Auckland
Regional Council
TE RAUHITANGA TAIAO

Ecological Monitoring of the Okura Estuary: 2003 - 2004

December 2004 Technical Publication 257

Auckland Regional Council
Technical Publication No. 257, December 2004
ISSN 1175 205X ISBN 1-877-353-75-2

www.arc.govt.nz

Printed on recycled paper

Ecological Monitoring of the Okura Estuary 2003-2004: testing the continued application of regional models

Dr R.B. Ford
Dr M.J. Anderson
B. Davison

Prepared for:

Auckland Regional Council
Private Bag 92012
Auckland

AUCKLAND UNISERVICES LIMITED
A wholly owned company of
THE UNIVERSITY OF AUCKLAND
Department of Statistics and
Leigh Marine Laboratory
University of Auckland
Tel: 61-9-373-7599
Fax: 61-9-373-7018
Email: *r.ford@auckland.ac.nz*

December 2004

Executive Summary

The purpose of the current monitoring program is to determine whether land disturbance associated with varying degrees of urbanisation in the surrounding catchment of Okura estuary causes ecologically damaging sedimentation to the intertidal soft-sediment infauna in the estuary, and in this way to verify the validity of modelling and environmental risk predictions used to underpin development planning decisions. It is further expected that effects of sedimentation may be most pronounced after periods of relatively heavy rainfall.

The sampling design, methodology and analyses we have developed provides for the detection of environmental perturbations at individual sites within estuaries and also at large scales across whole estuaries within an appropriate regional context. The five estuaries included in the monitoring program are: Puhoi, Orewa, Waiwera, Okura and Mangemangeroa. The use of control charts, which can highlight either short-term "pulse" or long-term "press" deviations of biological structure, precisely when and where they occur, provides a powerful tool for monitoring. In addition, we have developed models of the biological data in response to environmental characteristics that need not be estuary-specific, but may be applied across the entire sampling design, providing greater power to detect and characterise effects. Simultaneous measurements of environmental variables not only provide a basis for modelling existing assemblage structure during this "pre-impact" stage, but will also provide key insights into the potential specific causes of any significant biological changes observed in the future.

Through analysis of environmental variables (such as bed height movement, amount and texture of trapped and ambient sediments, distance from the mouth of the estuary, etc.), we have identified three general categories of hydrodynamic energy into which each site in the monitoring program can be classified, regardless of the estuary in which it occurs. These classifications have remained consistent over the past two years. Sites classified as "high-energy" are characterised by relatively large amounts of bed movement (erosion and accretion), relatively large amounts of sediment deposition in traps and coarser grain-size textures, "low-energy" sites are characterised by relatively little bed movement and deposition but with finer textured sediments, while "medium-energy" sites are intermediate in these characteristics.

Organisms living in the estuary appear to respond in a fairly consistent manner to these hydrodynamic conditions, with the environmental variables explaining approximately 47% of the variation in the species variables at the site level. Similar suites of organisms have been associated with each of the energy classifications over the past two years of sampling. More particularly, high-energy sites generally harbour greater densities of the pipi *Paphies australis*, the cumacean *Colorustylis* spp. and the amphipod *Waitangi* sp. Medium-energy sites are characterised by relatively higher densities of the cockle *Austrovenus stutchburyi*, the bivalve *Nucula hartvigiana*, the anemone *Anthopleura* spp. and the polychaete worm *Prionospio sp.* They also tend to have greater numbers of taxa than either low or high-energy sites. Low-energy sites were characterised by relatively high densities of several polychaetes (*Notomastus sp.*, Pseudopolydorid complex, Nereid/Nicon complex, *Capitella sp.* and Oligochaetes) and copepods.

Temporal change in these estuaries, either in terms of hydrodynamic conditions or in terms of biological variation, has been rather inconsistent in character, short-lived and small in size relative to the spatial variation due to different hydrodynamic energy regimes and the variation from site to site. Seasonal effects are minor, meaning that the monitoring program can use the full power of all temporal sampling events without having to stratify information on a seasonal basis.

Effects of rainfall events were, however, detected, especially at several sites within the Puhoi estuary, where a "zig-zag" pattern on control charts was observed. This suggests that the assemblages are perturbed by a rainfall event, but then, by the time of the following census, they have returned back to what they were before, thus indicating a "pulse" effect of little ecological consequence. Such pulse effects were not in a similar direction across sites having different hydrodynamic energy regimes. In fact, assemblages at low-energy sites tended to have characteristics more like high-energy sites after a rainfall event, and vice versa. This suggests that rainfall events may provide a mechanism for "mixing" of taxa along the length of the estuary, perhaps through greater overall flow, greater wave action or both. Understanding the mechanisms generating the observed patterns would require further experimental studies.

TABLE OF CONTENTS

1. INTRODUCTION

1.1. Background

Increased rates of sedimentation in coastal areas can cause important impacts on estuarine and marine ecosystems (GESAMP 1990). Rain falls on catchments, flows through rivers and carries an estimated 400 million tonnes of sediment from the landmass of New Zealand to the ocean (Hicks and Griffiths 1992). Changes in land use can be a vital factor in determining the quantity and quality of sediments eroded from the land, with land cleared for construction eroding at a rate approximately 2000 times that seen in forests (USEPA 1973). Increasing intensity of rainfall is predicted by climate change scenarios and is another factor likely to result in an increase in the amount of sediment transported by rivers through estuaries and to the ocean (Griffiths 1981, 1982, 1990, Hicks 1990). Sediment transported by rivers passes through estuaries on the way to the ocean, and estuaries are often characterised by high rates of sediment deposition (Dyer 1986). Changes in sediment inputs due to changes in land-use, climate or a combination of the two are therefore likely to show impacts in estuarine environments.

Sedimentation can affect macrofaunal community structure over a number of scales, from centimeters to hundreds of kilometers (Edgar and Barrett 2000, Benedetti-Cecchi et al. 2001). Previous reports by Auckland Uniservices for ARC on this topic have reviewed the literature in this area (Anderson et al. 2001b, Anderson et al. 2002, Honeywill et al. 2002, Ford et al. 2003c). In the time since the last of these reviews, five relevant papers have been published, all demonstrating negative impacts of sedimentation on soft-sediment infauna in Northern New Zealand (Cummings et al. 1996, Ellis et al. 2004, Lohrer et al. 2004, Thrush et al. 2003a, Thrush et al. 2003b). Biological impacts of sedimentation have been seen to vary with both the taxa examined and the depth of sedimentation (Thrush et al. 2003a, b, Lohrer et al. 2004). As little as 3mm of terrigenous sediment was enough to decrease diversity in the Whitford embayment, repeated depositions of thin layers had a cumulative effect, decreasing diversity even further (Lohrer et al. 2004). Factors influencing recovery from sedimentation have been isolated and include: chlorophyll *a* concentrations, total carbohydrates, phosphorous (P), nitrogen (N) and coarse sand in the sediments (Cummings et al. 2003b). Site environmental factors that dissipated or fractured the deposited sediment (increased wave disturbance, flow velocity, and the wetting and drying of the deposited terrestrial sediment) or increased the availability of colonists (distance to channel, inundation time) were also seen to speed recovery (Thrush, *et al.,* 2003a). Benthic diversities and abundances were also decreased with increasing sedimentation in mangrove habitats (Ellis *et al.* 2004).

Various NIWA reports for the ARC have been completed or drawn to our attention over the last year that deal with either the issue of estuarine sedimentation or patterns and responses of benthic communities in estuaries. Here, we examine both of these issues. In the Mahurangi estuary a gradual decline in densities of *Macomona liliana* and *Austrovenus stutchburyi* and a loss of diversity at some sites in the intertidal was observed from 10 years of monitoring data, and linked to an increase in fine sediments (Cummings *et al.* 2003a). The diversity in a part of the Puhoi estuary and the whole of Whitford embayment (including Mangamangeroa estuary) has been assessed (Lundquist *et al.* 2003; Senior, *et al.* 2003). In Puhoi estuary the relatively low diversity seen in the upper estuary was related to high levels of sedimentation (4.1 – 5.8mm.yr cf. Okura estuary 0.5 to 3.5mm .yr) recorded from this estuary (Lundquist *et al.* 2003; Swales *et al.* 2003). A conceptual model was then developed that described two intertidal community types; one sheltered from tidal currents and one with little influence of catchment runoff (Lundquist *et al.* 2003).

Okura estuary is located near the northern edge of the North Shore area of Auckland and is under increasing pressure from urbanisation This increasing pressure of development has raised concerns that potential associated increases in sedimentation will negatively impact the ecology of the estuary itself. Such concerns are particularly relevant given the status of the Okura estuary as a marine reserve.

Considerable research has been completed on various aspects of the estuary, including:

- the habitats in the estuary have been described (Honeywill *et al.* 2002);
- the sedimentation and hydrological patterns/characteristics of the estuary have been studied (Green and Oldman 1999; Stroud *et al.*1999);
- the biology and ecology of the soft-sediment benthic fauna have been described (Hewitt *et al.* 1998; Norkko *et al.* 1999; Saunders and Creese 2000; Anderson *et al.* 2001a, b);
- the potential impacts of urbanisation resulting from increased sedimentation have been modelled (Cooper *et al.* 1999; Swales *et al.* 1999; Stroud and Cooper 2000); and
- fine sediment deposits to depths of greater than 2-3cm that resided for more than 7 days were found to be sufficient to kill almost all of the organisms in intertidal sediments in the Okura estuary (Norkko *et al.* 1999).

The pilot report of Anderson *et al.* (2001a) and subsequent annual report (Anderson *et al.* 2001b) showed that assemblages in Okura were found to vary significantly with depositional environment (High, Medium or Low, as modelled in Cooper *et al.* 1999) and with the rank distance of sites from the mouth of the estuary. More specifically, bivalves and gastropods were found to be more abundant in the Medium/Low depositional areas compared to the High depositional areas, whereas the abundances of certain worms and crabs were found to be greatest in the High depositional areas. It was clear from these studies that the depositional environments modelled by Cooper *et al.* (1999) were useful in predicting spatial patterns of changes in benthic assemblage structure.

In 2002, monitoring within Okura was expanded and intensified, focusing on the spatial scale of greatest variation: individual sites. A greater number of sites were sampled from within each depositional environment and, in addition, concomitant measurements were made of several environmental characteristics. This was an important change to the monitoring program, as it allowed explicit modelling of spatial variation in macrofaunal assemblages in response to environmental characteristics. It was found that up to 70% of the spatial variation in biodiversity could be explained by the physical variables measured (Anderson *et al.* 2002). In particular, the grain-size characteristics of ambient and trapped sediments, the overall amount of sediment trapped, the distance from the mouth of the estuary and bed height movement were all useful in modelling assemblage dynamics. Greater replication at the site level also allowed seasonal effects and effects of precipitation (temporal factors which were weaker in their impacts than spatial factors) to be detected. In addition, an examination of overall changes through time within Okura over longer time periods was initiated (Anderson *et al.* 2002).

