer distinctions are masked in the overall plot when the larger dissimilarities between these three northern estuaries and the other estuaries are being shown.

There were no significant differences in the dispersions (temporal variability in community structure) among estuaries (PERMDISP, $F_{6,77} = 1.17$, $P = 0.4033$). Average BC dissimilarity in community structure among time points for each estuary ranged from just 18 to 21% (Fig. 9, upper bar graph). Thus, despite these differences, the communities, when considered across entire estuaries as a whole, were very stable, remaining, on average, 80% similar through time.

When considering the average variation through time within individual sites (i.e., with $n = 10$ measures from each estuary), as opposed to the average whole-estuary-level variation, some slight differences among the estuaries were apparent (Fig. 9, lower bar graph). The lowest average within-site dissimilarity through time occurred for Mangemangeroa (30%) and the greatest occurred for Puhoi (39%). Thus, the communities, when considered at the site level, were generally also very stable, remaining, on average, from 60 to 70% similar through time.

4.3 Relative sizes of temporal and spatial variation in community structure

Partitioning of community structure according to the full experimental design (Table 3) indicated the following relationships with respect to the relative sizes of components of variation:

Site(Est) > Estuary > Time > Est x Time

Clearly the spatial variation among sites and among estuaries was the greatest, with temporal variation being small in size for Time and Est x Time, although all of these components were significantly larger than zero ($P = 0.0001$, Table 3). The column labeled "Sq.root" in Table 3 also provides a more specific interpretation in terms of the

Bray-Curtis measure. For example, the standardised average dissimilarity (in BC units) of a given site from its estuary centroid is estimated at ~32% (Table 3).

The MDS plot of main effect centroids (Estuary, Time and Site – here treated as a fixed factor with levels from 1-10) reflects the results shown in the PERMANOVA partitioning rather well (Fig. 10). The most important factor (Sites) is shown along the first (horizontal) MDS axis, as a gradient from the outer (right) to the inner reaches of estuaries. The second-most important factor (Estuaries) is shown along the second (vertical) MDS axis, with the northern estuaries at the top and the southern estuaries at the bottom. Interestingly, Okura is placed closest to Mangemangeroa in terms of its overall community composition (keeping in mind that these estuary centroids are averages across all sites and times from time 20 onwards). Finally, variation through time (from time 20 onwards) overall is of much less importance, with different time points forming a tight cluster more-or-less in the middle of the ordination diagram.

4.4 Relative importance of seasonal and rainfall-driven effects

How much of the temporal variation is attributable to seasonal effects or effects of rainfall-driven sampling? Additional partitioning of the variation among time points attributable to the specific contrasts of Season and Rainfall indicates that these effects are detectable (i.e., statistically significant), but are quite small in size (Table 3). The component of variation for Season (25.6) makes up about a third of the Time component of variation (78.7), but Rainfall (6.8) only accounts for relatively little - about one eleventh of this.

A separate MDS plot of the time centroids alone shows the seasonal effect quite clearly (see the lower plot of Fig. 10). A slight suggestion of a rainfall effect (triangles vs. circles) is apparent for the winter/spring samplings (in blue), but is not apparent for the summer/autumn samplings (in rose) (Fig. 10).

Table 3.

Partitioning of multivariate variation in assemblages according to the primary factors in the monitoring experimental design using PERMANOVA.

					Component of variation	
Source	df	MS	Pseudo-F	P	Estimate	Sq.root
Estuary	6	55331	2.86	0.0002	207.51	14.41
Time	19	5382	10.09	0.0002	78.74	8.87
Season	1	15708	24.29	0.0002	25.61	5.06
Rainfall	1	4675	7.07	0.0002	6.83	2.61
Site(Estuary)	63	19776	37.07	0.0002	1086.30	32.96
Est × Time	98	1165	2.18	0.0002	63.11	7.94
Est × Season	6	1612	2.49	0.0002	10.97	3.31
Est × Rainfall	6	790	1.20	0.1522	1.47	1.21
Residual	1053	533			533.46	23.10
Total	1239					

Figure 9.

MDS plot of estuary centroids (averages from *n* = 6 x 10 = 60 cores) at each time point from time 20 (August 2004) onwards, based on abundances of 153 taxa. Numbers indicate the time points of sampling according to “Time serial” values given in Appendix 3.

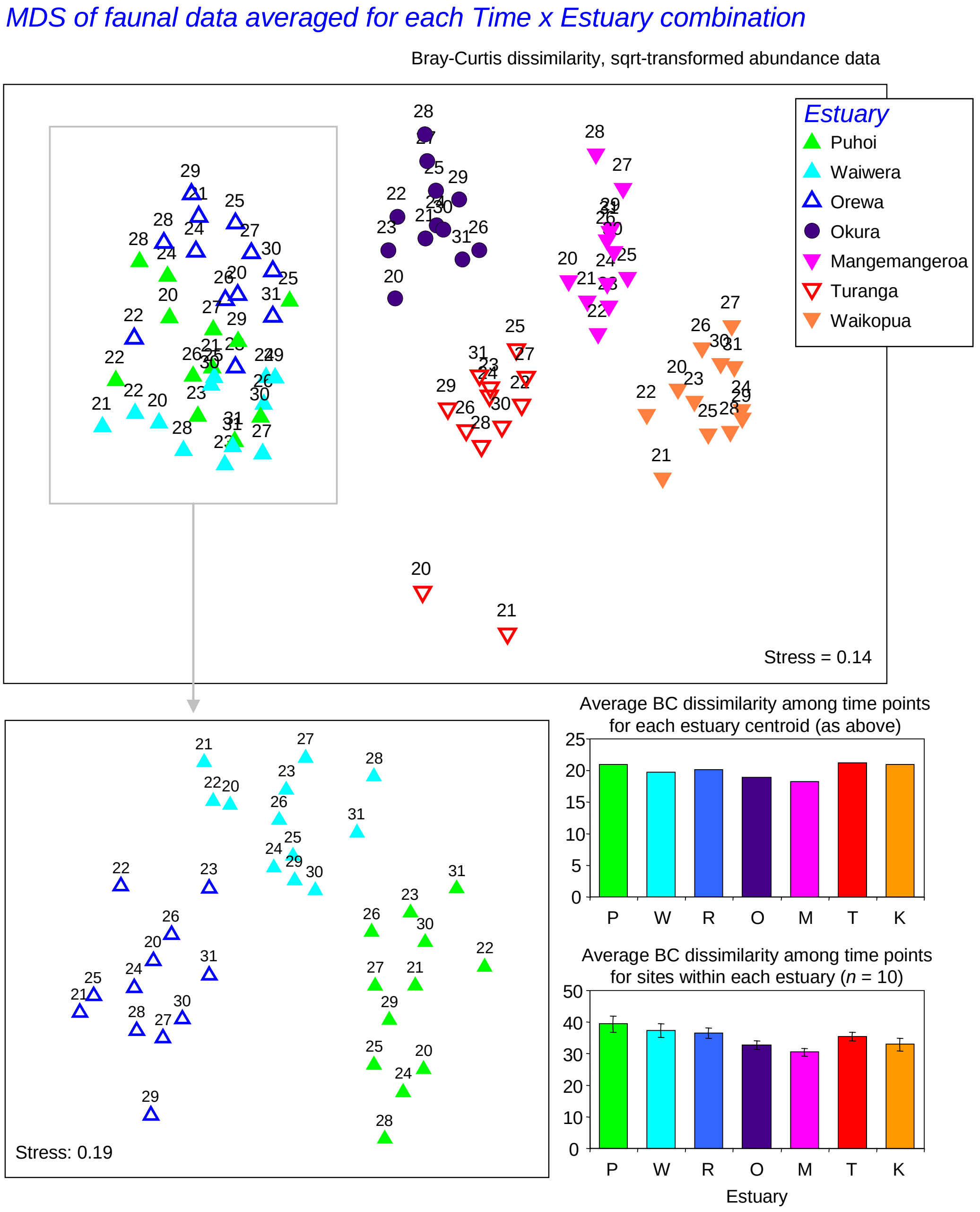
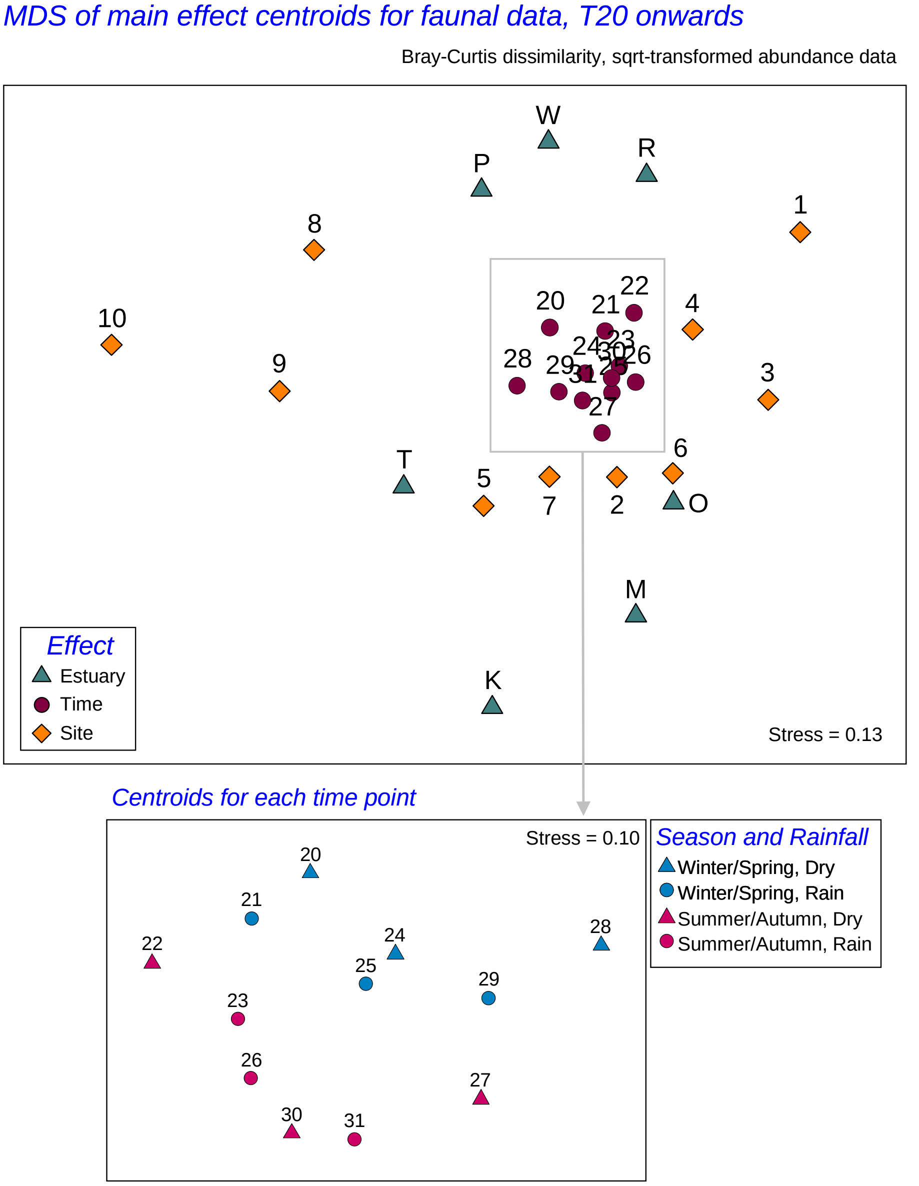


Figure 10.
MDS plot of main effect centroids, based on abundances of 153 taxa. Estuary centroids are averages from 6 cores x 10 sites x 12 times = 720 cores. Site centroids are from 6 cores x 7 estuaries x 12 times = 504 cores. Time centroids are from 6 cores x 10 sites x 7 estuaries = 420 cores.

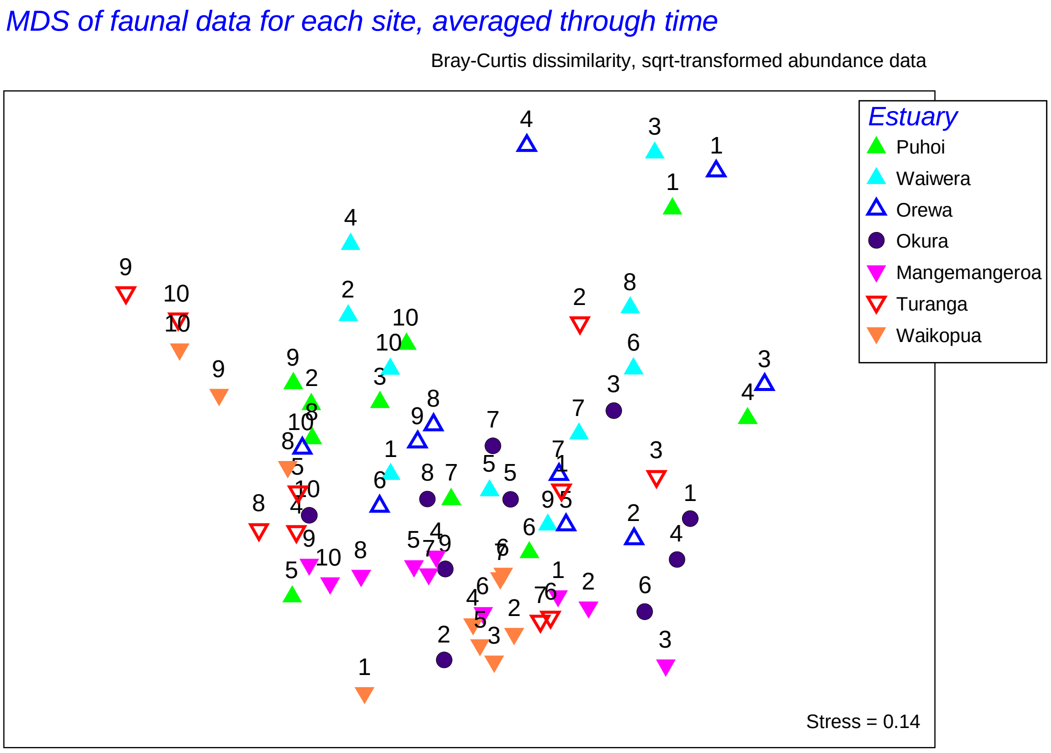


4.5 Similarities among sites across the region, integrated through time

Patterns of similarity among sites across the region are apparent from the MDS plot of site centroids, averaged through time (Fig. 11). Sites from the northern estuaries occur mostly in the upper half of the diagram, while the southern estuaries are found primarily in the lower half, with Okura spanning the central area. A gradient from the outer to the inner reaches of the estuaries, moving from right to left in the diagram, is apparent for the southern estuaries. In contrast, the northern estuaries do not necessarily show a clear ordering of the site numbers. Instead, certain sites appear to have affinity in community structure, such as Puhoi sites P3 and P10 being located near to Waiwera sites W2, W4 and W10. In terms of a gradient in community structure (primarily along the first MDS axis, yet forming a kind of "horseshoe"), at one extreme we see sites 9 and 10 in the inner reaches of Turanga and Waikopua (at the far left). At the other extreme (upper right) are sites 1, 3 and 4 from Orewa, sites 1 and 4 from Puhoi and site 3 from Waiwera. All of the estuaries have sites that span the majority of the range along this gradient.