In 2003, the monitoring programme to cover four additional estuaries: Puhoi, Waiwera, Orewa and Mangemangeroa, in order to provide an appropriate regional basis for making inferences regarding potential impacts of sedimentation at the scale of the entire estuary. Sampling was done before and after heavy rainfall events in each of two seasons. Monitoring of environmental characteristics was also continued at all sites for those factors found to be especially useful for modelling communities in Okura, namely bed height movement (erosion/accretion), sedimentation (as measured by sediment traps) and grain-size characteristics of ambient and trapped sediments (Anderson *et al.* 2002). This allowed sites across all of these estuaries within the region to be modelled in terms of specific environmental characteristics. A gradient from low to high-energy environments was modelled from environmental data and sites could essentially be categorized as belonging to one of three classes based on their hydrodynamic conditions, regardless of which estuary was under consideration (Ford *et al.*2003c). Variation in responses of benthic fauna and overall community structure matched variation along the hydrodynamic gradient quite well. Communities in high-energy environments were characterised by high counts of *Paphies* spp., and the crustaceans *Waitangi* sp. and *Colorustylis* spp. Communities in low-energy environments were characterised by high counts of polychaetes, particularly the *Nereid/Nicon complex*, and capitellids and oligochaetes. The sites with medium-energy hydrodynamics in terms of environmental conditions showed high counts of the cockle *Austrovenus stuchburyi,* and the polychaetes *Notomastus* sp. and *Prionospio* sp and larger numbers of taxa compared to either low or high-energy environments. The hydrodynamic conditions quantified in Okura estuary were well within the range of environmental conditions measured across the other four estuaries. Thus, the expanded monitoring program will prove extremely useful for long-term monitoring of both individual sites and the Okura estuary as a whole within an appropriate regional context.

1.2. Purpose of the present report

The purpose of the present report is to address the following questions:

1. Do the physical characteristics of the sites within Okura continue to fall within the range of physical characteristics measured for the other estuaries? That is, can the estuaries chosen be considered to be good reference estuaries for ongoing monitoring and detection of impacts at Okura?

2. Is the environmental model of high, medium and low-energy sites across all estuaries still valid and consistent with current information?

3. Can differences in biological communities from high, medium and low-energy sites still be detected, and if so, are these differences driven by similar differences in relative abundances of taxa as those seen last year?

4. Has the addition of ambient sediment information at the level of individual replicates improved our ability to model the biological communities?

5. Are there estuary-specific effects on communities (e.g. due to runoff of contaminants or other issues) that cannot be explained by the measured environmental variables?

6. What is the relationship between the fauna and the measured environmental variables? Can the biological communities be successfully modelled by the environmental variables? If so, how variable is this through time and how specific is this to different estuaries? Will sites in different estuaries with similar physical characteristics have similar biological communities?

7. What are the temporal patterns in assemblage structure observed for the 2003-2004 sampling year? Are there identifiable seasonal effects or effects due to precipitation? Are these effects, if present, consistent across sites with different energy levels, or are they able to be characterised by particular biota?

8. What are the long-term patterns of variation for all sites across all estuaries? Are there any current signs of important sudden ("pulse") or gradual ("press") changes in the fauna since monitoring of all estuaries began in August 2002? If so, are such changes different for assemblages occurring in the different energy environments? Where and when are these effects occurring and are they able to be characterised by changes in particular biota?

2. METHODS

The field and laboratory methods used were identical to those used in this study last year (Ford et al. 2003c), except in regard to the sampling of ambient sediments. Last year, grain sizes of ambient sediments were only processed for one of the four sampling times. Grain sizes of ambient sediments were the set of variables that explained the greatest proportion of variation in the macrofaunal community across all estuaries last year (Ford et al. 2003c). It was of interest to determine whether ambient sediments were temporally variable in their textural composition and whether this may be correlated with any temporal changes in biota. Thus, a core of ambient sediment was processed for each biological sediment core in the present study. Ambient sediments were pre-treated with hydrogen peroxide (a new step in the pre-treatment procedure) prior to deflocculating (an established step in the pre-treatment procedure) in order to standardise methods across Auckland Regional Council marine programmes (Ford et al. 2003a). This change in methodology from last year should result in an overall small decrease of fine sediments recorded (up to 5%) (Ford et al. 2003b) compared to previous studies.

2.1. Location of Sites and Sampling Methods

2.1.a. Selection of sites

The estuaries chosen for sampling were Puhoi, Waiwera, Orewa, Okura and Mangemangeroa (Fig. 1). This was on the basis of them being:

a) located both north and south of the potentially impacted estuary (Okura);

b) of similar length to Okura estuary (~1-3 km in an upstream direction);

c) aligned in an approximately east-west direction and opening out towards the east, so that events of heavy rainfall may be expected to affect them in similar ways.

Sites were chosen within each estuary on the basis of three criteria:

a) to cover the gradient from the mouth to the upper reaches of the estuary;

b) to span the range of sediment grain sizes available within each estuary; and

c) to avoid confounding of the gradient, wherever possible, with the environmental variables (e.g., it was important that not all sites with fine sediments be located in the upper reaches of the estuary).

Ten sites were sampled in each estuary. GPS locations of these sites are listed in Appendix A. Sites were labelled alphabetically and sequentially (A - J) from the mouth of the estuary (A) to its upper reaches (J) (Fig. 2). In the presentation of results sites within estuaries are generally referred to by a two-letter abbreviation. The first letter indicates the estuary (Fig. 1), while the second letter indicates the position of the site in the estuary relative to the mouth (from A-J). For example, site OJ indicates the site at

Okura estuary furthest from the mouth and site ZC indicates the site in Mangemangeroa estuary that is third closest to the estuarine mouth. In Okura we chose three sites from each of the three previously modelled depositional classes (High, Medium and Low) plus an extra High depositional site. Sites A-J for Okura in the present report (Fig. 2) were labelled sites 2, 5, 6, 8, 9, 10, 11, 13, 14 and 15, respectively, in a previous report (Anderson et al. 2002).

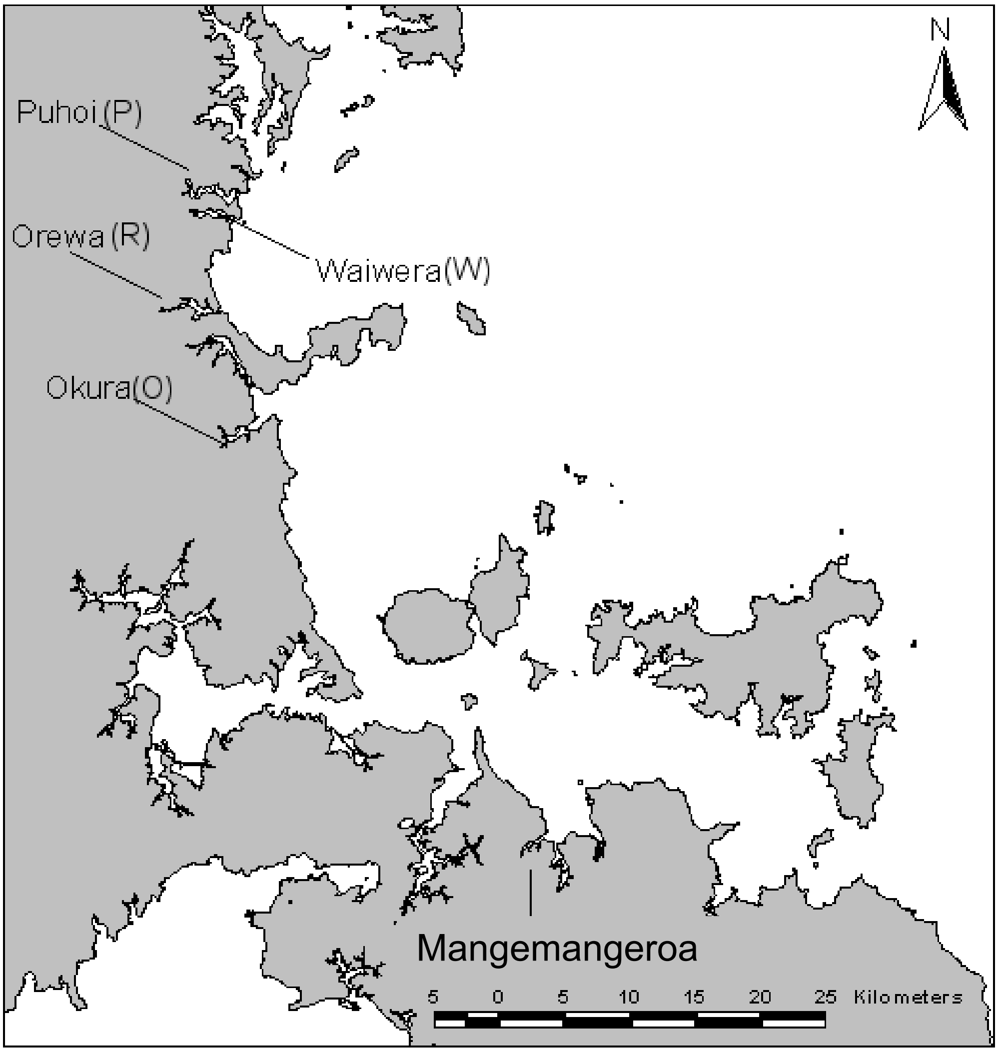

Figure 1. Map of the East Coast of the Auckland Region showing all five estuaries sampled. Abbreviations used for estuaries in reporting results are shown in brackets after each name.