Figure 11.

MDS plot of site centroids averaged through time (*n* = 6 cores x 12 time points = 72 cores) from time 20 (August 2004) onwards, based on abundances of 153 taxa.



4.6 Spatial variation in communities explained by measured environmental variables

All twelve environmental variables taken together explained 52.2% of the spatial variability in the biotic data at the site level (DISTLM, Table 4). The single most important variable was the percentage of mud (< 63 μm) in the ambient sediments ("mud"), which alone explained 20.5% of the faunal variation (Table 4). In the forward selection procedure, this was followed by the percentage of fine sand (63-124.9 μm) in ambient sediments ("fine.s"), the percentage of mud in trapped sediments ("t%mud"), then tidal height ("th"). These four variables alone explained over 40% of the faunal variation (Table 4). Bed height ("bh") and organic content, either in ambient sediments ("a%org") or traps ("t%org"), explained little, and did not appear to add anything important to the model, over and above what was already explained by other variables (Table 4).

Table 4.

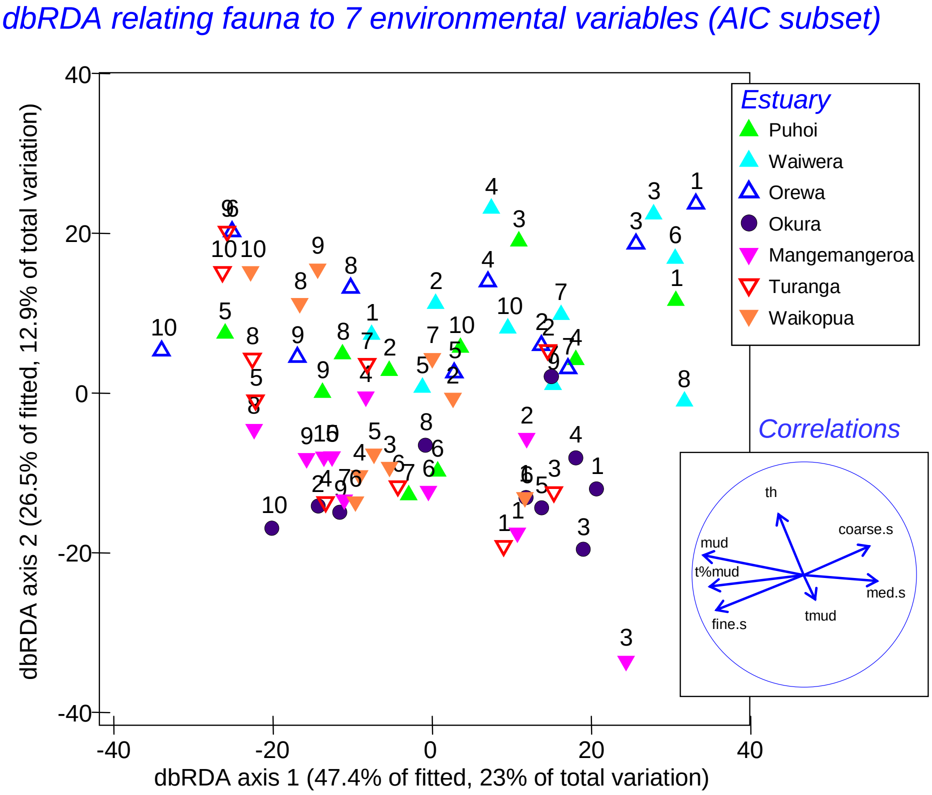
Results of DISTLM relating faunal data, based on Bray-Curtis dissimilarities of square-root-transformed abundances, with environmental variables, either individually (marginal tests) or sequentially in a forward selection procedure (sequential tests). Prop. = proportion of explained variation, Cumul. = cumulative proportion of explained variation. Variables are described in Table 2. Note that only 4 out of the 5 ambient sediment variables are needed for modeling, as the five variables together sum to 100%, which is why the variable "coarse.s" is not included in the forward selection procedure. Note also that "a%org" and "t%org" were square-root transformed and "tsed" was log-transformed, prior to analysis.

	Marginal tests			Sequential tests			
Variable	F	P	Prop.	F	P	Prop.	Cumul.
mud	17.52	0.0001	0.205	17.52	0.0001	0.205	0.205
fine.s	13.51	0.0001	0.166	7.90	0.0001	0.084	0.289
t%mud	15.62	0.0001	0.187	5.65	0.0001	0.056	0.345
th	6.11	0.0002	0.082	6.08	0.0001	0.056	0.401
shell	3.33	0.0036	0.047	4.24	0.0001	0.037	0.438
med.s	8.23	0.0001	0.108	3.01	0.0025	0.026	0.464
tmud	2.14	0.0452	0.030	2.61	0.0074	0.022	0.485
bh	0.64	0.7324	0.009	1.17	0.2872	0.010	0.495
sqr(a%org)	1.88	0.0745	0.027	1.08	0.3407	0.009	0.504
sqr(t%org)	4.11	0.0009	0.057	0.98	0.4345	0.008	0.512
log(tsed)	7.27	0.0001	0.097	1.19	0.2778	0.010	0.522
coarse.s	8.68	0.0001	0.113				

A more parsimonious model was obtained using the AIC criterion, which included just 7 of the 12 variables and yet explained 48.5% of the faunal variation. These variables were: the ambient grain size variables ("mud", "fine.s", "med.s" and "coarse.s"), two variables obtained from sediment traps ("tmud" and "t%mud") and tidal height ("th"). The first two axes of a distance-based redundancy analysis (dbRDA) on these 7 variables (Fig. 12) allowed most of the fitted variation (74%) to be visualised and, importantly, showed patterns that were remarkably similar to the unconstrained MDS plot of the site centroids (i.e., compare Fig. 12 with Fig. 11). This means that these environmental variables do a good job of capturing the most salient features, gradients and spatial relationships apparent in the biotic data.

The circle in the inset for Fig. 12 shows the Spearman rank correlations between each of the 7 variables and the two dbRDA axes: the longer the arrow, the stronger the relationship. For example, the percentage mud in ambient and trapped sediments and the percentage of fine sand increases from right to left across the ordination diagram, while the proportions of coarse and medium sand increase from left to right. Tidal height and the total amount of mud accumulating in traps are the variables primarily responsible for differences among sites along the second (vertical) dbRDA axis.

Figure 12.
Distance-based redundancy analysis relating fauna (153 taxa) to 7 environmental variables chosen as the best parsimonious subset using the AIC criterion. The inset shows a unit circle (radius = 1) with the raw Spearman rank correlations of individual environmental variables with each of the dbRDA axes as arrows.



4.7 Numerically dominant fauna at individual sites

Temporal variability was not large, relative to spatial variation among sites; communities were quite stable at individual sites through time. To characterise the community structure at each site, for future reference, the top 10 numerically dominant taxa, in terms of proportional abundances, have been summarised and provided (in table form) in Appendix 8. These tables identify the fauna by their abbreviations (given in Appendix 5).

These tables are provided here primarily as a baseline reference for future monitoring, but there are several interesting emergent patterns worth noting. For Puhoi, site P1 and site P10 are dominated by pipi (*Paphies australis*, abbreviated "Papaus") – on average, over half of the individuals recorded at site P1 (53%) and nearly a quarter (24.8%) at site P10 were pipi (Appendix 8). Cockles (*Austrovenus stutchburyi*, abbreviated "Ausstu") were numerically dominant at site P6 (21.1%) and they were also proportionately quite abundant at P4 (ranking second at 17.7%), which was dominated (45.9%) by barnacles ("Barnac"). At sites P2, P3 and P9, the numerically dominant taxon was the Corophidae family of amphipod crustaceans ("Cordae"), followed by capitellids and oligochaetes ("Capoli"), while sites P7 and P8 were dominated by these worms and also by spionid polychaete worms in the taxon "Polydorid complex" (abbreviated "Polyco")[7].

Waiwera as a whole is rather remarkable because the majority of the sites are dominated numerically by bivalves. Over half of the sites are dominated by cockles (sites W2, W5, W6, W7, W9 and W10), which account for between 18 and 32% of the abundances in those sites (Appendix 8). Two more sites, W3 and W8, are dominated by pipi, accounting for, on average, 47.5% and 32.4% of the abundances of organisms recorded at those sites, respectively. Sites W1 and W4 were dominated, instead, by capitellids and oligochaetes.

At Orewa, a degree of dominance by pipi ("Papaus") was evident at sites R1, R3 and R4. For many of the sites where pipi occur in large numbers, the evenness across the community is relatively low, and the top 5 species often account for over 90% of the abundances recorded at the site, on average. Average species richness is also often lower at such sites (Appendix 8). Corophid amphipods ("Cordae"), orbinid worms ("Orbins"), nereid worms ("Nerdae") and the spionid worm *Aquilaspio aucklandica* ("Aquauc") all featured prominently and variously at sites R6, R8, R9 and R10.

Okura is remarkable in that, much like Waiwera, most of the sites are dominated by cockles (O1, O3, O4, O5, O6 and O7, see Appendix 8), which accounted for between 17% and 25% of the samples, on average, at those sites. The remaining sites (O2, O8, O9 and O10), were dominated by the capitellid worm *Heteromastus filiformis* ("Hetfil") and the bivalve *Nucula hartvigiana* ("Nuchar") also featured prominently at many of the sites in Okura. Overall, there appeared to be greater evenness in the communities at Okura, as the first 5 taxa (with the exception of site O3) accounted for only between about 53 and 69% of the total abundances, on average. Although the bivalve *Macomona liliana* was never proportionately dominant, it did appear within the top ten rank proportional abundance at 7 out of the 10 sites in Puhoi and Waiwera and in 9 out of the 10 sites in Orewa and Okura (Appendix 8).

The numerically dominant taxa in Mangemangeroa included the bivalve *Nucula hartvigiana* (sites M1 and M2), the capitellid *Heteromastus filiformis* (sites M6, M8, M9 and M10) and barnacles (sites M3, M4 and M7). Also, the spionid worm *Aquilaspio aucklandica* ranked in the top 4 at every site and ranked first at site M5 (Appendix 8). Cockles were not as prominent here, although they did appear within the top 10 in rank proportional abundance at 9 out of the 10 sites. Pipi, however, were not in the list of the top ten taxa for any of the sites in Mangemangeroa.

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[7] The category of spionid polychaete worms called "Polydorid complex" herein includes the species *Boccardia syrtis*.

Community composition was quite variable among the sites at Turanga. Pipi were numerically dominant at site T2, ranked 6th at site T3, but did not appear in the list of the top ten for any other site. Low diversity and total abundance were recorded at sites T9 and T10, which were dominated by corophid amphipods, crabs (*Helice*, *Macrophthalmus* or *Hemigrapsus*, "Helmac"), capitellids and oligochaetes, and the worms *Aquilaspio aucklandica* and *Heteromastus filiformis*.

Waikopua was characterized by having quite high diversity at its outer sites, with between 30 and 37.2 taxa recorded per site, on average, for sites K1-K6. *Nucula hartvigiana* was the dominant bivalve at sites K2-K7. Sites K9 and K10 were similar in composition to the communities at sites T9 and T10 described above. These four sites had relatively low diversity: the average number of taxa for these sites only ranges from 10 to 14. In addition, sites K9 and K10 have consistently quite low total average abundances, with only 15 and 19 organisms, respectively.

4.8 Model of expected changes in community structure with increasing mud content of ambient sediment

As seen in §4.6, the percentage of mud (< 63 μm) in ambient sediment is the strongest single variable we measured at explaining spatial variation in community structure across the region. In addition, longer-term "press" impacts of fine sediment on community structure that we would expect to occur at a site should be detectable as a shift (from wherever it began along this gradient) towards communities that are found in muddier environments. Thus, a model of this gradient was constructed, where the position of the community from any site at any given time point can be placed in order to assess its position with respect to potential impacts in the long run.

Canonical analysis showed that the existing communities found in sites across the region (averaged through time) can indeed be used to successfully discriminate along the physical gradient of ambient percent mud, with a canonical correlation (using m = 20 principal coordinate axes[8]) of $\delta = 0.938$ (Fig. 13). Each of the estuaries has sites that are spread along the majority of this gradient. Next, it is important to characterise more specifically which species are changing along this gradient and how. What percentage mud is optimal for different species and how tolerant are the most abundant species to the percentage mud of ambient sediments?

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[8] The number of PCO axes was chosen by minimizing the leave-one-out residual sum of squares. See Anderson and Robinson (2003) for details.

Figure 13.

Canonical analysis of principal coordinates (CAP) to model the percentage of mud (< 63 µm) in ambient sediment using fauna (153 taxa) from each site, averaged through time (from time 20, August 2004, onwards). Each point is an average of 6 cores x 12 points = 72 cores.