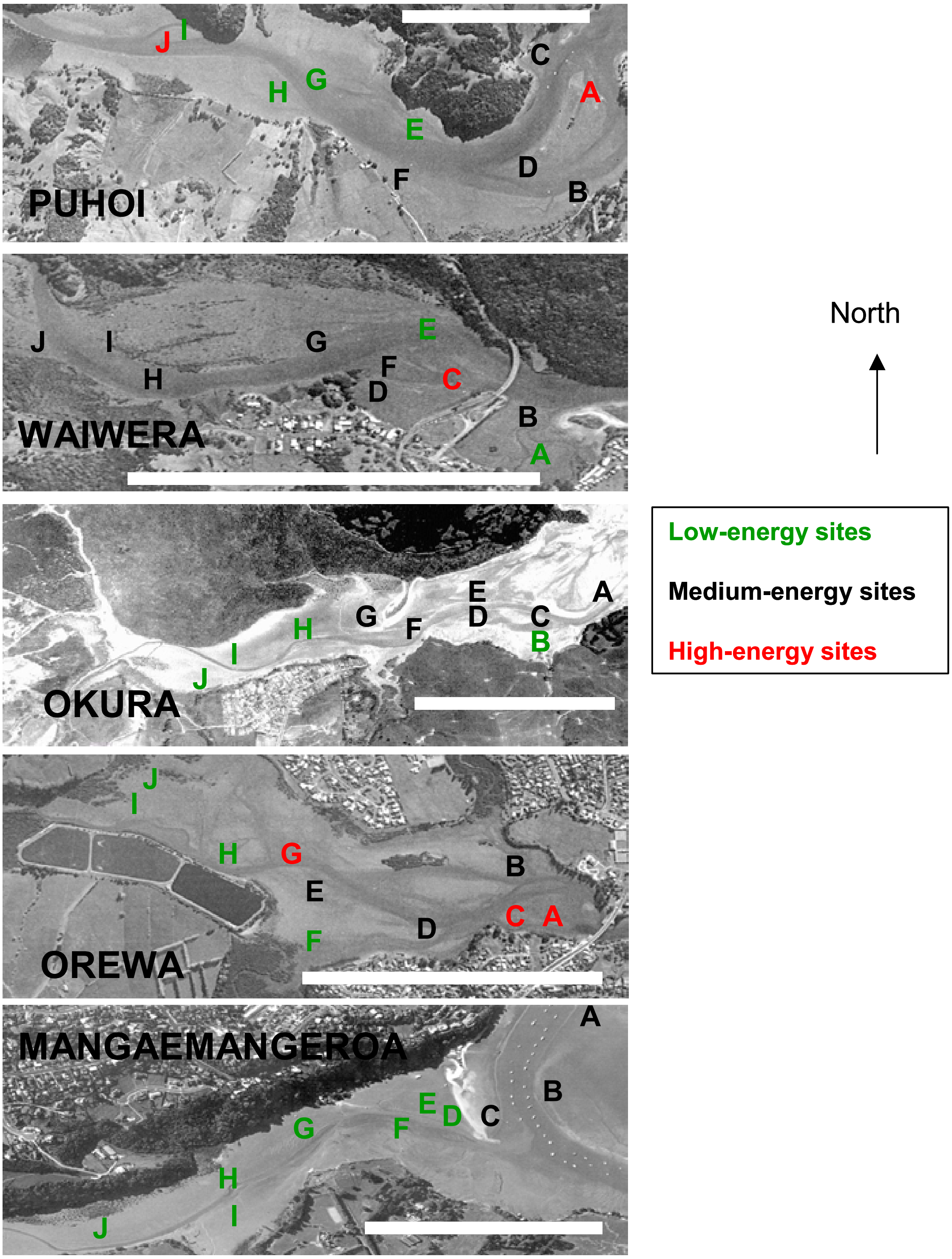

Figure 2. Maps of all estuaries showing sites in each of three environmental groupings. Bars equal 1km in the horizontal direction only. Note scales are unequal in the horizontal and vertical planes. Estuary flats vary in width up to 200m.

2.1.b. Timing of sampling

Sampling occurred within 2 discrete 3-month blocks (hereafter referred to as seasons): August - October 2003 (Winter/Spring (W/S) and February - April 2004 (Late Summer (LS)). Within each season, sampling was event-driven and occurred twice: (i) once 7-10 days after a rainfall event, defined as ≥ 15mm of rainfall in a 24-hour period ('Rain') and (ii) once when such a rainfall event had not occurred in ≥ 10 days ('Dry'). Examination of seventeen years of data from the Leigh Marine Laboratory meteorological records showed that a rainfall event of 15 mm was an event that could be reliably expected to occur at least twice in every season. Rainfall was gauged from the St. Heliers weather station, which is a site central to all estuaries. Data were obtained from: http://homepages.paradise.net.nz/tmcgavin/current_nzweather.html.
All estuaries were sampled within a period of 5 days at each of the four times of sampling (Table 1).

Table 1. Sampling dates for 2003-2004.

Sampling Period	Estuary	'Rain' Sampling	'Dry' Sampling
Winter/Spring 2003	Waiwera	31st August 2003	11th October 2003
	Puhoi	27th August 2003	12th October 2003
	Orewa	28th August 2003	13th October 2003
	Okura	29th August 2003	10th October 2003
	Mangemangeroa	31st August 2003	9th October 2003
Late Summer 2004	Waiwera	13th February 2004	26th March 2004
	Puhoi	12th February 2004	22nd March 2004
	Orewa	11th February 2004	24th March 2004
	Okura	10th February 2004	25th March 2004
	Mangemangeroa	9th February 2004	23rd March 2004

2.1.c. Field 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 flag. There were $n = 6$ cores obtained from random positions within each area by choosing a random number between 0 and 49 and between 0 and 24 for the x and y-axes, respectively. Cores were circular in shape, measuring 130 mm in diameter and 15 cm deep. 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 taxonomic identification. All organisms retained were preserved in 70% isopropyl alcohol with 0.01% rose bengal.

Where possible, organisms were identified to the species level. Some specimens were unable to be unambiguously identified, and are grouped together. 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. Some polychaetes could be identified to species level, while others could only be identified to the genus or family level (see Appendix B).

2.1.d. Field sampling of environmental variables

One core (38 mm diameter x 15 cm deep) was obtained to sample ambient grain sizes of sediments adjacent to each faunal core, and all samples were analysed. Samples were sub-sampled to obtain a representative known weight of dry material (~50 g). Samples were pre-treated as described in Ford et al. (2003). Sub-samples were then treated with 10% Hydrogen peroxide until fizzing ceased, to dissolve organic matter. Sub-samples were then dried and deflocculated for at least 12 hours (using Calgon $2 g.l^{-1}$) and wet sieved on a stack of sieves (500, 250, 125 and 63μm) and each fraction (>500, 250-499, 125-249, 63-124 and <63μm) 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.

2.1.e. Measurement of sedimentation and rainfall

Sedimentation was characterised at each site by a combination of a sediment trap and a depth-of-disturbance rod. A sediment trap (36 mm diameter by 50 cm deep) was placed at the lowest point of each site so that the opening was 20-25 cm above the sediment surface. These traps collected sediment settling from the water column. 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. 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. Due to scour 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.

Sediment traps were deployed at each site in the field for a period of approximately one month at a time, such that a continuous record was gained from June 26, 2003 (except for sediment traps lost). At deployment and collection, measurements were also taken of the depth-of-disturbance rods. 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 (see section 2.1.d.).

Table 2 contains a summary of all the environmental variables measured and used in subsequent analyses and models.

Table 2. List and description of environmental variables used in analyses.

Group	Variable Name (abbreviation)	Description
Ambient Grain Size (AmbGS)	GS1 – GS5	Five variables expressing the absolute (at replicate level) or average (at site level) percentage of grain sizes of ambient sediments falling into particular size classes at each sampling:
	GS1	< 63 microns
	GS2	63- 124.9 microns
	GS3	125- 249.9 microns
	GS4	250 - 499.9 microns
	GS5	> 499.9 microns
Trapped Total (TrapTot)	Avdep	Average total sediment deposition obtained in traps ($g.cm^{-2}.day^{-1}$) over the sampling year
	sddep	Standard deviation in total sediment deposition obtained in traps ($g.cm^{-2}.day^{-1}$) over the sampling year
	Avfin	The average weight of trapped sediments < 63 microns (g) over the sampling year
Trapped Grain Size (TGS)	TGS1 – TGS5	Five variables expressing the average percentage of grain sizes of trapped sediments falling into particular size classes over the period of the sampling year:
	TGS1	< 63 microns
	TGS2	63- 124.9 microns
	TGS3	125- 249.9 microns
	TGS4	250 - 499.9 microns
	TGS5	> 499.9 microns
Trapped standard deviation in Grain Size (TsdGS)	sdTGS1 – sdTGS5	Five variables expressing the standard deviation in percentage of grain sizes of trapped sediments falling into particular size classes over the period of the sampling year:
	sdTGS1	< 63 microns
	sdTGS2	63- 124.9 microns
	sdTGS3	125- 249.9 microns
	sdTGS4	250 - 499.9 microns
	sdTGS5	> 499.9 microns
Recently trapped sediments (Trap*)	dep*	Average total sediment deposition obtained in traps over a period of approximately one month prior to biological sampling ($g.cm^{-2}.day^{-1}$)
	dep%fin*	The percentage of trapped sediments < 63 microns obtained in traps over a period of approximately one month prior to biological sampling
	depfin*	The weight of trapped sediments < 63 microns obtained in traps over a period of approximately one month prior to biological sampling (g)
Distance (D)	D	Rank distance of site from the mouth of the estuary (1-10)
	D2	Rank distance squared (D^2)
Erosion	BH	Average change in bed height (erosion/accretion) ($cm.day^{-1}$) over the sampling year
	sdBH	Standard deviation of change in bed height ($cm.day^{-1}$) over the sampling year
	BH*	The change in bed height over a period of approximately one month prior to biological sampling

2.2. Statistical Analyses

Significant *P*-values from statistical analyses at a level of alpha <0.05 will be displayed in bold type.

2.2.a. Analyses of environmental data

Ambient sediments were collected and processed for the full experimental design and so were analysed using a four-factor non-parametric multivariate analysis of variance (NPMANOVA, Anderson 2001a), based on Euclidean distances of the four grain-size classes (GS1-4, GS5 is redundant when the other four variable are fitted). The factors were Estuary (5 levels, fixed), Distance class (10 levels: A-J, fixed), Season (2 levels, fixed) and Precipitation (2 levels, fixed). These tests were done using 999 permutations of the raw data (Anderson 2001b). Precision estimates (= standard error/mean) were also obtained for sample sizes from n = 2 to n = 6 in order to assess an appropriate level of replication needed to estimate variation in ambient sediment grain sizes per site.

Univariate plots (boxplots and plots of means and standard errors) of several individual environmental variables were made for all sites in all estuaries. This was particularly useful to determine the nature of the variation in these variables at other estuaries compared to the values observed for sites at Okura.

To visualize patterns in environmental data non-metric multi-dimensional scaling (MDS, Kruskal and Wish 1978) was used as a robust ordination method (e.g. Clarke 1993). Labels were superimposed on the MDS plots to identify the specific estuary and site. This was helpful to assess whether any patterns existed due to either a) estuary, or b) distance within each estuary. All multivariate analyses of environmental data (alone) were done on the basis of Euclidean distances. Environmental data were averaged at the site level through time because not all variables were measured at each time. Data were then standardized to *z*-scores (i.e. each variable was transformed by subtracting its mean and dividing by its standard deviation, also called normalisation).

When sampling began in Okura estuary, there were existing hydrodynamic models of the estuary and surrounding catchment. No such models were available for the other estuaries included in this investigation. As such, it was necessary to attempt to characterise the sites we sampled in terms of the environmental data. To characterise the sites, we used hierarchical agglomerative group-average clustering (UPGMA) (e.g. Legendre and Legendre 1998). This method was chosen because of its relative robustness in identifying genuine clusters, as shown by simulation studies (Belbin and McDonald 1993, Milligan 1996). In addition to the agglomerative method, a divisive method of finding groups was also used, called k-means partitioning (MacQueen 1967, Legendre and Legendre 1998). This method requires the user to specify the number of groups to be identified *a priori*. The method then partitions the individual observations into the specified number of groups in such a way as to minimize the sum of squared Euclidean distances from observations to their group centroid. In our case, for the environmental data sets we chose to find the best partition into three groups, based on patterns obtained last year (Ford *et al.*2003c).