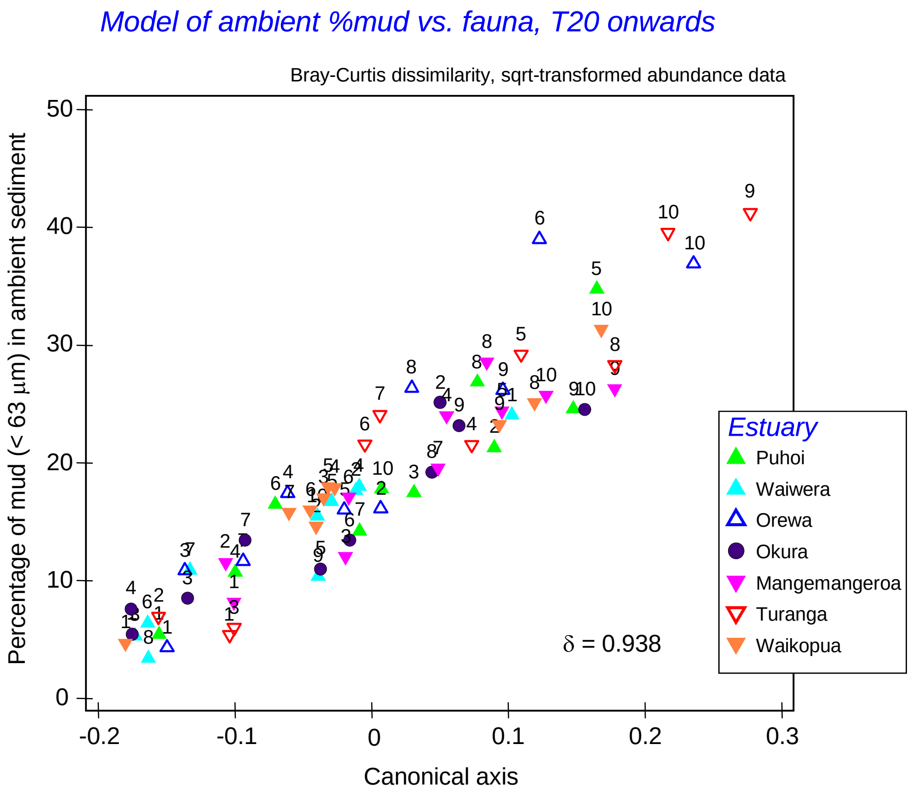
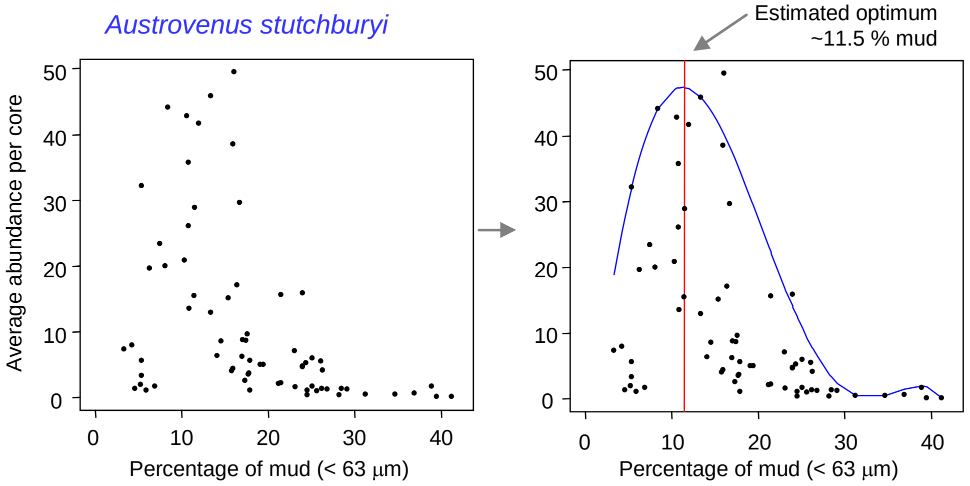


Figure 14.

Relationship between *Austrovenus stutchburyi* (cockles) and percentage mud in ambient sediment. Each point is an average of 6 cores x 12 time points =72 cores at each site. The polynomial regression spline model for the 95th percentile is shown in blue, with the maximum from the model (interpretable as an estimated optimum for the species) indicated by a red line.



A scatterplot of one of the most prominent species, the cockle, *Austrovenus stutchburyi*, reveals that the relationship (in this case) is certainly not linear, that it is probably unimodal, but also there is significant heterogeneity for different values of percent mud (Fig. 14, left). This type of relationship and scatter motivated the models used here: polynomial quantile regression splines on the 95th percentile (see §3.6.8). This type of model forms a sort of "envelope" around the abundance values. For *Austrovenus*, the model indicates a peak in abundance at 11.5% mud, which is taken here as an estimated optimum for this species (Fig. 14, right).

Similar models were fitted to the 20 most numerically abundant taxa across the whole dataset. These individual models, with taxa ordered from lowest to highest in terms of their estimated optimum percentage mud content, are shown in Figs. 15 and 16. Remarkably, only two out of the 18 individual taxa, namely Nereidae and *Paracalliope* spp., had scatterplot patterns that precluded any reasonable attempt at modeling a meaningful relationship between their abundance and ambient percentage mud (simple scatterplots for these are shown at the bottom of Fig. 16). For the rest, relationships were one of: (i) decreasing with increasing mud content (e.g., *Paphies australis*, *Colurostylis* spp., *Anthopleura aureoradiata*, Fig. 15), (ii) unimodal with fairly narrow tolerance (e.g., *Waitangi brevirostris*, *Aonides oxycephala*, *Nucula hartvigiana*, Exogoninae), (iii) unimodal with moderate to broad tolerance (e.g., *Austrovenus stutchburyi*, *Macomona liliana*, *Heteromastus filiformis*, Orbinids, Figs.15 and 16), or (iv) increasing with increasing mud content (Corophidae and crabs, Fig. 16).

Figure 15.

Relationship between individual taxa (as indicated) and percentage mud in ambient sediment. Each point is an average of 6 cores x 12 time points =72 cores at each site. The polynomial regression spline model for the 95th percentile is shown in blue, with the maximum from the model (interpretable as an estimated optimum for the taxon) indicated by a red line.

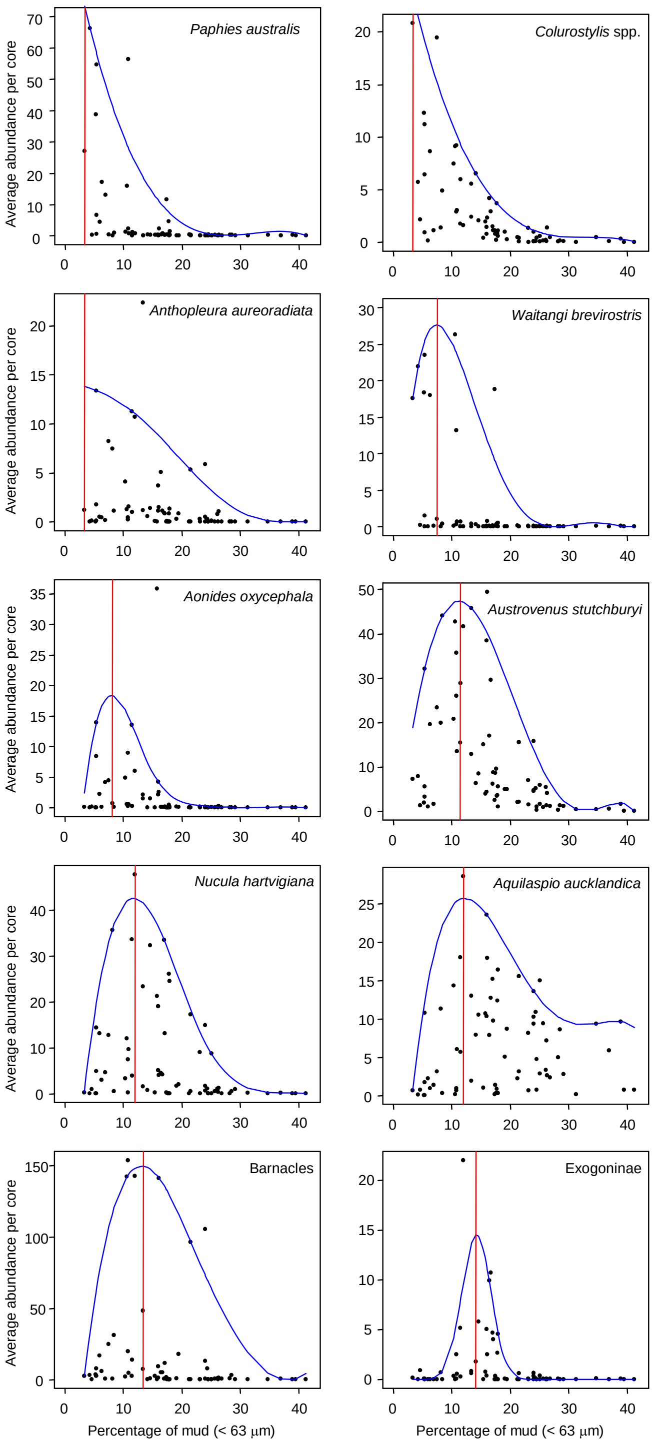


Figure 16.

Relationship between individual taxa (as indicated) and percentage mud in ambient sediment. Each point is an average of 6 cores x 12 time points =72 cores at each site. The polynomial regression spline model for the 95th percentile is shown in blue, with the maximum from the model (interpretable as an estimated optimum for the taxon) indicated by a red line. Two taxa (bottom panel) showed no clear relationship.

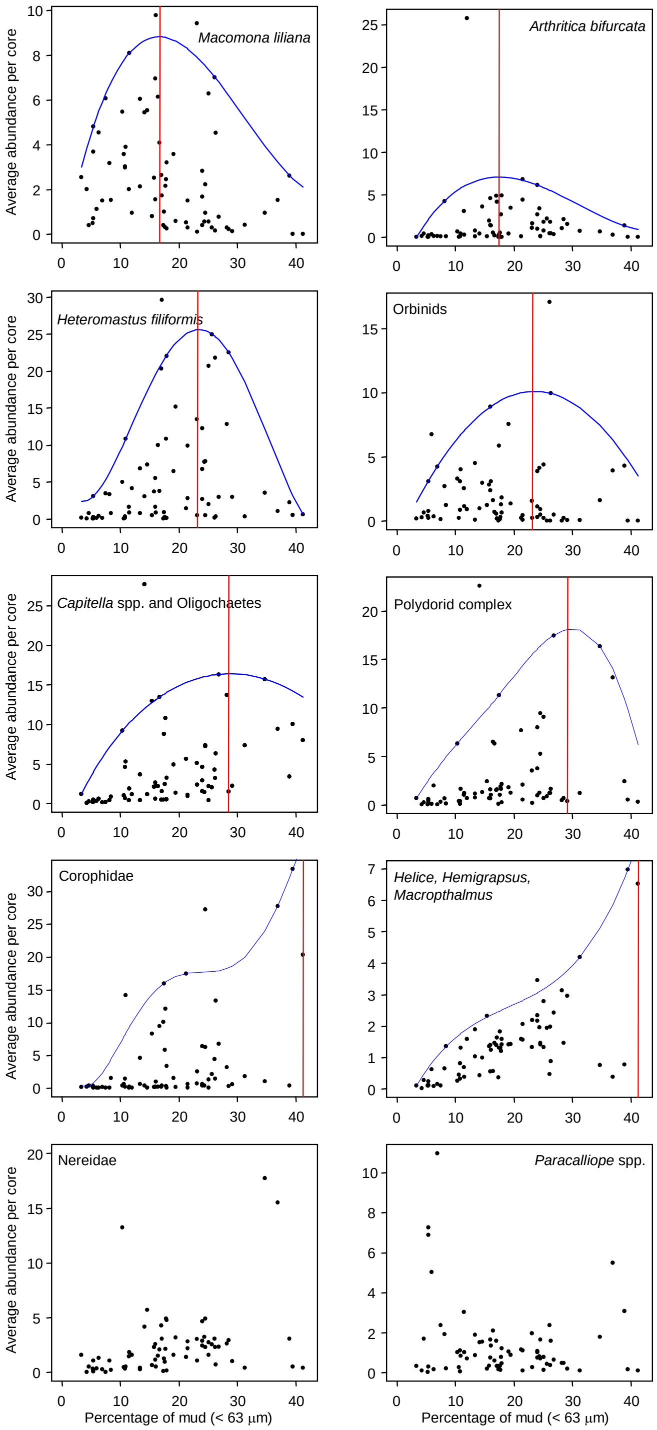


Table 5 shows a list of the top 20 most abundant taxa, ordered according to their estimated optimum percentage mud from these models, with pipi (*Paphies australis*), the cumacean *Colurostylis* spp. and anemones (*Anthopleura aureoradiata*) at the sandy end, and crabs, corophid amphipods and polydorid spionid worms at the muddy end of the spectrum.

Table 5.

Estimated optimum percentage mud for each of the top 20 most abundant taxa (i.e., having the largest total average abundance at the site level, summed across all sites). Two of these did not show any clear relationship with percentage mud ("NA").

Abbrev.	Name	Group	Rank abund.	Est. opt. %mud
Papaus	*Paphies australis*	Bivalvia	6	3.4
Colspp	*Colurostylis* spp.	Cumacea	10	3.4
Antaur	*Anthopleura aureoradiata*	Anthozoa	16	3.4
Waibre	*Waitangi brevirostris*	Amphipoda	12	7.5
Aonoxy	*Aonides oxycephala*	Spionidae	15	8.1
Ausstu	*Austrovenus stutchburyi*	Bivalvia	2	11.5
Nuchar	*Nucula hartvigiana*	Bivalvia	3	12.0
Aquauc	*Aquilaspio aucklandica*	Spionidae	4	12.0
Barnac	Barnacles	Cirripedia	1	13.4
Exodae	Exogoninae	Syllidae	20	14.2
Maclil	*Macomona liliana*	Bivalvia	11	16.7
Artbif	*Arthritica bifurcata*	Bivalvia	17	17.4
Hetfil	*Heteromastus filiformis*	Capitellidae	5	23.2
Orbins	Orbinids	Orbiniidae	14	23.2
Capoli	*Capitella* spp. and Oligochaetes	Polychaeta	7	28.5
Polyco	Polydorid complex	Spionidae	9	29.2
Cordae	Corophidae	Amphipoda	8	41.2
Helmac	*Helice*, *Hemigrapsus, Macrophthalmus*	Decapoda	18	41.2
Nerdae	Nereidae	Nereidae	13	NA
Parspp	*Paracalliope* spp.	Amphipoda	19	NA

Based on Table 5 and Figs. 15 and 16, we expect a gradual turnover of these taxa in terms of dominance at sites occurring along the canonical gradient of ambient percentage mud. To explore this idea, the top ten taxa in terms of proportional abundance were examined along a series of representative sites from sandy through to muddy habitats (Fig. 17), and compared with the list in Table 5 (which is also given schematically for reference at the bottom of Fig. 17).