A principal component analysis (PCA) was used to simplify the 26 environmental variables (many of which were highly correlated) down to a few dimensions, which could be interpreted in terms of the overall environmental gradient in physical variability among sites. The PCA biplot provides information regarding the correlation of each variable with principal component axes. Variables with the highest correlations to axes (longest arrows) are most important in describing variation along the gradient identified by the PC axes.

2.2.b. Analyses of biological communities

Non-metric multi-dimensional scaling (MDS) ordinations (unconstrained ordinations) were also used to display the biological data. Symbols were superimposed to investigate potential effects of: a) estuary and distance and b) high, medium and low-energy sites identified using the environmental data. All multivariate analyses of biological data were done using Bray-Curtis dissimilarities of ln(y+1)-transformed species abundances for data pooled at the site level.

2.2.c. Relating biological data to environmental variables

Direct models of the faunal data versus the environmental data were constructed using permutational multivariate multiple regression (McArdle and Anderson 2001). These were obtained by forward selection of (i) individual environmental variables and (ii) logical sets of environmental variables, as outlined in Table 2 above. Analyses were based on the Bray-Curtis dissimilarity matrix calculated from ln(y+1)-transformed species abundances. P-values were obtained using 4999 permutations of raw data (for marginal tests) or permutations of residuals under a reduced model (for sequential tests), as required (Anderson 2001b).

To visualize relationships among variables and to determine which environmental variables might be driving ecological patterns, distance-based redundancy analysis was done. Once again, the Bray-Curtis measure on ln(y + 1) transformed data formed the backbone of the analysis, and principal coordinates were obtained before running the RDA (see Legendre and Anderson 1999 for details). The length and direction of arrows in the dbRDA biplot indicates the relative strength and direction of the relationships between individual environmental variables and the RDA axes.

Although our approach above was purely to use the environmental data alone to characterise the important spatial influences on the organisms, it is also possible that other environmental factors not measured, which are specific to each estuary, could influence community structure. We can test the extent to which this may be happening by testing the effect of different estuaries on the fauna, given the environmental data that were collected. This was done using permutational multivariate analysis of covariance. We first fit the model of the data with the environmental variables and then, given that these were already in the model (as covariables), tested whether adding the factor of "Estuaries" to the model would significantly increase our ability to explain variation in the biological assemblage data. This analysis was based on Bray-Curtis dissimilarities of log-transformed abundances and a *P*-value was obtained using 999 permutations of residuals under the reduced model.

2.2.d. Relating biota to energy groupings and the environmental gradient

We would hope that the most important gradients that describe biological changes in a landscape will also be well represented by gradients in the environmental variables working together in concert. This will occur if we have chosen to measure environmental variables that are important to the organisms under investigation.

In addition to relating fauna to the environmental variables directly (using regression and dbRDA) we also examined the extent to which the overall variation among assemblages was well correlated with overall variation along the environmental energy gradient. This was done by superimposing the values of sites on the first PC axis (from the environmental data) onto the MDS plots (obtained using biological data) as "bubbles". If the environmental gradient (as defined by the first PC) is good at determining the ecological structure of biological communities, then we should see obvious patterns of gradation in the bubbles superimposed on the MDS plots.

In addition, canonical analysis of principal coordinates (CAP), was used to examine and characterise the effect of the different energy groupings (derived from the environmental data) on the biological assemblages (Anderson and Willis 2003, Anderson and Robinson 2003). Species showing high correlations with the canonical axes from the CAP plots (as seen by long arrows on the biplot) were then examined more explicitly with univariate plots.

Another approach that we used to demonstrate the form of the relationship between environmental and biological data was to do a direct canonical correlation analysis (CAP) of the biological data versus PCA axis 1 obtained independently using the environmental data. This plot could provide some guidance as to the nature of the relationship between the two sets of variables and, more particularly, where along the environmental gradient the strongest biological changes are occurring.

2.2.e. Temporal effects on biological communities

Once three separate groups of sites had been identified (using k-means) on the basis of the environmental variables, each of these groups of sites were examined for their variability through time. This was achieved by doing three separate NPMANOVA analyses (one for each group of sites) investigating Season (2 levels: W/S and LS, fixed), Precipitation (2 levels: Rain vs. Dry, fixed) and their interaction. These analyses were based on Bray-Curtis dissimilarities of $\ln(y + 1)$ transformed species abundance data, with *P*-values obtained using 999 permutations of the raw data. Terms found to be significant were then investigated more fully by doing appropriate pair-wise comparisons and by examining ordinations to visualize patterns using non-metric MDS and CAP plots.

There have now been 8 separate times of sampling of all estuarine sites consistently over a period of 20 months (from August 2002 to March 2004) by researchers from the University of Auckland. A further goal of this study is to examine whether recognizable temporal trends are becoming evident in different energy environments. More particularly, we should wish for a monitoring program to be able to detect, as soon as possible, when a particular site may be going "awry" by reference to the natural variability we have observed (i) at other similar sites and (ii) at that site for all previous times. Recently, Anderson and Thompson (in press) have extended the idea of control charts from the engineering literature where it is used for univariate response variables to allow for monitoring of multivariate species abundance data. More particularly, the criterion they suggested is the dissimilarity (deviation) of a new observation at a site at time t, from the centroid (average) of the previous observations at that site up to and including time $(t - 1)$. If the system is "in control", each new observation for the assemblage should "bounce around" some "target" centroid for that site through time. However, if there is an impact that dramatically alters the assemblage, then we can expect this dissimilarity to be large relative to the values we have seen for it (and for other similar sites) in the past.

Thus, the basic idea is to plot the Bray-Curtis dissimilarity of a site at time t from the centroid of the observations (based on all previous times) and examine if it is large relative to other such values across the spatial array of sites. We can use bootstrapping of the observations through time within a site (under the null hypothesis that the system is “in control”) to put a 95% upper confidence bound on this value (Efron and Tibshirani 1993, Davison and Hinkley 1997). For further details, see Anderson and Thompson (in press). This sort of criterion will likely pick up on sudden dramatic changes at a site. However if the changes are more gradual, then a different criterion can be used, such as the distance from the new observation at time *t* from a centroid based on the first *b* (baseline) observations in the series. We have found that a baseline of only 1 or 2 observations actually works quite well for picking up gradual trends (Anderson and Thompson, in press).

In the present case, it was possible to generate multivariate control charts for each of 50 different sites (6 from High, 23 from Medium and 21 from Low energy areas). Separate analyses were done to obtain appropriate confidence bounds for sites from each of the 3 different energy groupings and results are given in separate plots for each estuary for clarity.

2.2.f. Computer programs

Non-metric MDS plots, bubble plots, UPGMA dendrograms and SIMPER analyses were obtained using the computer program PRIMER v. 5 (Clarke and Gorley 2001). K-means partitioning was achieved using the program Kmeans.exe written by P. Legendre. Principal coordinates with correction for negative eigenvalues were obtained using the program DistPCoA.exe (written by M. Anderson and P. Legendre). Kmeans.exe and DistPCoA.exe are available from the following website:
http://www.fas.umontreal.ca/BIOL/Casgrain/en/labo/index.html.
Distance-based RDA was done using the MultivEcol computer package (by B. McArdle and M. Anderson) written for use with the R computer language (Ihaka and Gentleman 1996). Non-parametric MANOVA, MANCOVA, multivariate multiple regression and CAP analyses were performed using the programs NPMANOVA.exe, DISTLM.exe, DISTLM-forward.exe and CAP.exe, respectively, written by M. Anderson and available from the following website:
http://www.stat.auckland.ac.nz/people/~mja.
The program ControlChart.exe (written by M. Anderson) was used to calculate the dissimilarities required for control charts and to do the bootstrapping to calculate the upper 95% confidence bounds. The program Precision.exe (written by M. Anderson) was used to calculate precison at different levels of replication. Univariate plots were generated using SigmaPlot^{TM} 2000, version 6.10.

3. RESULTS

3.1. Analyses of environmental data

The patterns seen with respect to environmental variables measured in 2003-04 were in close agreement with those documented in last year's report (Ford *et al.*2003c). Sites in Okura estuary were again intermediate in their environmental characteristics by comparison to sites in the other four estuaries. This further reinforces our choices for both estuary and site selection in terms of providing a large-scale regional baseline for understanding any possible environmentally-driven estuary-wide changes in Okura over time.

3.1.a. Ambient sediments

Ambient sediment data were highly variable at all levels investigated, as shown by the significant four-way interaction (SexPxExD, Table 3). No generalisations can therefore be made about the influence of season, precipitation, estuary or distance from the mouth of the estuary on ambient sediments. Ambient sediments (averaged over the whole year, Fig. 3) were dominated by the sediments in the 125-250 micron diameter range. Sites RF and ZC were the only two sites to counter this trend, being dominated by fine sediments (<63µm) and coarse sediments (>500µm), respectively. Similar trends in sediment composition occurred but the percentages of finer sediments (<125µm) were markedly lower in most sites in 2003-04 by comparison to 2002-03 (see Fig. 7 in Ford *et al.* 2003c and Appendix C in both reports). The change in methodology for sample processing could account for an approximate 5% reduction in the percentage of fine sediments (<63µm) between years, due to organics being included in previous quantifications of the fine fraction (Ford *et al.* 2003b). The rise in percentage weight of the three coarse fractions and the decline in the percentage weight of the two fine fractions this year compared to last year (5-11%, Table 4), indicates that this change was probably due to more than a small methodological adjustment. Examination of ambient sediment by month of collection (Appendix C) shows a large decrease in the finer fractions, and corresponding increase in the coarser fractions, in March 2004 in comparison to all other sampling times. The only exception to this pattern was at Mangemangeroa site C (up until now the coarsest site in this study), which showed a marked increase in fine sediments.

Due to the high costs associated with processing ambient sediments and the fact that analyses of all other environmental variables are done at the site level, we investigated the potential to decrease the sampling effort per site for ambient sediments. Estimates of precision (= SE/mean) were obtained for each ambient grain size fraction per site for a random draw of n = 2, 3, 4 or 5 cores and for the actual n = 6 replicate cores of sediment sampled for each site x time combination. Results indicated that increasing replication within sites from n = 2 up to n = 6 had very little effect on precision (Appendix F) with precision for all variables, regardless of sample size, being well below the usual desired precision of 0.5. Therefore, a reduction in the sampling effort per site for ambient sediments is warranted. Nevertheless, due especially to the rather large changes in the patterns of ambient sediments at the time of the March 2004 sampling, we recommend that sampling of ambient sediments be continued at each time of sampling, along with all other variables.