At the sandy end of the spectrum (e.g., site W3), there is indeed a predominance of pipi (Papaus), the amphipods *Waitangi brevirostris* (Waibre) and cumaceans *Colurostylis* spp. (Colspp) (Fig. 17). Moving along the gradient (e.g., site P4), these species are still present and abundant, but are no longer the primary dominants – they are replaced by barnacles (Barnac) and cockles (Ausstu) and the appearance of other taxa within the top ten, such as *Nucula hartvigiana* (Nuchar). Further along (e.g., site R5), cockles are the dominant taxon, and other species also begin to appear in abundance, such as *Aquilaspio aucklandica* (Aquauc), orbinids (Orbins) and the bivalve *Macomona liliana* (Maclil).

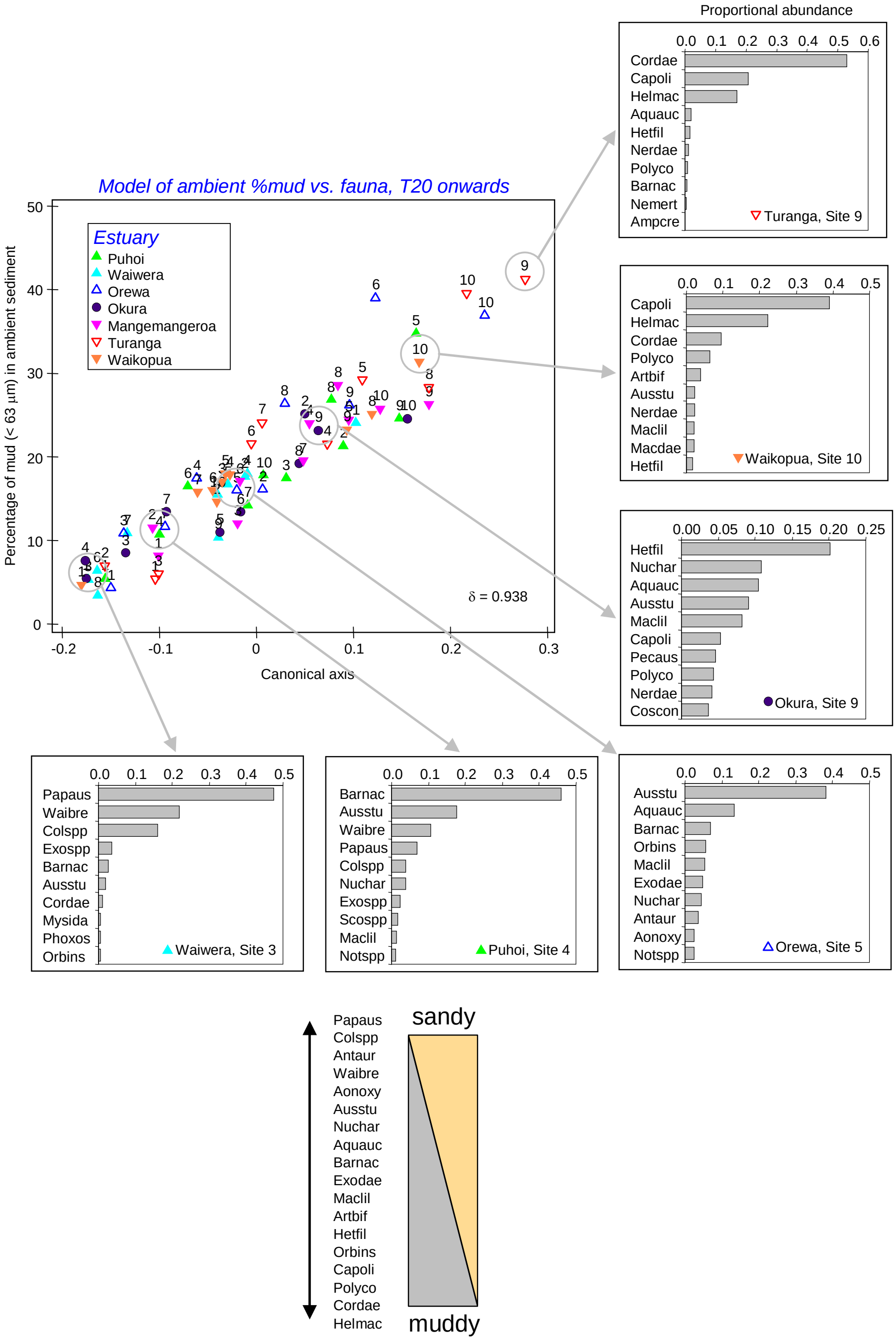
At sites having even more mud content (e.g., site O9), numerical dominance shifts towards other species: *Heteromastus filiformis* (Hetfil) and *Aquilaspio aucklandica*

(Aquauc), although cockles, *Nucula* and *Macomona* are also still present and fairly abundant. There is also greater evenness in these communities in the middle of the gradient – the dominance curve is much less steep (the most abundant species here occupies only about 20% of the total abundance, rather than 40 - 50% or more, which occurs in sites at the extreme ends of the spectrum). Moving towards still muddier sites (e.g., K10), the dominant taxa are capitellids and oligochaetes (Capoli) and crabs (Helmac), although some bivalves (Ausstu, Maclil) are still apparent within the top ten taxa. Finally, at the muddiest site in this study (i.e., site T9), corophid amphipods (Cordae) dominant, along with crabs (Helmac) and capitellids and oligochaetes (Capoli). No bivalves occur within the top ten most abundant taxa at this site.

Although occurrences of rarer taxa are not considered here, they also would naturally contribute to the turnover of species along this gradient, and are included in the full canonical model (Fig. 13). The individual univariate models of the abundant taxa (Figs. 15 and 16) do, however, provide a useful characterization of the nature of the transitions in community structure predicted with changes in the mud content of ambient sediments (Fig. 17).

Figure 17.

Species turnover along the canonical gradient in percentage mud of ambient sediment for a series of representative sites, as indicated. Individual barplots show proportional abundances for the top ten numerically dominant taxa at each of the sites. The list of species expected to turnover along the gradient from sandy to muddy habitats, as given in Table 5, is shown schematically at bottom, for reference. Abbreviations for taxa are as given in Appendix 5.

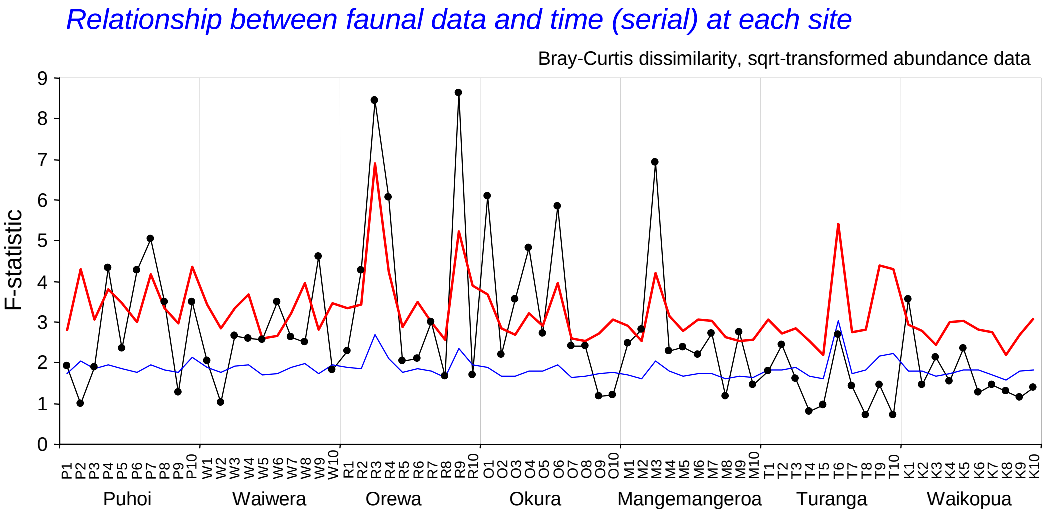


4.9 Sites having significant directional changes through time and which show evidence of sediment impacts

Eighteen (out of 70) sites showed statistically significant directional changes in community structure through time ($P < 0.008$), even after correcting for multiple tests (Fig. 18). These sites were: at Puhoi (P4, P6, P7, P8), Waiwera (W6, W9), Orewa (R2, R3, R4, R9), Okura (O1, O3, O4, O6), Mangemangeroa (M2, M3, M9) and Waikopua (K1).

Figure 18.

Tests of the relationship between communities and time (the ordered values of "Time serial", Appendix 3) for each of the 70 sites in the monitoring programme. The F-statistic is shown in black for each site, with larger values indicating a stronger relationship. The blue line indicates the value of F that would need to be exceeded to be statistically significant at the uncorrected 0.05 level. The red line indicates the value of F that would need to be exceeded to be statistically significant at the corrected family-wise 0.05 level across all 70 tests. Only the sites with values of F above the red line were investigated further.



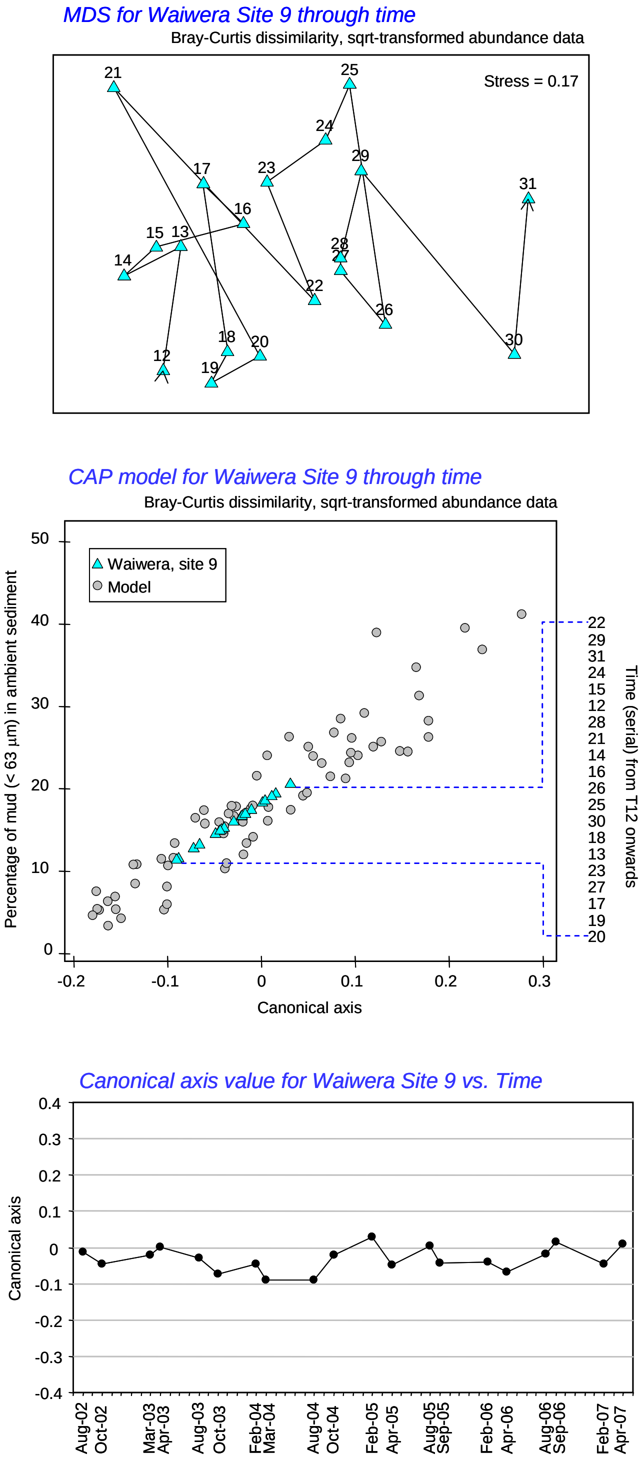
It has already been shown that the ***magnitude*** of temporal variation is quite small, both within individual sites and for estuaries as a whole (see §4.1, §4.2 and §4.3). However, it is still of interest to examine trajectories through time for individual sites, to place them along the canonical gradient in percentage mud (developed in §4.8), and determine whether the directional change detected is in a direction (i.e., traveling towards a community structure) that is characteristic of muddier environments.

An example of this procedure is shown for Waiwera site 9 in Fig. 19. First (top panel), we see the trajectory through time for the community in an MDS plot, from time 12 (August 2002) onwards. The gradual movement of the community from the left to the right of the diagram attests to the fact that there is indeed non-random directional change through time, as was detected and shown for this site in Fig. 18. Next (middle panel), we project each of these points (communities) into the canonical model (obtained from spatial data), which places it along the canonical axis. Increases in the value of the canonical axis through time would indicate that community structure is moving towards the types of communities found in muddier environments. Although we can place labels onto these points to identify their position in time (from time 12 to time 31), it is difficult to perceive from this whether there are any worrying trends. Potential trends in movement of the community along the canonical axis are better seen in a simple plot of these values through time (bottom panel, Fig. 19). In this example, for site W9, it is clear that there was no trend along this canonical axis (mud gradient) with time, and therefore no evidence that the directional change was related to increased mud in the ambient sediments.

This process was repeated for each of the 18 sites that showed some directionality, but none of them showed any worrying trends (Fig. 20). The communities in each of these sites occurred within different parts of the range of the canonical axis along the mud gradient (e.g., Okura site 1 is a relatively sandy site, while Mangemangeroa site 9 is a relatively muddy site, Fig. 20). However, for each of these sites, temporal variability was either stable in terms of its position along the axis, or, in some cases, showed weak evidence of a slight decrease (e.g., Waikopua, site 1), which is no real cause for concern. In general, despite there being some temporal trends in the data for some sites, the magnitude of changes were small in size and there was no evidence of any existing longer-term “press” impacts due to sedimentation.

Figure 19.

Example of the procedure used to investigate temporal trends for individual sites (in this case, Waiwera site 9), first using unconstrained MDS (top panel), then by placing the time points into the canonical model for percentage mud (middle panel) and finally by examining the value of the canonical axis for the site through time (bottom panel).



MDS for Waiwera Site 9 through time

Bray-Curtis dissimilarity, sqrt-transformed abundance data

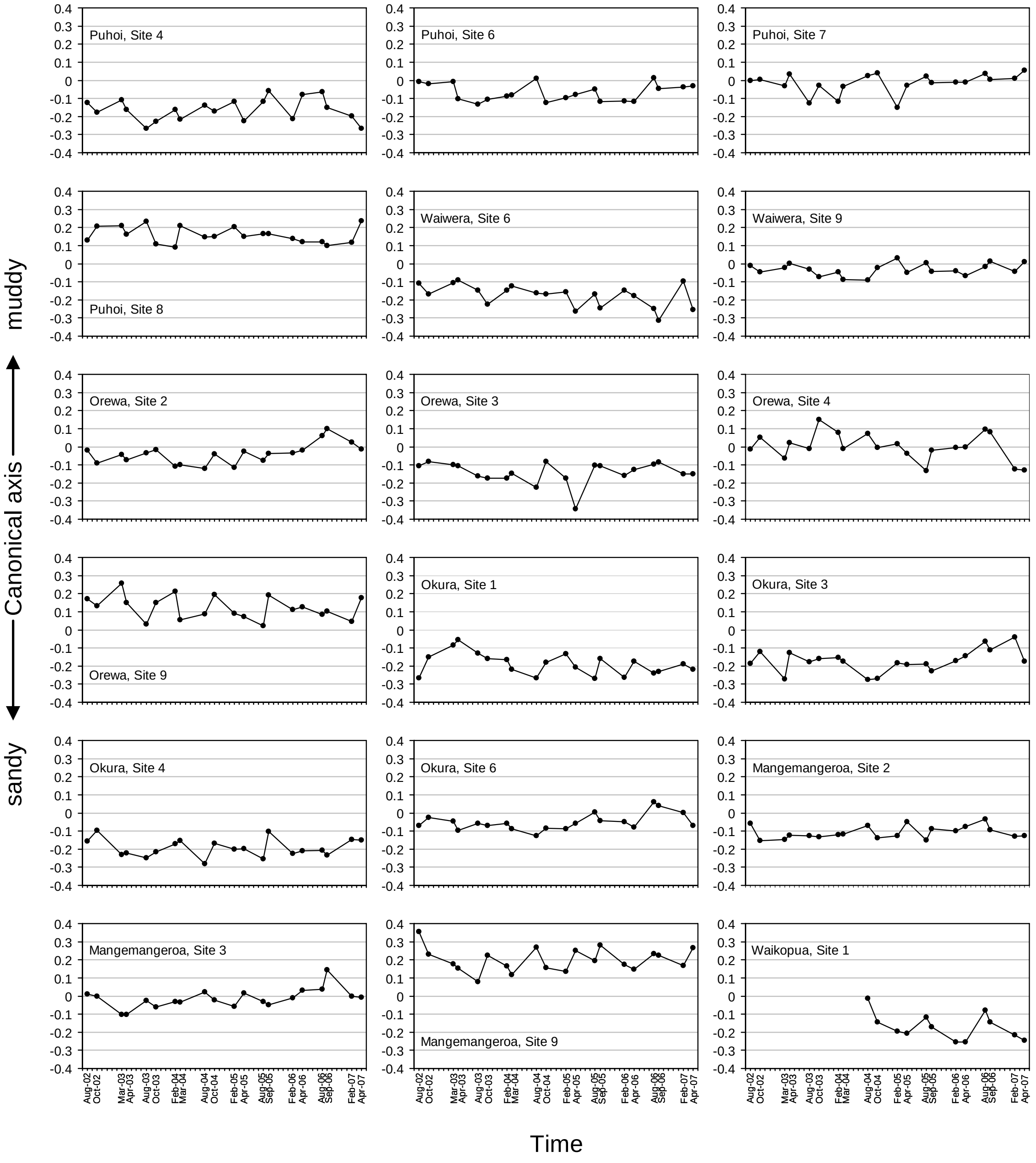
CAP model for Waiwera Site 9 through time

Bray-Curtis dissimilarity, sqrt-transformed abundance data

Canonical axis value for Waiwera Site 9 vs. Time

Figure 20.

Relationship between the community structure along the canonical axis for percentage mud versus time for each of the sites at which directional temporal change of some kind was detected (see Figs. 18 and 19).



4.10 Temporal and spatial patterns in abundances of bivalves

4.10.1 *Austrovenus stutchburyi* - cockles

Cockles have been found at every site (in every estuary) over the course of the monitoring period and the average cockle density in each estuary as a whole has been very stable through time (Fig. 21). The only evidence of a trend in cockle density was at Okura, where cockle abundance increased by between 0.7% and 1.5% per month between April 2000 and August 2005 ($P < 0.001$). Since August 2005, the total abundance of cockles at Okura has been decreasing; recent surveys have yielded densities similar to those found at the inception of monitoring (Fig. 21). The general stability of cockle abundances means that spatial comparisons among estuaries and among sites within estuaries (averaging through time) adequately characterise cockle abundances across the region (see Fig. 22).

The average densities of cockles at Turanga and Waikopua were significantly lower than the other estuaries ($P < 0.0001$, Fig. 22). Orewa, Waiwera and Okura consistently had the highest densities of cockles, averaging between 800 and 1000 individuals per m^2 (more than three times those at Turanga or Waikopua). Variation in the abundances of cockles among sites within each estuary was very high; large numbers of cockles were consistently found at certain sites, including: P4, W5, W7, R2, R5, O1, O3, O6 and M3 (Fig. 22).

The distribution of cockle sizes was relatively stable over time at all estuaries and at sites within estuaries. Juveniles were the dominant size class at Puhoi, Waikopua and Waiwera (making up, on average, 51%, 57% and 70% of the total population respectively). In Okura and Mangemangeroa, relatively larger cockles (i.e. individuals >15mm) were more dominant (50% and 54% of the population, respectively), while abundances were split fairly evenly among all three size classes at Orewa and Turanga (Fig. 21).

There is evidence of seasonality in juvenile cockle densities at: Puhoi ($P = 0.017$), Waiwera ($P < 0.001$) and Waikopua ($P = 0.003$). At Puhoi, we estimate that the average density is higher during winter/spring by between 14 and 138 juveniles per m^2. At Waiwera, we estimate that the average density is higher in winter/spring by between 172 and 339 juveniles per m^2. At Waikopua, we estimate that the average density is lower in winter/spring by between 233 and 241 juveniles per m^2. It is possible that sampling in winter/spring has included individuals from recruitment pulses occurring over the spring/summer period at Puhoi and Waiwera. It should be noted, however, that Waikopua has only had three complete seasons of sampling, so the estimated seasonal effect at this estuary (which, unlike the other estuaries, indicated fewer individuals in winter/spring, on average) is unlikely to be robust.

Figure 21.

Time series of cockle densities (per square metre) for different size classes at each estuary. Density of the smallest size class (individuals < 4 mm) is shown in red, the mid-size class (individuals 4-15 mm) is depicted by the distance between red and blue lines and the largest size class (individuals >15 mm) is depicted by the distance between blue and black lines. Size-class proportions averaged over all sampling occasions are also displayed for each estuary.

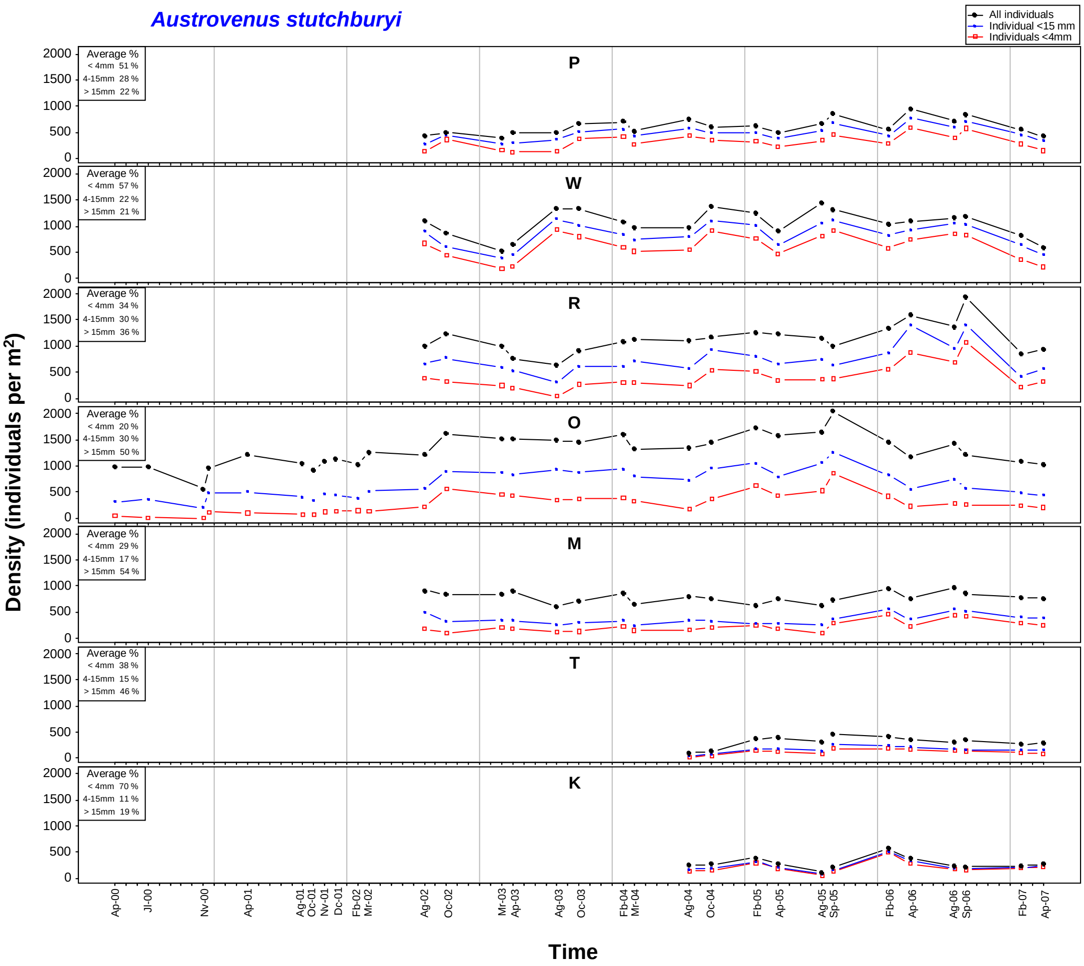
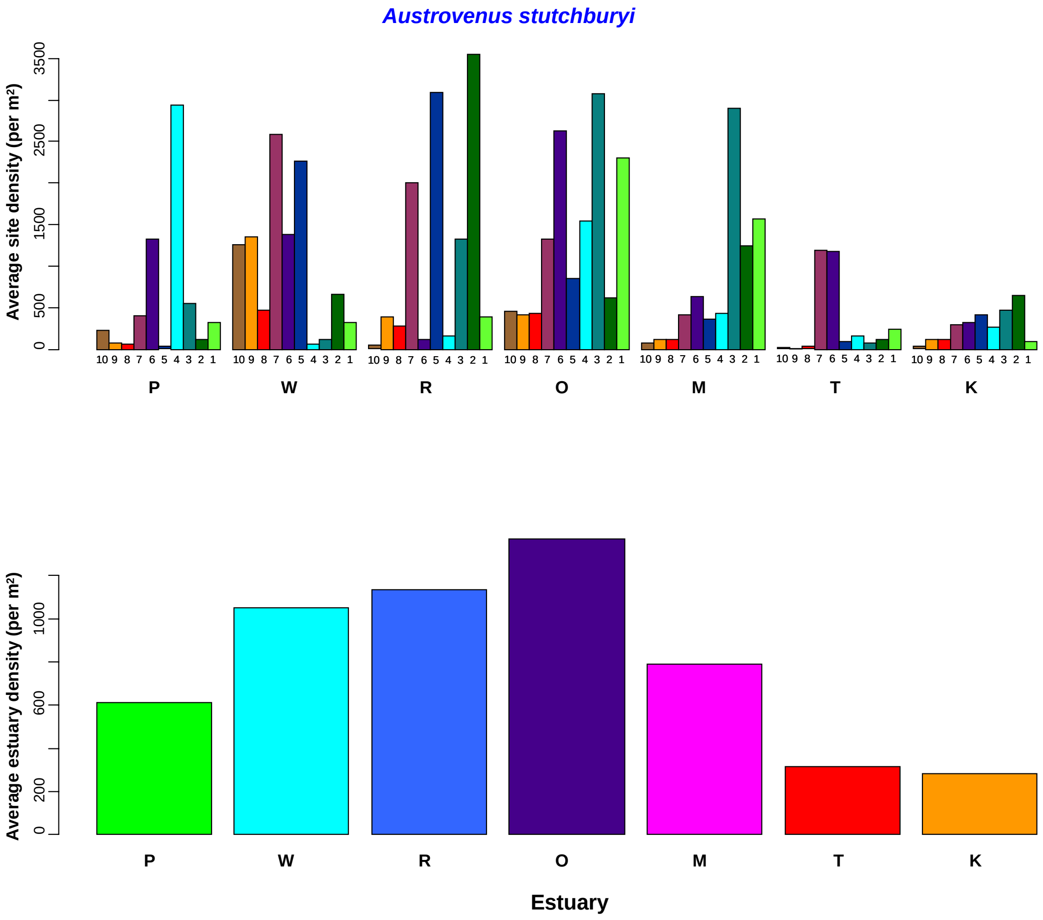


Figure 22.

Density of cockles (per square metre) for estuaries and sites within estuaries, averaged over all sampling occasions.



4.10.2 *Paphies australis* – pipi

With the exception of a recruitment pulse in October 2002 (and a second pulse in February 2004 at Orewa), populations of pipi at the level of whole estuaries have been extremely stable (Fig. 23). At these dates, a large influx of juveniles (i.e. individuals < 4 mm) led to substantial, but temporary, increases in abundance at the four northern estuaries. For example, densities of pipi at Orewa increased from 1040 per m^2 in August 2002 to 4701 per m^2 in October 2002. Similar (if less dramatic) changes in density were also seen at the other northern estuaries at this time. Densities of pipi at Orewa spiked again in a similar fashion in February 2004 (Fig. 23). However, discounting the high densities found during these recruitment pulses (which caused only brief changes), then there have been no clear trends nor any evidence of seasonal fluctuations in the overall estuary-level densities of pipi.