3.1.b. Bed height

In all estuaries, median values for bed height change were close to zero, however the variability (as measured by the interquartile range, which is the shaded area within each box) varied among sites by more than an order of magnitude (0.3–7.5mm.day^{-1}, Fig. 4). All sites in Mangemangeroa showed low variability, as previously observed (Ford *et al.*2003c). Bed level variation was high at the same sites that showed this pattern last year, i.e., sites PJ, OC and WC. However much more variability in bed height overall was evident from the 2003-2004 data than was evident in the 2002-2003 data. In addition, sites OC and RD were markedly more erosive, sites RF, WA, WF and WJ were more depositional, while sites OG, OI, PD, PF, PG, PH, RE and WC showed more variable bed height measurements but not in any consistent direction. The depositional sites were all characterised by very fine ambient sediments. The erosional sites were all characterised by relatively coarse ambient sediments. By contrast, sites that showed markedly more variable bed height measurements were a mixture of what was characterised last year as low, medium or high-energy sites. This discrepancy in bed height measurements indicates that there was much more change in bed height in 2003-04 compared to last year and at a few sites this activity was skewed towards an overall accretion or erosion over time. An outlier in the data set was the bed height measurement for site OG for the 17 days preceeding September the 23rd, 2003 when this site recorded 208 mm of erosion, however no real change in ambient sediment grain size was observed between August and October for this site. Sites in Okura estuary generally showed intermediate bed height changes compared to the other estuaries. In addition, changes in bed height were not necessarily correlated with distance from the mouth of the estuary.

3.1.c. Trapped sediments

Sediment deposition varied among sites by several orders of magnitude. The median values of sediment deposition at sites ranged from 0.006 (site PB) to 1.76 g.cm^{-2}.d^{-1} (site RC, Fig. 5). Sediment deposition was very spatially variable, with relatively high and low depositional sites often being in close proximity to each other (e.g., see Orewa sites A-D). Sites that showed high rates of sediment deposition in traps (e.g., Puhoi A and J, Waiwera C, Orewa A and C) also showed medium to large variability in bed height change. Sediment at sites PA, RC and WC occasionally accumulated to a depth of greater than 35cm within the tube. Resuspension of sediments from traps may have occurred at these sites (White 1990). Thus, large measurements of sediment deposition are therefore acknowledged as being conservative estimates. Mangemangeroa showed the least deposition of sediments across the whole estuary compared to other estuaries. All median values of sediment deposition at sites in Okura were intermediate between these extremes. These results are nearly identical to last year's results (Ford *et al.*2003c), where the same pattern was seen, with the same sites showing high deposition of sediments in traps (OA, PA, PJ, RA, RC, RG, WC and WH) and the same sites showing the highest and lowest rates of deposition. The grain size composition of trapped sediments was highly variable (Fig. 6). The highest average percentage of fine sediments in traps was found at site PE (68% of sediments <63μm diameter) and the coarsest sediments were found at site WC (>90% of sediments >125μm diameter). The texture of sediments trapped at sites in Okura estuary was between these two extremes. The patterns seen in the texture of trapped sediment among sites are consistent with last year's results (Ford *et al.* 2003c), however a few anomalies were noted. The 2003-2004 results showed markedly more coarse sediments trapped at site PJ and markedly more fine sediments (<63μm) in the traps at site WG. Mangemangeroa sites were again dominated by fine sediments (<63μm) in the traps. The percentage of fine sediments found in traps was lower than that found last year, however this decrease (44% on average in 2003-2004 cf. 38% on average in 2003-2004) was likely caused simply by a change in methodology between years.

Table 3. Permutational MANOVA examining the effects of season, precipitation, estuary, distance and their interactions on the ambient sediment data at all times of sampling. The analyses were based on Euclidean distances for raw data. *P*-values were obtained using 999 permutations.

Source	df	SS	MS	F	P(perm)	P(MC)
Season (Se)	1	27347.59	27347.59	84.36	**0.001**	**0.001**
Precipitation (P)	1	23930.35	23930.35	73.81	**0.001**	**0.001**
Estuary (E)	4	75628.27	18907.07	58.32	**0.001**	**0.001**
Distance (D)	9	64705.23	7189.47	22.18	**0.001**	**0.001**
SexP	1	42243.56	42243.56	130.30	**0.001**	**0.001**
SexE	4	21973.87	5493.47	16.94	**0.001**	**0.001**
SexD	9	11946.85	1327.43	4.09	**0.001**	**0.001**
PxE	4	16313.39	4078.35	12.58	**0.001**	**0.001**
PxD	9	11871.65	1319.07	4.07	**0.001**	**0.001**
ExD	36	166451.44	4623.65	14.26	**0.001**	**0.001**
SexPxE	4	12645.83	3161.46	9.75	**0.001**	**0.001**
SexPxD	9	9778.09	1086.45	3.35	**0.001**	**0.001**
SexExD	36	43600.72	1211.13	3.74	**0.001**	**0.001**
PxExD	36	40649.06	1129.14	3.48	**0.001**	**0.001**
SexPxExD	36	35395.21	983.20	3.03	**0.001**	**0.001**
Residual	1000	324195.46	324.20			
Total	1199	928676.57				

Table 4. Average ambient grain size percentage weight (in grams) for 2002-2003 (*n* = 12) and for 2003-2004 (*n* = 24).

Grain Size	2002 - 2003	2003 - 2004
<63μm (GS1)	23.7	16.4
63–125μm (GS2)	25.5	14.1
125–250μm (GS3)	41.8	49.1
250–500μm (GS4)	4.4	10.6
>500μm (GS5)	4.6	9.0

3.1.d. Characterization of sites in terms of environmental variables

Multivariate analyses of environmental characteristics showed no consistent patterns in terms of differences among estuaries or different distances along estuaries. MDS plots of all sites done separately at each time (Fig. 7) showed the most clumped or "internally similar" estuaries in terms of environmental characteristics were Okura and Mangemangeroa. In contrast, the most "internally dissimilar" estuary (i.e. having the greatest environmental variation among sites) was Orewa estuary. This pattern is extremely similar to the one seen last year for environmental data (see Fig. 11 in Ford *et al.*2003c).

The dendrograms of sites at each of the four times (based on hierarchical agglomerative clustering, Appendix D) suggested relative differences among sites in environmental conditions were fairly consistent over time. We examined the consistency through time of the three-group model obtained last year (Ford *et al.*2003c) using the k-means divisive partitioning algorithm. Environmental groupings were obtained separately at each of the four times, then sites were assigned to the group in which they were classified most frequently. In the case of a site being classified equally to 2 groups, then it was assigned to the group having the fewest sites. The groups of sites obtained from this process are shown in Table 5. When this table is compared to last year's table (see Table 3 in Ford et al.2003c) 86% of the sites were assigned to the same groups, including the exact same assignment of all 10 sites in Okura estuary. The high-energy group had the fewest sites, but had the largest internal variability (Fig. 8). The low-energy group was the largest and most homogeneous group. Sites from Okura estuary and Mangemangeroa estuary only occurred in medium and low-energy groups, while the other three estuaries had at least one site in each group (high, medium and low-energy).

Principal component analysis was used to characterise these three "environmental" groupings in terms of the original environmental variables (Fig. 8). A separate PCA was done on all sites at each of the four sampling occasions in order to assess whether the main factors generating environmental variability were consistent over time. For all PCAs done, the first two axes explained 45-49% of the variability in the environmental data. Due to the high levels of similarity in the patterns seen in separate PCA plots at each time, a single PCA is shown here that includes data from all sampling times. A gradient from high to low-energy sites appears to be ordered along PC axis 1. That is, high-energy sites all occur to the left of the plot, medium-energy sites in the middle and low-energy sites to the right (Fig. 8). In addition, medium-energy sites were high scoring on PC axis 2 and low-energy sites were low scoring on PC axis 2. The environmental variables that most strongly correlated with PC axis 1 were TGS3, Avdep and TGS1. The environmental variables that most strongly correlated with PC axis 2 were D and D^2. Thus, moving from left to right in Fig. 8 corresponds to a shift from sites with a low average deposition of trapped sediments which are characterised by fine sediment (low-energy sites) to sites with a high deposition of trapped sediments with higher percentages of sediment in the coarser grain-size classes (high-energy sites). Moving vertically down the plot corresponds to moving from the inner to the outer reaches of the estuary (i.e. sites J to A, respectively).

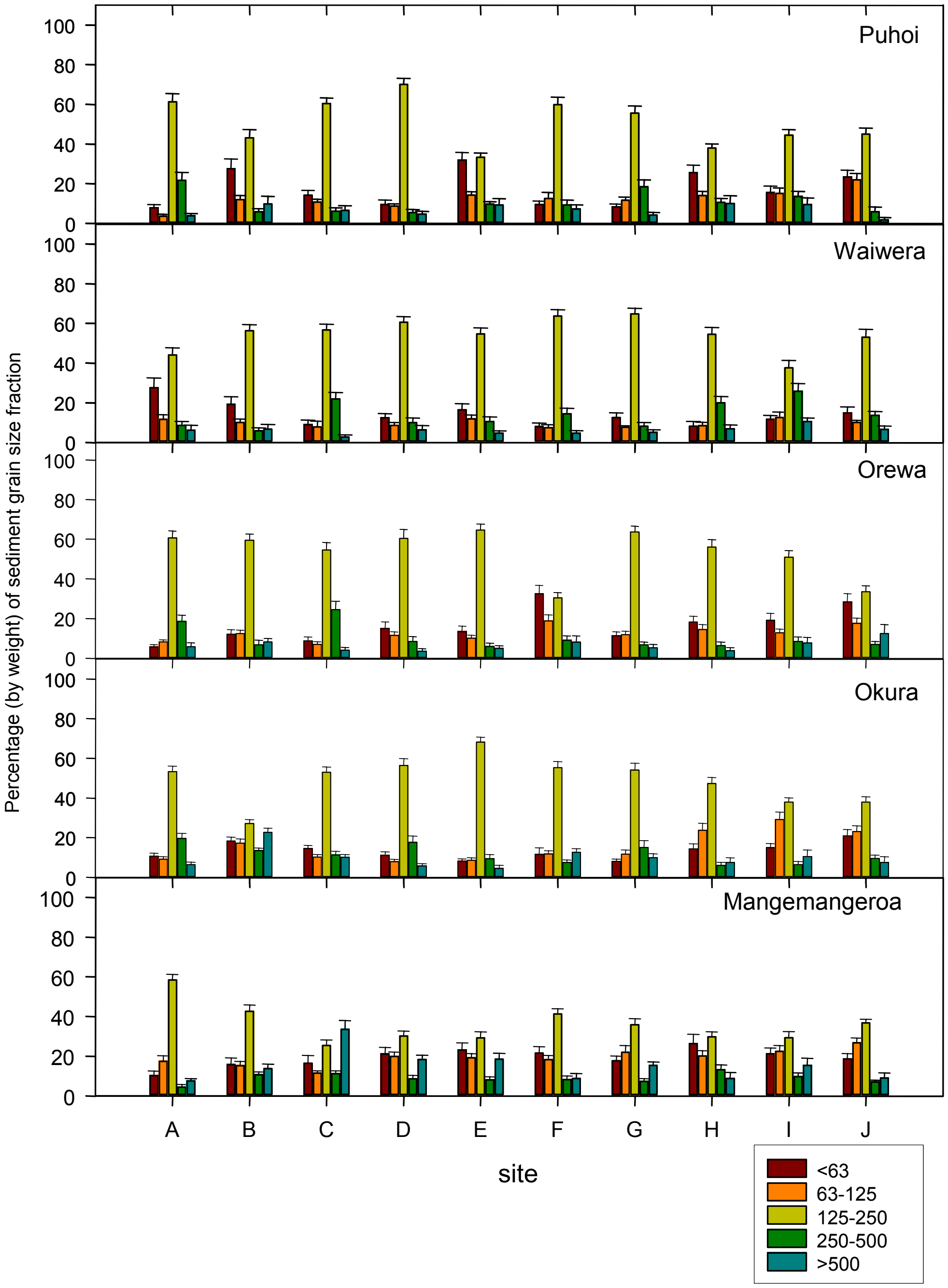

Figure 3. Mean (+S.E., *n* = 24) percentage of ambient sediments of different grain sizes averaged across all four sampling times from August 2003 to March 2004.