Pipi were found in greatest abundance at the three most northern estuaries (Puhoi, Orewa and Waiwera) ($P < 0.0001$), but their distribution was very patchy among individual sites (Fig. 24). Orewa contained the greatest sampled density of pipi, averaging approximately 1500 per m^2, but nearly all individuals were found at only three sites: R1, R3 and R4. Similarly, pipi at Puhoi and Waiwera were only found in high density at a few select sites (P1, P4, P10 and W3, W6 and W8, respectively) Of the southern estuaries, Waikopua and Mangemangeroa, in particular, had very low densities, averaging only ~75 individuals per m^2 (Fig. 24).

In most estuaries, the size-class distributions of pipi were relatively stable. Juvenile pipi dominated the size distribution in every estuary except Okura (Appendix 9) and Mangemangeroa (and the latter estuary had a very low numbers of pipi). Moreover, O1 was the only site showing prolonged periods where abundances of pipi were not dominated by juveniles (Appendix 9). On average, the proportion of juveniles in the northern estuaries varied between 81 and 93% of the population.

Figure 23.

Time series of pipi densities (per square metre) for different size classes at each estuary. Density of the smallest size class (individuals < 4 mm) is shown in red, the mid-size class (individuals 4-15 mm) is depicted by the distance between red and blue lines and the largest size class (individuals >15 mm) is depicted by the distance between blue and black lines. Size-class proportions averaged over all sampling occasions are also displayed for each estuary.

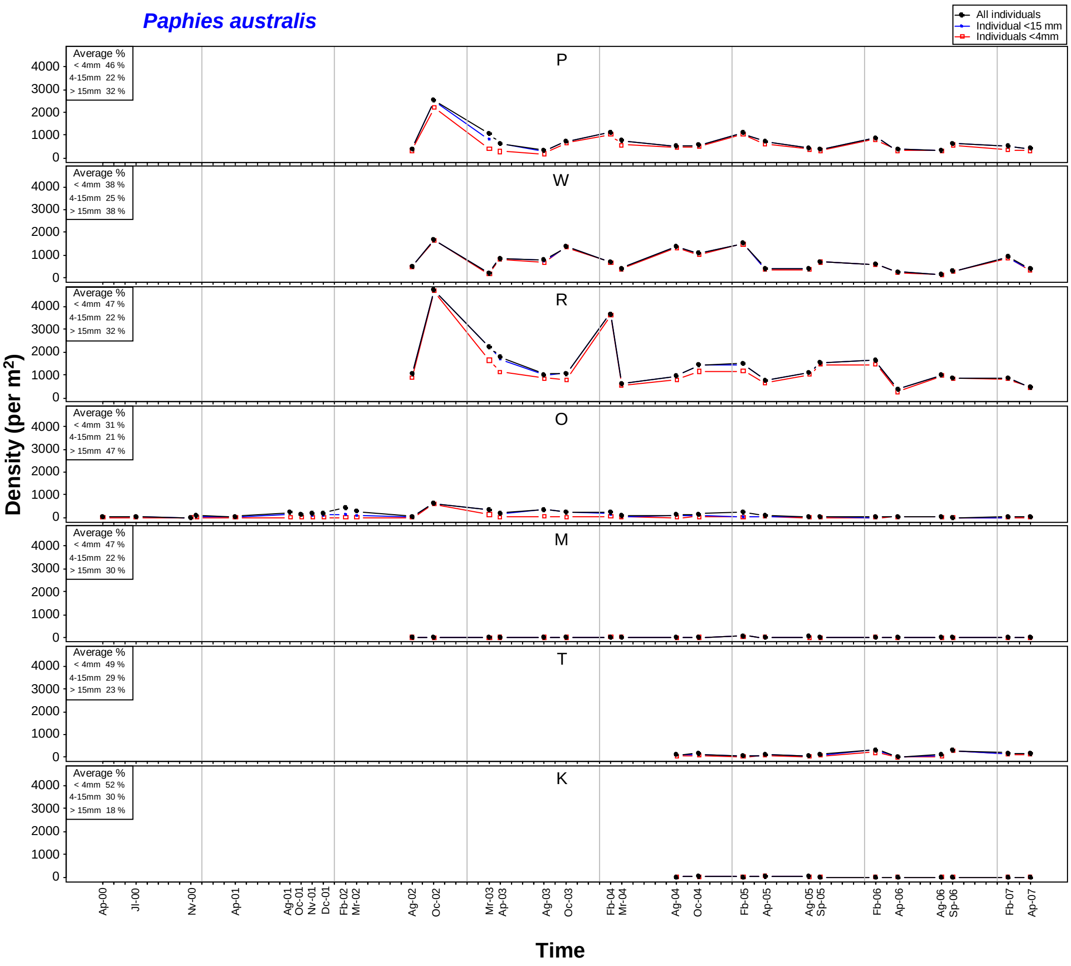
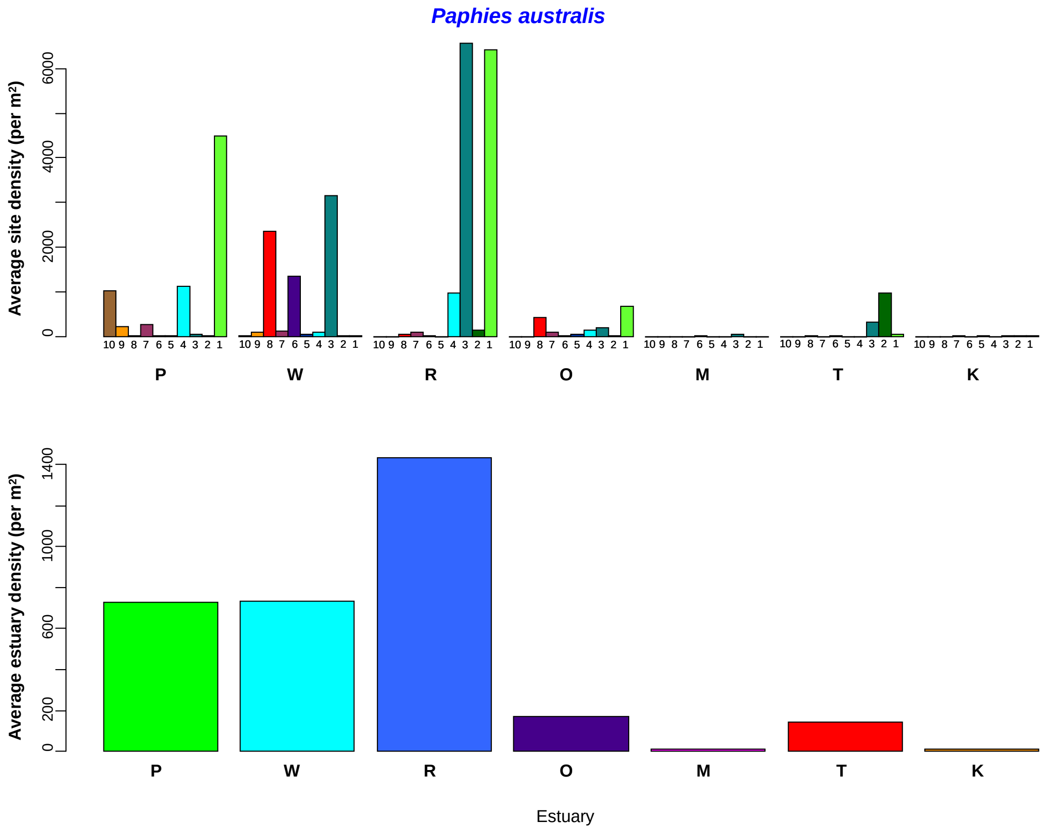


Figure 24.

Density of pipi (per square metre) for estuaries and sites within estuaries, averaged over all sampling occasions.



4.10.3 *Macomona liliana* – wedge shells

Macomona were less abundant than cockles or pipi, but occurred in moderate densities at all monitored estuaries (an average of > 75 individuals per m^2 was typically found even in Turanga, the estuary having the smallest total abundance). There were greater abundances of *Macomona* at sites near the mouth of the estuaries of Mangemangeroa, Turanga and Waikopua; they were more broadly distributed across the entire range of sites within Okura and Orewa, but were more abundant at sites in the middle of the northern estuaries (Fig. 25).

The highest average densities of *Macomona* were found at Orewa and Okura: approximately 270 and 225 individuals per m^2, respectively (Fig. 25). However, the increased average density at these two estuaries is due to a single large recruitment pulse that was sampled in April 2006 (Fig. 26). Until that time, all estuaries contained *Macomona* populations that were very stable and similar in densities. Although the recruitment pulse led to an increase in juvenile density at every estuary, particularly large increases were found at Orewa and Okura. At Okura, *Macomona* density increased to 866 per m^2 (the previous sampled density was 302 individuals per m^2). At Orewa, density increased from 168 to 1244 individuals per m^2 in April 2006. However, since that time *Macomona* density has decreased and the densities sampled in April 2007 at all estuaries were similar to the levels found prior to the juvenile influx (Fig. 26). There was no evidence of any overall trend (either increases or decreases) in *Macomona* in any of the estuaries.

Disregarding the effect of the pulse of juveniles in April 2006, the proportion of *Macomona* abundances within each size class was quite stable (Fig. 26). Juveniles were, on average, the most abundant size class in every estuary except Okura, where individuals >15mm were the numerically dominant size class (Appendix 9). There was evidence of seasonality in juvenile *Macomona* density at Turanga (P = 0.004). At Turanga, we estimate that the average density is higher in winter/spring by between 13 and 64 juveniles per m^2. However, with only three complete seasons sampled at Turanga the estimates of seasonality effects are unlikely to be robust.

Figure 25.

Density of *Macomona* (per square metre) for estuaries and sites within estuaries, averaged over all sampling occasions.

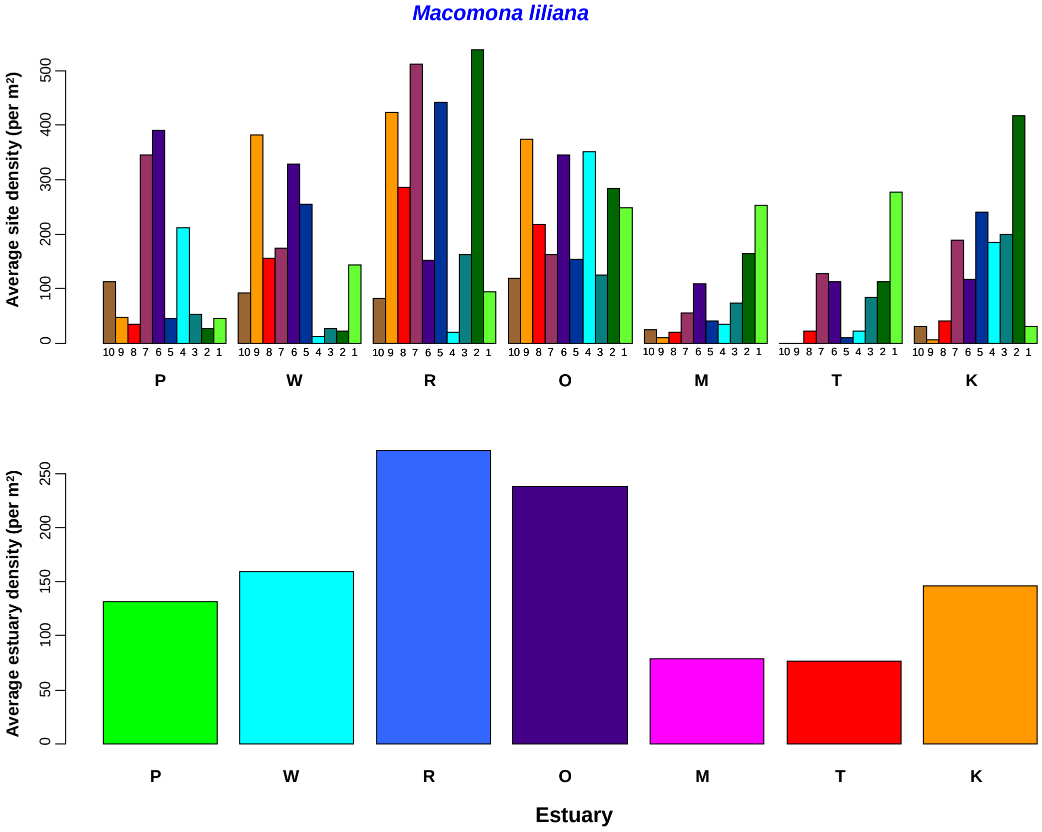
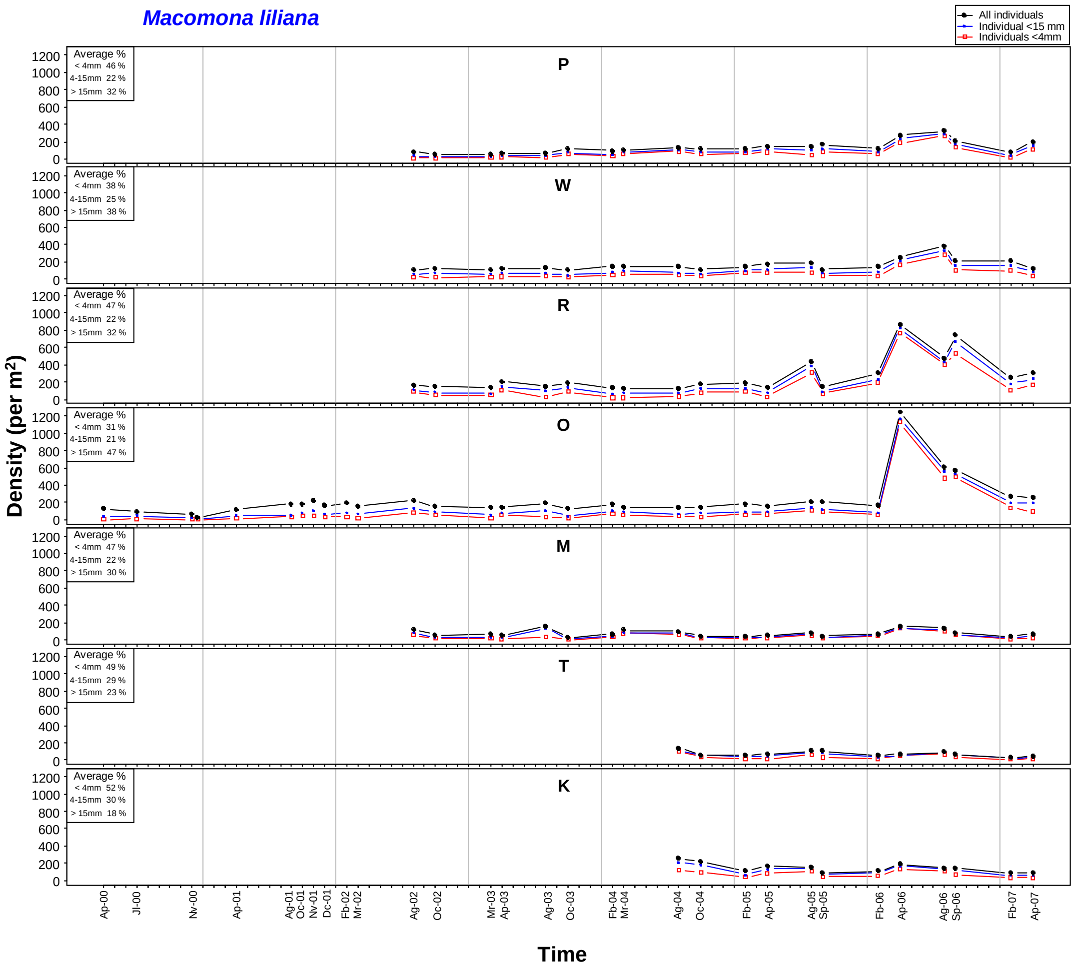


Figure 26.