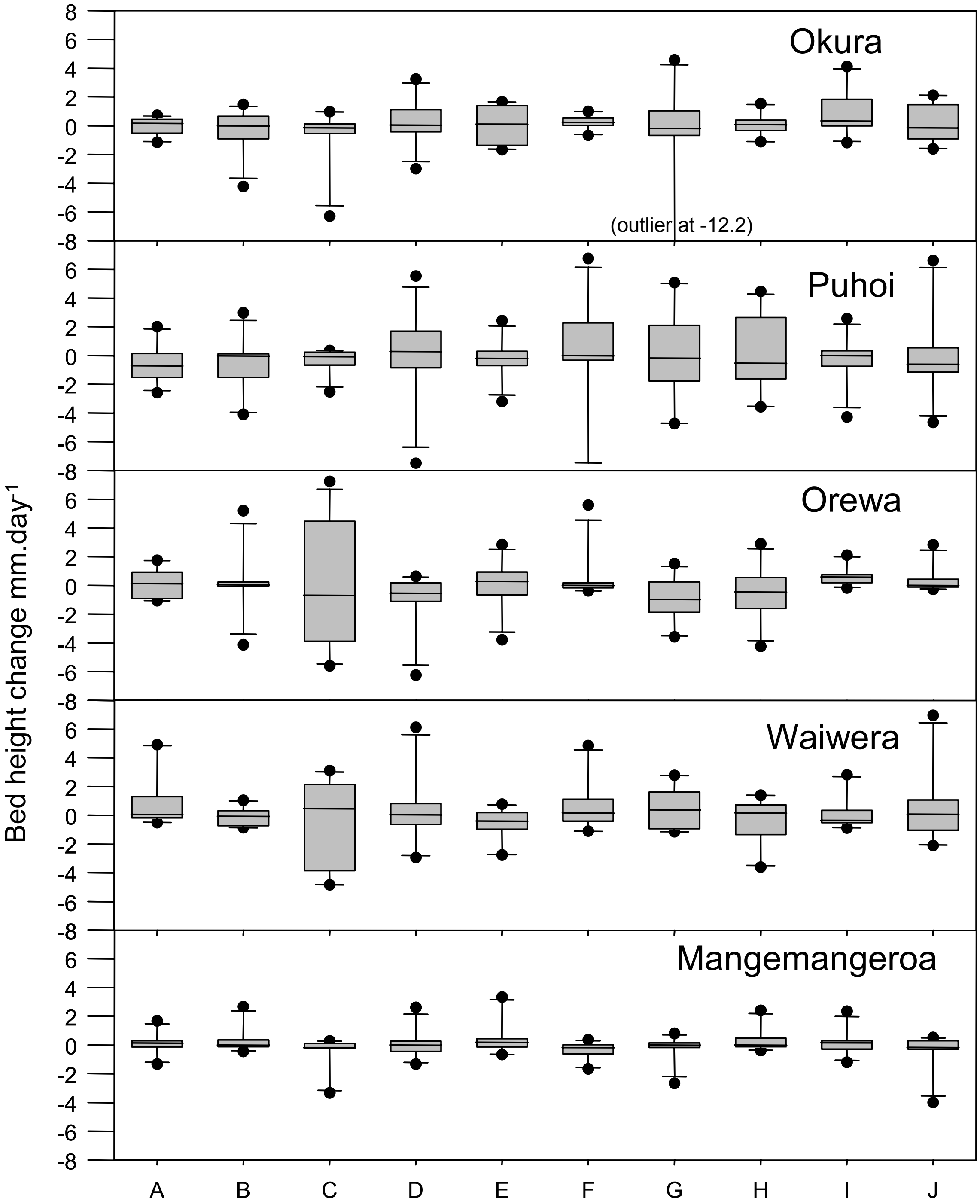

Figure 4. Bed height change at all sites in all estuaries over the entire sampling period. Sample sizes were either *n* = 10 or *n* = 11 times.

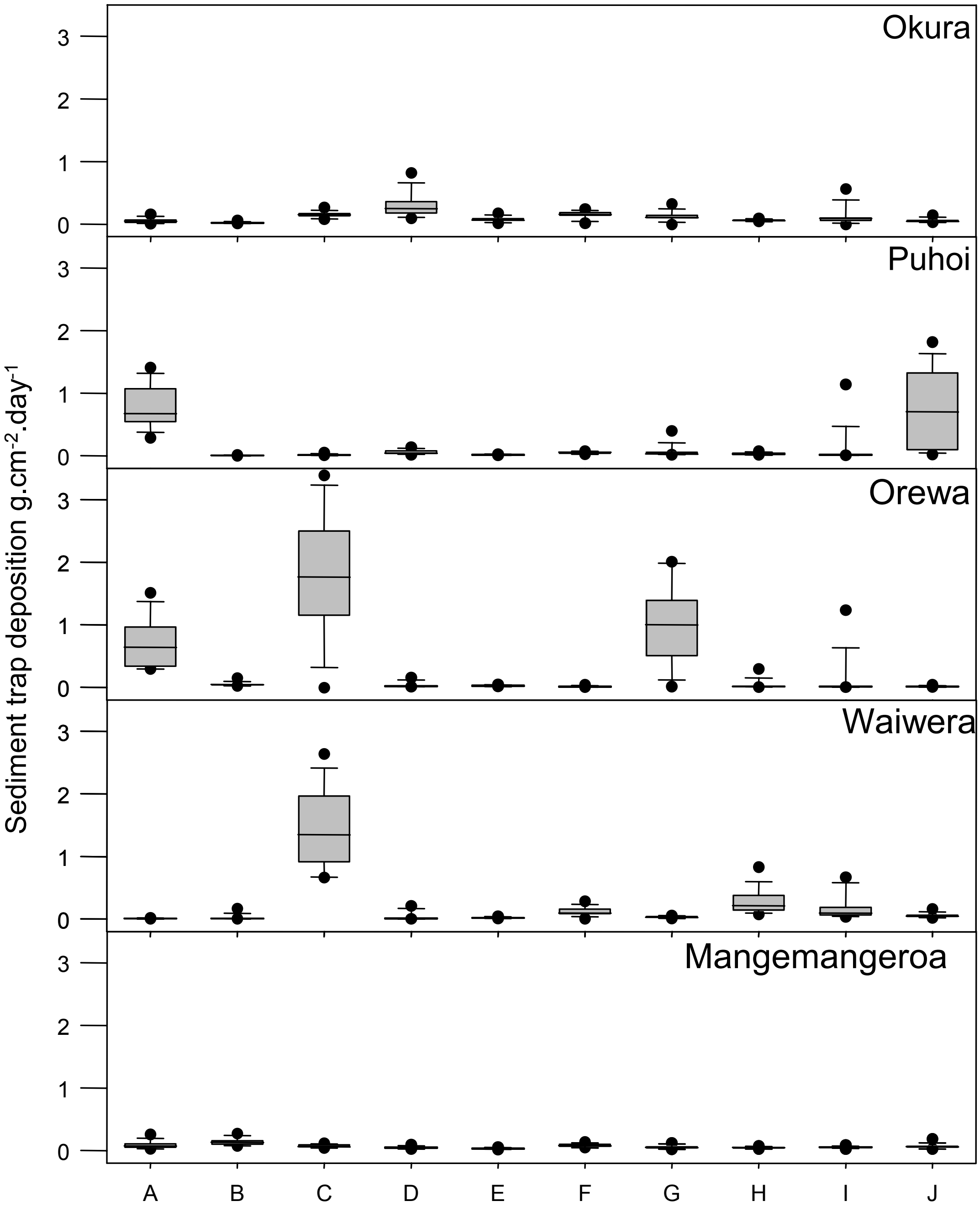

Figure 5. Sediment trap deposition rate at all sites in all estuaries over the sampling period. Sample sizes varied from *n* = 8 to *n* = 11 times.

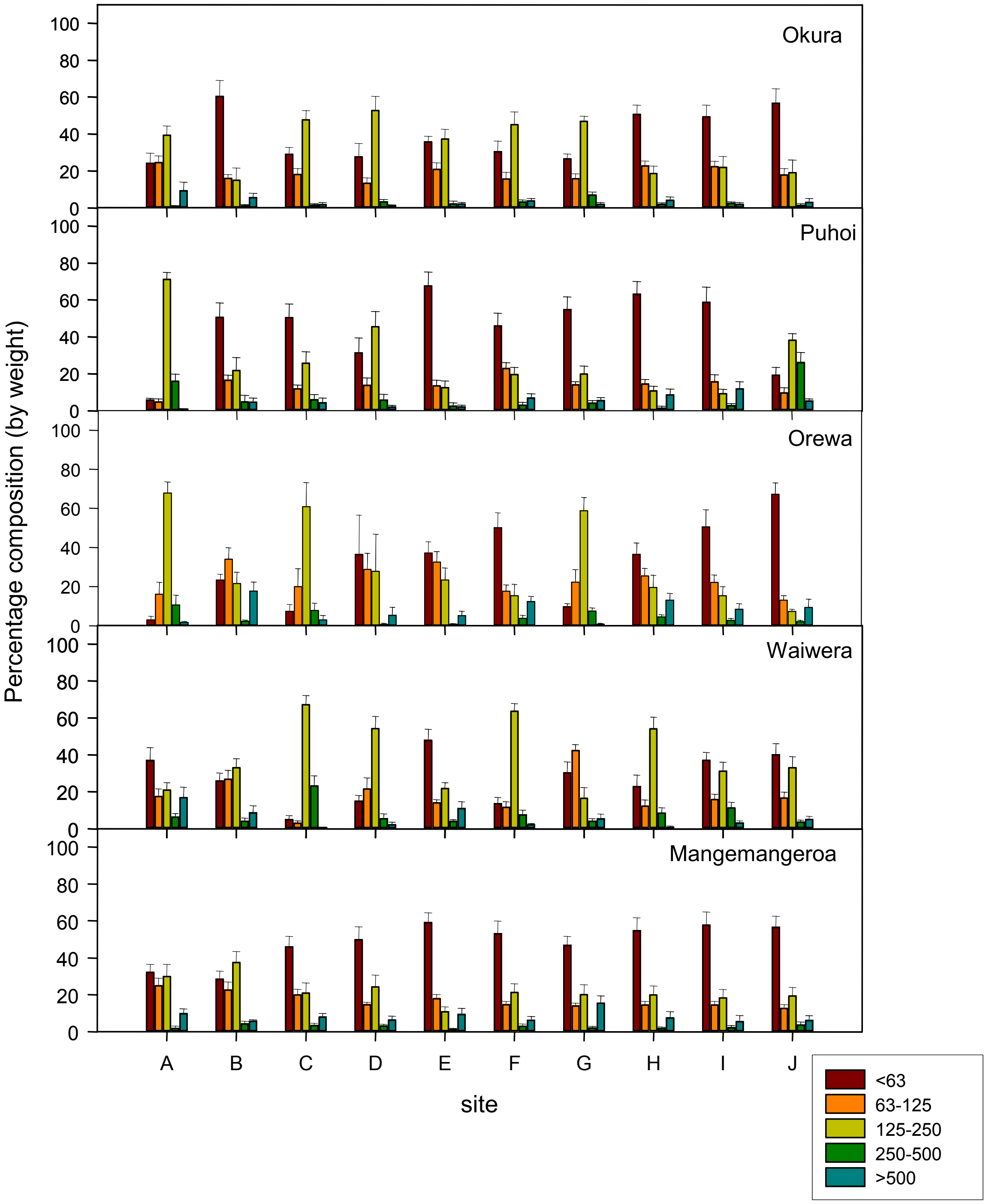

Figure 6. Mean (+S.E.,*n* = 6-10) percentage composition of sediment of different grain sizes collected in traps for all sites in all estuaries pooled over the sampling period.

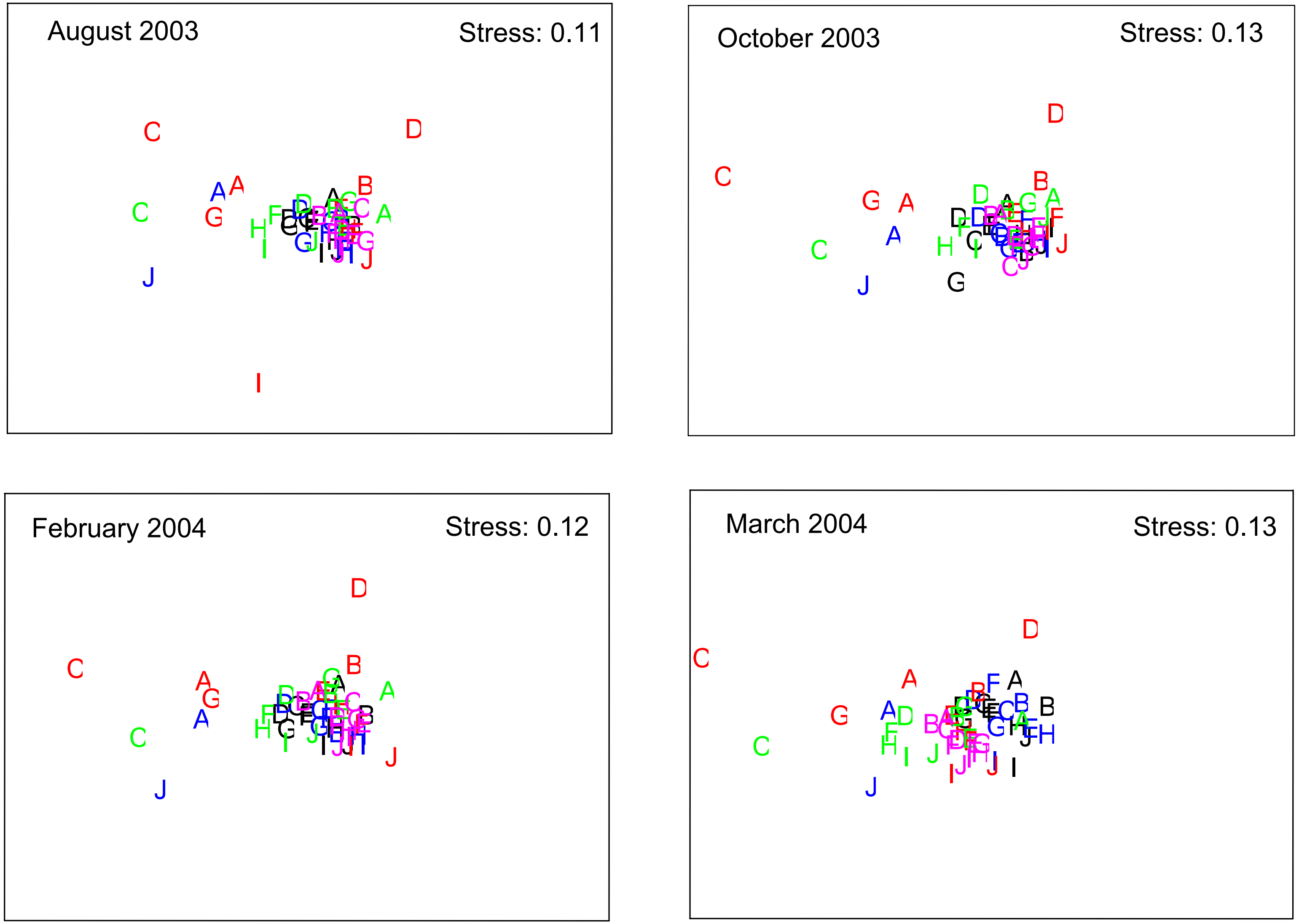

Figure 7. MDS plots of environmental data for all sites in all estuaries done separately for each time. The analyses were based on normalised Euclidean distances. Observations were pooled at the site level (*n* = 6). Sites are indicated by a coloured letter: the letter indicates the site within an estuary (A-J), while the colour represents the estuary, with Blue = Puhoi, Green = Waiwera, Red = Orewa, Black = Okura and Pink = Mangemangeroa.

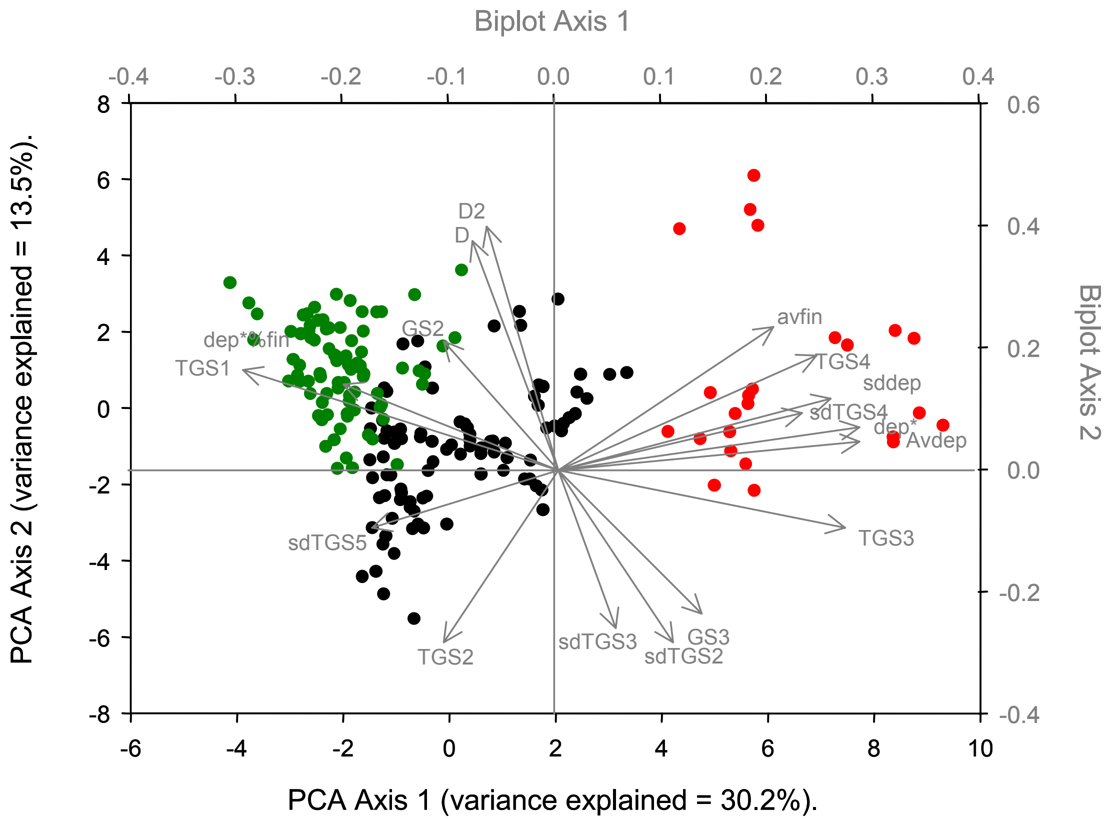

Figure 8. Principal component analysis (PCA) based on the environmental variables with specification of sites as High (dots in red), Medium (dots in black) and Low (dots in green) energy sites. Observations were pooled at the site level. Membership of sites in groups is shown in Table 6. Abbreviations and descriptions of environmental variables are given in Table 2. The axes values in grey relate to the biplot arrows.

Table 5. K-means generated groups of sites having different hydrodynamic energy levels based on the environmental data. The analyses were calculated from normalised environmental data. Observations were pooled at the site level. The numbers below the group headings indicate the number of sites in each group. Numbers in brackets indicate the number of times, out of 4, that each site was classified into that group.

ESTUARIES	High 6	Medium 23	Low 21
OKURA		OA (4) OC (4) OD (4) OE (4) OF (4) OG (4)	OB (2) OH (3) OI (3) OJ (3)
PUHOI	PA (4) PJ (4)	PB (4) PC (4) PD (4) PF (3)	PE (3) PG (2) PH (3) PI (3)
OREWA	RA (4) RC (4) RG (3)	RB (3) RD (4) RE (4)	RF (4) RH (2) RI (4) RJ (3)
WAIWERA	WC (4)	WB (4) WD (4) WF (4) WG (3) WH (3) WI (2) WJ (2)	WA (2) WE (2)
MANGEMANGEROA		ZA (4) ZB (4) ZC (3)	ZD (3) ZE (3) ZF (3) ZG (3) ZH (3) ZI (3) ZJ (3)

3.2. Analyses of biological communities

A list of all taxa recorded (total = 108) and their total counts are given in Appendix B. Plots of the nine numerically dominant taxa (which constitute 67% of the individuals) are shown organised by estuary and site in Appendices G1 to G5.

3.2.a. Patterns with estuary and distance

MDS ordinations of assemblage data at each time (Fig. 9) showed similar patterns to last year (Ford *et al.* 2003c). MDS plots of sites at each time showed clumping of sites (relative similarity among assemblages) within Okura (in black) and within Mangemangeroa (in pink), in comparison to the other estuaries on the plots. The relative similarity among assemblages at sites in the upper reaches of the estuaries (G, I, J) was also apparent, compared to the wider spread of sites A-F and H in the plots.