Time series of *Macomona* densities (per square metre) for different size classes at each estuary. Density of the smallest size class (individuals < 4 mm) is shown in red, the mid-size class (individuals 4-15 mm) is depicted by the distance between red and blue lines and the largest size class (individuals >15 mm) is depicted by the distance between blue and black lines. Size-class proportions averaged over all sampling occasions are also displayed for each estuary.



4.11 Temporal and spatial patterns in diversity

Diversity has increased over time, on average, across all estuaries from August 2002-August 2005 (Fig. 27). This is likely a consequence of increases in taxonomic resolution as the monitoring programme has progressed. From about August 2004 onwards, however, there has been clear stability in the diversity of taxa at the level of whole estuaries (Fig. 27). Seasonal variation in diversity was apparent at all estuaries, with peaks in diversity often recorded around August, but the timing of peaks varied from year to year and from one estuary to the next, so consistent seasonal effect sizes were not really feasible to estimate from the limited within-year frequency of sampling of this monitoring programme.

There was significantly greater estuarine-level diversity at Okura, Mangemangeroa and Waikopua, which generally recorded ~10 more taxa, on average, than the other estuaries (Fig. 27, Table 6). These three estuaries also showed greater average diversity at individual sites (Table 6, Fig. 28). Whereas Okura and Mangemangeroa had large average diversity recorded at virtually all sites (average site-level diversity ranged from 21-35 species), Waikopua had greater variation in diversity among sites: some sites were quite depauperate (an average of 11.6 taxa from K10) and other sites were very rich (an average of 37.1 taxa from site K2) (see Table 6, Fig. 28 and Appendix 8). Individual sites from all estuaries were also markedly consistent in the number of taxa recorded through time (Fig. 28).

Table 6.

Average diversity (number of taxa) for whole estuaries and the average and range in diversity for individual sites within each estuary for time 20 (August 2004) onwards (more details at the site level are given in Appendix 8). Letters (a, b) next to the estuary-level averages indicate groups that do not differ significantly in their overall diversity from pair-wise comparisons ($P > 0.05$).

	Estuary		Site	
	Average		Average	Range
Puhoi	52.67	b	20.9	(15.9 - 28.8)
Waiwera	49.00	b	20.5	(12.8 - 28.9)
Orewa	49.92	b	21.7	(13.3 - 28.8)
Okura	58.25	a	27.1	(20.8 - 33.0)
Mangemangeroa	58.67	a	27.2	(21.9 - 35.1)
Turanga	51.67	b	21.4	(10.3 - 33.4)
Waikopua	60.00	a	27.0	(11.6 - 37.1)

Figure 27.

Total diversity (number of taxa) recorded within each estuary through time.

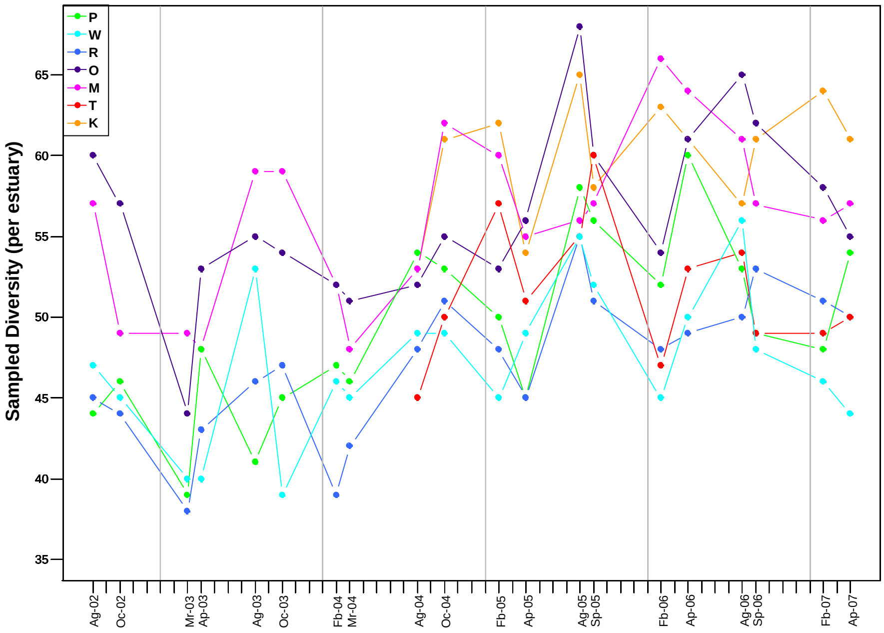
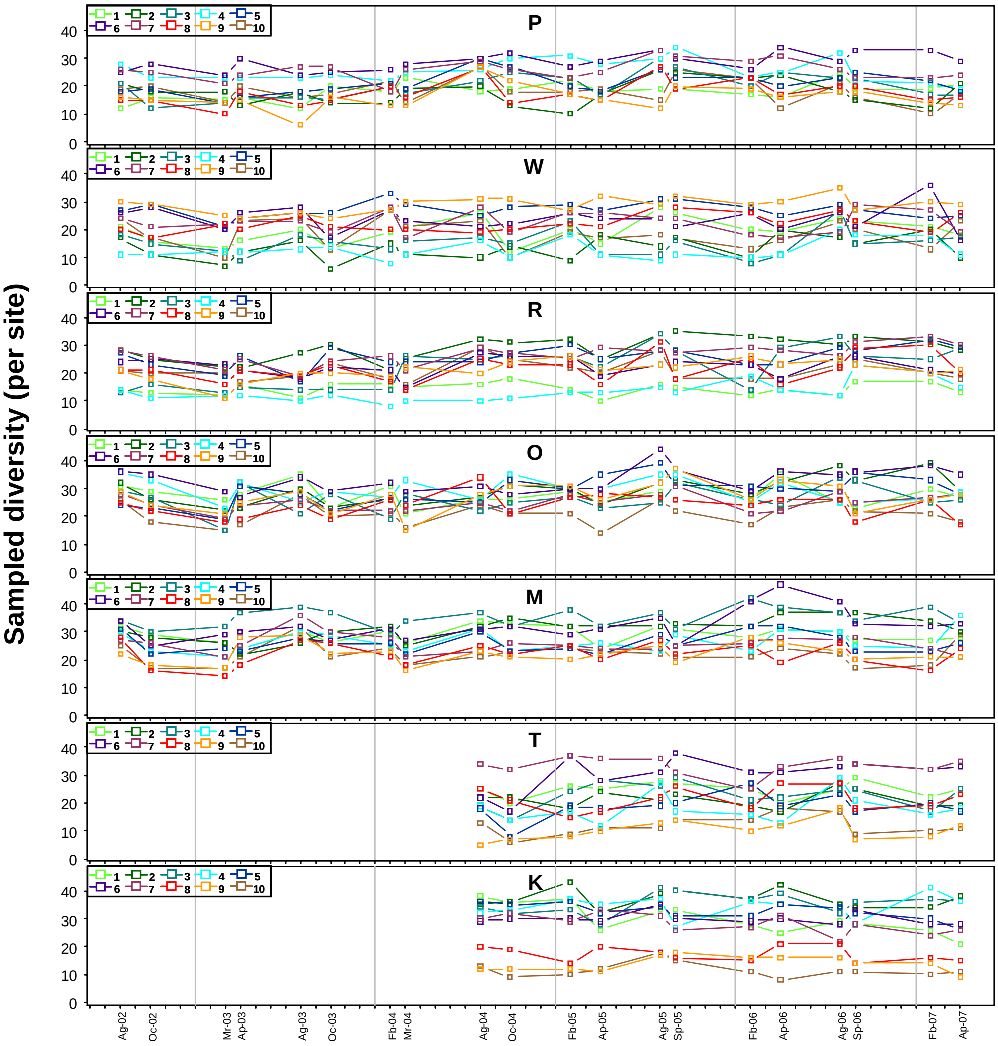


Figure 28.

Total diversity (number of taxa) recorded within each site within each estuary through time.



5 Discussion

In direct response to the central question of this study, the answer is unequivocally ***yes***. These data do indeed provide the start of an excellent initial baseline against which future impacts can be detected. However, ongoing monitoring is absolutely essential for this programme in order to establish a sufficient baseline to incorporate explicit measurements of multi-year cycles, such as El Niño / La Nina weather patterns and inter-generational population dynamics. Longer time series of data are critical in order to distinguish human impacts from natural cycles occurring across these longer time scales. The relative consistency across shorter time scales (less than 5 years) observed in the baseline data obtained thus far is, however, an excellent start to developing longer-term models. These patterns of temporal consistency are demonstrated by:

- ☐ The magnitude of temporal variation was small and limited compared to spatial variation among sites and among estuaries.
- ☐ Communities at individual sites and individual estuaries have remained stable over the past 7 years of monitoring and are easily characterised in terms of dominant component fauna. No sites currently show any evidence of impacts expected from increased muddiness.
- ☐ Overall diversity (number of taxa) and the densities and size-class proportions of individual bivalve species (*Austrovenus*, *Macomona* and *Paphies*) have all remained stable over the course of the monitoring programme, at the scale of individual sites and whole estuaries.
- ☐ Measured environmental variables, especially ambient sediment texture and data from sediment traps, explain the most important gradients in biotic variation well, reinforcing the potential for causative links to be inferred under future impact scenarios.

More specifically, the questions numbered 1-11 in the introduction are addressed in greater detail in § 5.1 - 5.11, respectively, below.

Once again, to re-iterate, although current data do provide an excellent initial baseline, continued monitoring is essential in order to identify and characterise longer-term natural cycles for these estuarine systems. Multi-year (greater-than-annual) cycles have been found for several benthic species in Manukau harbour, which has been monitored at some sites for the past 20 years (Funnell et al. 2003; Hewitt and Thrush 2007). Weather patterns in the Auckland Region can be affected by multi-year factors such as the El Niño Southern Oscillation (ENSO) and temperature trends from global warming. Gradual 'press' types of impact cannot be distinguished from multi-year cycles of natural change without continuous data over longer periods of time. Ongoing monitoring is therefore crucial to build up a regional understanding of potential cumulative impacts and long-term natural temporal patterns.

5.1 Temporal stability in the communities at individual sites through time

Individual sites contained identifiable community structures that were quite stable over time, as evidenced by the distinct clusters seen in MDS plots (Figs. 2-8). Although temporal variation differed significantly among sites, community structure at the majority of sites was, on average, 60-70% similar through time (measured using Bray-Curtis). Temporal stability in benthic estuarine communities at the scale of individual sites has also been reported in the Auckland region for the Manukau and Waitemata harbours (Turner et al. 1995; Nicholls et al. 2002; Funnell et al. 2003), although direct comparisons are difficult because of differences in the physical extent of the sites sampled and the multivariate methods used to measure temporal variation.

The fact that the spatial positions of different sites correspond to clear shifts in community structure bodes very well for the monitoring programme's ability to detect future significant changes in communities. It is precisely these current spatial differences in communities among sites within the estuaries that would be expected to change under future sedimentation impact scenarios. For example, Cummings et al. (2003) found that spatial differences among sites in the Mahurangi decreased significantly (i.e., communities at sandier sites became more like those at muddier sites) with impacts that were linked to fine sediment inputs.

5.2 Temporal stability in the communities of whole estuaries through time

Estuaries as a whole also demonstrated rather remarkable temporal stability in community structure (Fig. 9). Communities at the whole-estuary level remained ~80% similar through time, and individual estuaries were clearly identifiable from others, in terms of overall community structure and the numerically dominant taxa (Appendix 8). This contrasts with the large temporal variation in communities, generally caused by strong seasonal differences in rainfall, temperature, productivity and recruitment, that has been observed in other parts of the world (e.g., Flint 1985; Holland 1985).

5.3 Temporal variation is small compared to spatial variation

Partitioning according to the full sampling design of the monitoring programme demonstrated that variation in community structure among sites within estuaries was the largest, followed by variation among estuaries and, finally, variation among time points (Table 3, Fig. 10). It follows that any future significant changes in community structure would correspond directly to substantial increases in measured temporal variation, similar to the levels observed among sites, and would therefore be easily detected by this monitoring programme.

5.4 Relative importance of seasonal and rainfall-driven effects

Although seasonal and rainfall-driven effects were detected as being statistically significant, they were small in size (Table 3, Fig. 10). Seasonal effects, however, comprised a substantial proportion of the measured temporal variation, and certain species did demonstrate seasonal patterns. For example, juvenile cockles were significantly more abundant in winter/spring than in summer/autumn and overall diversity (number of taxa) per estuary also tended to be higher at August samplings. Seasonal variation was certainly substantial enough to warrant continued semi-annual monitoring: that is, sampling at least once within each of the two existing seasonal time-frames should still occur every year. Although this frequency does not allow seasonal variation (such as peaks in abundances) for individual species to be characterised within any particular year, it does allow the likely range in variation caused by seasonal effects to be measured annually on an ongoing basis.

Although the evidence for a consistent rainfall-driven effect was statistically significant, its magnitude was very small (only about one eleventh of the already small temporal variation). Thus, the event-driven sampling design of this monitoring programme has failed to find any biologically important effects of pulses of heavy rainfall, at least at the levels of rainfall that historically has triggered sampling (15 mm in a 24-hour period). Whether rainfall is treated in an ANOVA-style design (as here) or as a quantitative gradient (as in Ford et al. 2007), the ecological effects of rainfall measured so far have been genuinely negligible, suggesting that the communities in these estuaries are currently resilient to environmental changes associated with the levels of rainfall encountered regularly each year. These results contrast with the study by Flint (1985) and others (cited therein) which indicated that rainfall pulses increase freshwater and detrital inputs into estuaries and are strongly linked with increased overall primary and secondary productivity. These results also contrast with the expectation that heavy rainfall would cause increased inputs of terrigenous sediment, with negative impacts on benthic infauna.

The most likely reason for the lack of significant ecological impacts of rainfall, to date, is that the rainfall threshold used for triggering sampling has been too low. Catastrophic effects from sediment run-off are expected to occur from severe storms (e.g., Norkko et al. 2002; Hewitt et al. 2003). After consultation with the ARC, it was determined that, given these results to date, the design of the monitoring programme should be altered to target heavier rainfall events, regardless of when they might occur during the year. Furthermore, it is vitally important that ecological impacts, if detected, be linked to specific environmental changes in, for example, ambient sediment texture, fine sediments settling in traps and/or increased turbidity. Thus, sampling after rainfall will be focused in those estuaries (namely, Okura, Orewa and Mangemangeroa) where a greater number of relevant environmental parameters can be measured for monitoring (including quick-flow volume, peak flow and suspended sediment yield). This will provide for both the calibration of trap data and the establishment of stronger physical causative links and inferences in the event of future impacts.

5.5 Similarities among sites across the region

There was a strong general gradient in community structure apparent among sites across the region (Fig. 11). All of the estuaries had sites spanning the majority of the range along this gradient, which was primarily associated with the texture of ambient sediments (see §5.6). In the southern estuaries (Turanga and Waikopua), this gradient was strongly correlated with distance from the mouth of the estuary, but this was not necessarily the case for the northern estuaries (Puhoi, Waiwera and Orewa). Interestingly, all sites showed affinities in community structure with sites from other estuaries, which will make any estuary-wide or site-specific impacts through time readily apparent. Multiple sites will be available to act as "controls" or "references" against which impacted sites can be compared.

5.6 Environmental variables are highly useful for explaining biotic variation

The gradient in community structure among the sites was largely explained by the percentage of mud (< 63 µm) in ambient sediments (Table 4, Fig. 12), which alone explained 20.5% of the faunal variation. The twelve measured environmental variables included in this analysis explained the majority (52.2%) of the biotic variation, which is substantial and bodes well for establishing causal links in the future. In addition to the ambient sediment texture, the amount and percentage of mud in traps was also important, as was tidal height, in explaining biotic variation. As the texture of sediment in traps is likely to be correlated with suspended sediment inputs, its clear relationship with existing spatial gradients in community structure indicates that it will be a useful site-specific tool for ongoing monitoring, particularly as ambient sediments are not sampled as frequently as trapped sediments. For example, resuspension from the bed over time between biotic sampling events could mask changes in ambient sediments that have occurred from unusual amounts of fine sediment inputs, but such inputs would be unlikely to have been missed by the more frequently sampled traps at individual sites.

The percentage of biotic variation explained by the environmental variables is somewhat higher than that obtained in similar analyses contained in previous reports for these estuaries (e.g., 40 – 48%, Ford et al. 2003a; 2004; Ford and Anderson 2005). This is in spite of the fact that previous models used a greater number of predictor variables; they used 23-26 variables, compared to only 12 variables used in the present study (see Table 2). Furthermore, previous models fit a simple forward selection of all available variables (increasing the R^2 value), but did not attempt to find more parsimonious models, as was done in the present report using a multivariate analogue of the AIC criterion. This was not done before because this tool (now in PERMANOVA+) was simply not available. Greater explained variation in the current study (52.2%) is likely to be due to the fact that care was taken in the choice of the variables, and data were averaged over longer periods of time, which would have integrated out small-scale temporal noise. In all of the models, however, the texture of ambient sediments rates highly in terms of explaining biotic variation.

In a previous study that examined data from Okura estuary alone (Anderson et al. 2004), the percentage of biotic variation explained by environmental variables was quite high (70.75%). The reason for this being substantially larger than in the present study is likely due to the inclusion of a factor which arose from hydrodynamic modeling of the estuary (Cooper et al. 1999; Green and Oldman 1999). This factor contrasted areas of high versus medium or low depositional areas (HvML) within the estuary, and alone it explained ~32% of the biotic variation. Such refined hydrodynamic physical models are, unfortunately, not available for all of the estuaries in the region.

A fairly large fraction of biotic variation across the region remains unexplained (~48%). What remains in this unexplained fraction may include variation due to ecological factors that are outside the scope of the current monitoring programme, such as foraging by birds, predation by fish, harvesting or trampling by humans, bioturbation, recruitment pulses, migration and movement. Also unaccounted for explicitly in models to date are several other large-scale physical and chemical parameters, such as catchment-specific inputs, the degree of tidal flushing or wave-exposure. There is a great deal of scope for further research to develop and refine regional models of benthic communities.

5.7 Characteristics of individual sites

Due to the stability through time in community structure at individual sites, it was possible to characterise each site in terms of the numerically dominant fauna and expected diversity (Appendix 8). Certain sites (i.e., P1, P10, W3, W8, R1, R3, R4, T2) were dominated by pipi (*Paphies australis*). These were generally located in sandier environments and tended to have lower evenness than other communities. At Okura and Waiwera, the majority of the sites were dominated by cockles (*Austrovenus stutchburyi*). In Mangemangeroa, the bivalve *Nucula hartvigiana*, the capitellid *Heteromastus filiformis* and the spionid *Aquilaspio aucklandica* tended to dominate, whereas the muddier sites in Turanga and Waikopua were dominated by capitellids and oligochaetes and crabs. General stability in the dominance structures for benthic infauna has also been noted for other sites across the region (Waitemata: Nicholls et al. 2002; Manukau: Funnell et al. 2003). The characteristics of sites articulated here will serve as a clear baseline against which any future changes can be measured.

5.8 Predicting changes in communities with increasing mud content of ambient sediment

Following the excellent ideas presented in Thrush et al. (2003b), we developed a multivariate model of changes in community structure with increasing mud content of ambient sediments. We consider the model presented here to be quite robust for several reasons.

First, rather than identifying only a few species for the model, we utilised all of the available taxa to develop a canonical gradient. Multivariate community responses are more sensitive to environmental changes than single indicator species or diversity indices, and rare species may play an important role in distinguishing habitats (Ellingsen et al. 2007).

Second, the model was built at the site level from points obtained as averages over a fairly long period of time (6 cores x 12 time points from August 2004 onwards = 72 cores) for both the community data and ambient percent mud. Means of individual variables are well-known to have good statistical properties (approximate normality) and lower variance (inversely proportional to sample size), according to the central limit theorem.

Third, these data spanned a reasonably large geographical area and range of habitats. Although the extent of the sampling from this monitoring programme is not nearly as broad as the area spanned by the Thrush et al. (2003b) study – we have covered an area which is highly pertinent for making predictions within the Auckland region. In addition, although the range in percent mud found in Thrush et al. (2003b) is larger (from near zero to over 80% mud) than the range used in our models (which was 3.4% - 41.2%), this is probably due to the fact that we were using averages from many core samples. Mud content from individual cores in our study over this period ranged from 0.19 to 86.7%.

Finally, we characterised changes along this gradient using non-linear quantile regression splines on the 95th percentile for the 20 most numerically abundant taxa. Eighteen of these twenty taxa showed reasonably clear relationships along the mud gradient. We expect models of the 95th percentile to be less influenced by outliers than models of maxima. We also would expect the non-linear quantile regression splines to provide more flexibility with respect to the shape of the inherently non-linear responses of species to the gradient. These models are by no means presented as "the best possible models", but are, instead, considered to provide a flexible approach for characterising community changes for abundant taxa along the mud gradient.

Despite these differences, our results were highly comparable with those presented by Thrush et al. (2003b). Ten of the 13 species modeled by Thrush et al. (2003b) were also identified here as abundant enough for individual models. In addition, the relative ordering of taxa along the mud gradient, in terms of maxima, was very similar in these two studies (compare Fig. 4 in Thrush et al. 2003b with Figs. 15 and 16 herein). Our study supports and extends the work of Thrush et al. (2003b), which indicates that the response of benthic macrofauna to percentage mud is very strong and highly relevant for assessing longer term "press" responses of communities to changing environmental conditions of anticipated increased muddiness in estuaries.

5.9 Sites demonstrating directional change showed no current evidence for impacts

The canonical model is highly useful for ongoing monitoring, because it allows communities at individual sites to be placed along this gradient and tracked through time to assess whether impacts predicted from increased mud content are occurring. We suspect that the fauna may well respond to changes in environmental parameters (such as increased frequency of storm events or increased turbidity) before such changes necessarily alter ambient sediment beds.

Eighteen sites were found to exhibit directional changes through time. However, none of these were of sufficient magnitude nor in a direction that would indicate impacts from sedimentation at the present time. Thus, there is no current evidence of any negative impacts from sedimentation for any of the sites.

5.10 Temporal and spatial patterns in abundances of bivalves

Cockles were widespread across the monitoring programme and were remarkably stable through time, at the estuary level and at the level of individual sites. Densities of cockles were lowest at Turanga and Waikopua, while Orewa, Waiwera and Okura consistently had the highest densities. Okura has seen an increase (April 2000-August 2005), followed by a decrease in cockle abundances (since August 2005) which should be monitored closely into the future to ensure that no further decreases are sustained. It is possible that this is part of a long-term cycle in their numbers regionally. For example, cycles of 5-7 years have been described for several species in the Manukau estuary (Funnell et al. 2003; Hewitt and Thrush 2007). Clearly a longer time series will be needed to determine this. Interestingly, juveniles made up a substantial proportion of the cockle populations in certain estuaries (Puhoi, Waikopua and Waiwera), while larger individuals were more dominant in others (Okura and Mangemangeroa). The variation in cockle densities at the scale of sites is consistent with the large-scale spatial structures found for this species by Legendre et al. (1997). Correlations between adults and juveniles have been found to vary with spatial scale (Hewitt et al.1997). This is supported by our study, which found variation in the proportions of different size classes across sites.

Pipi tended to be very patchy in space and time and were found in very high abundances at a few select sites, primarily in the northern estuaries (i.e., P1, P4, P10, W3, W6, W8, R1, R3 and R4). Juveniles accounted for a very high proportion of the population in all estuaries except Okura, which showed a predominance of adults at site O1. Spikes in pipi abundance, due to recruitment events, were observed in October 2002 and February 2004, but were otherwise stable through time.

Macomona occurred in moderate densities at all monitored estuaries. There were greater abundances of *Macomona* at sites near the mouth of the southern estuaries; they were more broadly distributed across the entire range of sites within Okura and Orewa, but were more abundant at sites in the middle of the northern estuaries (Fig. 25). Apart from a single peak in abundance, driven by a pulse of juveniles, in April 2006, populations of *Macomona* were very stable through time. Small *Macomona* (< 4 mm) dominated densities, except at Okura, where adults dominated.

It is significant that Okura has greater proportions of resident adults of all three species of bivalves (Appendix 9), compared to the predominance of smaller size classes in all of the other estuaries. This highlights Okura's potential role in the region as a source of larvae, although the extent of larval exchange among estuaries is possibly quite limited and is presently unknown. Despite punctuated pulse recruitment events in the case of pipi and wedge shells, overall bivalve densities, at both the estuary and site scale, have been quite stable over the period of monitoring. Given this current relative stability that has been measured as a baseline, changes in overall bivalve densities will be easily detected in the presence of any significant large-scale sediment impacts (e.g., Cummings et al. 2003).

5.11 Temporal and spatial patterns in diversity

Diversity was greatest at Okura, Mangemangeroa and Waikopua. The high diversity of sites located in the outer portions of the Whitford embayment is consistent with the results reported in Senior et al. (2003). Monitoring is especially important for these high diversity areas. Currently, diversity is highly stable at individual sites and across whole estuaries. Although there is seasonal variation in diversity, the timing of peaks in diversity is not clear under the current limited within-year sampling. The inconsistency of the timing of seasonal peaks in abundances for different species has also been reported by Cummings et al. (2003) from Mahurangi.

5.12 Recommendations

- ☐ Monitoring of biota and environmental variables from all estuaries should continue as before, but it is no longer necessary to sample after periods of rainfall as defined under the former sampling triggers. The relative temporal stability recorded to date provides a good initial baseline, but there is not yet enough temporal data to identify natural longer-term (multi-year) patterns (such as El Niño/La Niña cycles, etc.).
- ☐ Sampling should continue to be done once in each season after relatively ‘dry’ periods (according to previous definitions), but event-driven sampling should be done according to new, more extreme, rainfall triggers (to be developed in consultation with the ARC and available rainfall data).
- ☐ Sampling after rainfall should focus on the estuaries of special interest and where a greater number of environmental parameters can be measured on an ongoing basis. These include, presently, Orewa, Okura and Mangemangeroa. Separate rainfall triggers should be established for each of these estuaries, as even intense rainfall events in the Auckland region are commonly very patchy.
- ☐ These additional environmental measures should be compared and correlated at various temporal and spatial scales with sediment trap data, to develop calibration models and to assist in the development of causal links under ongoing monitoring. If possible, similar environmental measurement tools should be installed at all of the estuaries to provide the most robust possible causal inference base across the region.
- ☐ Under present budgetary restrictions, we recommend sampling after heavy rainfall (as defined under new triggers) up to three times in each of the three nominated estuaries, regardless of when these happen during the year.

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