Assemblage data was plotted on an MDS showing the high, medium and low- energy symbols per site (Fig. 10). Low-energy sites generally showed good separation from medium and high-energy sites at each time. Medium-energy sites were generally biologically intermediate between low-energy sites (left end of plot) and high-energy (right end of plot) endpoints at all times. High-energy sites showed the most variability per number of sites present at each time.

3.2.b. Relating biological data to environmental variables

Permutational distance-based multivariate regression (McArdle and Anderson, 2001) with forward selection was used to determine which environmental variables (Table 2) were best at explaining patterns in the biotic assemblages. These analyses were based on 4 times of sampling for each of 50 sites, for a total of 200 observations. A total of 86 taxa (including groupings of some rarer taxa) were used. The analysis showed that 22 variables together explained 47.55% of the variance in the species data, which was significant (F = 1.79 P = 0.03, Table 6), and an improvement upon last year's percentage variation explained (36.58% Ford et al. 2003c). The variable that alone explained the greatest amount of variation in the species data was the average percentage of trapped fine sediment (<63 μm). The following variables: depfin*, BH*, D2 and GS1 did not have a significant relationship with the species data, when considered after fitting other environmental variables ($P > 0.05$ in each case, Table 6).

The analyses of whole sets of variables are shown in Table 7. The set of variables with the greatest explanatory power was the set describing variability in grain sizes of trapped sediments (TrapsdGS), which alone explained 26% of the variation in the species data. Together with the amount of trapped sediment (TrapGS), this explained 35% of the variance in the biota. In contrast to last year, ambient grain sizes of sediments (AmbGS) were less important, adding only a further 4% to the explained variance (cf. 23% in Table 7 of Ford et al. 2003c). The set of variables describing recently trapped sediment (Trap*), erosion and distance (Dist) were significant, which justified their inclusion in the model, but each only added an extra 1.4 – 1.6% to the explained variance. The sets of environmental variables were strongly correlated with one another, as evidenced by the large decrease in values for %Var between Table 7a and 7b (excluding the first fitted variable). The total variation explained by all variables was slightly greater than that obtained last year (47.0% this year compared to 41.2%

Ford et al. 2003c). This is not surprising, given that more variables were included in the analysis this year and ambient grain sizes were measured at every time of sampling.

To visualize these multivariate patterns, a distance-based redundancy analysis was done to compare the environmental variables to the species data (Fig. 11). The first two dbRDA axes on the plot explained 23.4% of the variability in the species data and 49.7% of the relationship between the species and the environmental variables. The variables that appeared to be most important in driving the environmental-biotic relationship were consistent between the dbRDA analysis (Fig. 11) and the modelling using multivariate multiple regression based on the Bray-Curtis measure (Table 6b). For example, the dbRDA plot showed TGS3, TGS1, dep%fin* and sdTGS4 to all have strong relationships with the species variables. All of these variables were also included as individual variables in the forward selection procedure (above) and indicate that trapped sediments were more important for explaining biotic variables this year than was found last year (compare Fig. 11 here with Fig. 17 in Ford et al. 2003c). Distance (D) and Distance squared (D2) were also strongly correlated with the biotic assemblages, indicating that, in general, low-energy sites tended to occur in the inner estuary and high-energy sites in the outer estuary. Lower-energy sites are therefore characterised by being in the inner estuary and showing less deposition but a higher proportion of fines deposited when compared to high-energy sites.

3.2.c. Estuary-specific effects

We considered that there could be special effects due to individual estuaries that were not taken into account by modelling sites using the measured environmental variables alone. However, after taking into account the variation explained by the environmental variables (47.5%), the variation explained by individual estuaries was only 3.9% (Table 8). Although only a small percentage, this was, nevertheless, statistically significant (Table 8), indicating that there were slight environmental differences among estuaries that were not measured by the environmental variables included in this study.

3.2.d. Relating biological data to environmental groupings

The canonical analysis of principal coordinates (CAP) comparing biological communities from different energy environments was highly significant (canonical correlations were δ_1^2 = 0.621 and δ_2^2 = 0.348, P = 0.001, 999 permutations). More particularly, the analysis showed that communities from low-energy sites were the most distinct (85% allocation success) compared to medium and high-energy sites (having 79% and 67% allocation success, respectively). Thus, distinctions among assemblages from sites having different energy levels were at least two times better than the 33% success that would be expected from a random allocation of sites into three groups. High-energy sites were characterised by relatively high densities of the bivalve *Paphies australis,* the cumacean *Colorustylis* spp. and the amphipod *Waitangi* sp. (Figs. 12, 13). Medium-energy sites were identified by relatively high densities of the bivalves *Austrovenus stutchburyi* and *Nucula hartvigiana* and the anemone *Anthopleura* spp. (Figs. 12, 13). Low-energy sites were distinguished by relatively high densities of the polychaetes of *Psuedopolydorid* complex, Nereid/Nicon complex and Copepods (Figs. 12, 13). Many of these taxa (5/9) were used to characterise the same energy environments in the same ways last year. The other characteristics used to classify medium-energy sites (*Prionospio* sp. and number of taxa) and low-energy sites (*Capitella* sp. + Oligochaetes and *Notomastus* sp.) last year also showed the same pattern this year (compare Fig. 12 here with Fig. 16 in Ford et al. 2003c).

3.2.e. Relating biological data to the environmental gradient

A further investigation of the relationship between the biological communities and the environmental data is provided by considering how well the gradient among the sites obtained using the environmental information alone (as quantified explicitly using PC axis 1 from Fig. 8) relates to patterns in the MDS plot obtained using the assemblage data alone. We examined this using bubble plots, superimposing the values for sites along the PC axis (which represents the environmental gradient from relatively high-energy sites to relatively low-energy sites) onto the biological MDS plot (Fig. 14). If a relationship is seen between environmental and biological data then a gradient of bubble sizes in the MDS plot is likely to be seen. Plots for August, October and February 2003 show an obvious gradient along the x-axis of the MDS plot of smaller bubbles to the left of the plot and larger bubbles to the right.. This trend was less convincing, however, for the March 2004 sampling time, which may have been caused by differences in ambient grain sizes at that time (see Appendix C.4).

Furthermore, a direct canonical analysis (CAP) correlating the biological data directly with the first principal component obtained independently from the environmental data gives a clear picture of the direct response of faunal assemblages to this environmental gradient (Fig. 15). This relationship was reasonably strong, with an R^2 of 0.637, and was highly statistically significant ($P = 0.0001$, 9999 permutations). The plot shows the high-energy group of sites as clearly distinguishable from the medium and low-energy sites, with a bit more overlap between the latter two groupings. The high-energy sites were, however, a bit more scattered about the fitted line of the relationship than either of the other two groups.

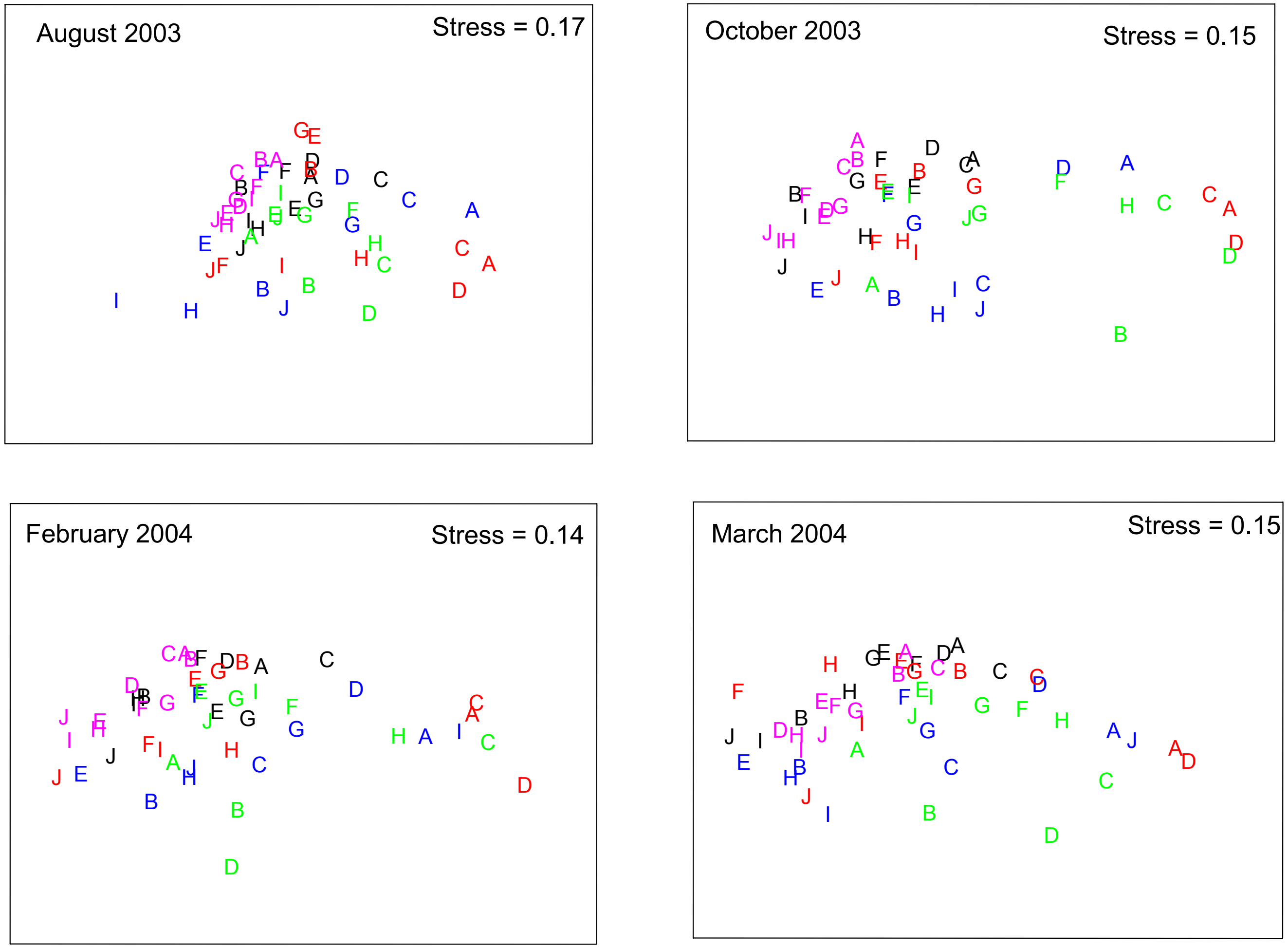

Figure 9. MDS plot of assemblage data from each time of sampling showing estuary and distance information. The analyses were based on the Bray-Curtis dissimilarity measure calculated from *ln* (*y* + 1)-transformed species data. Observations were pooled at the site level (*n*= 6). Sites are indicated by a coloured letter, as in Figure 7.

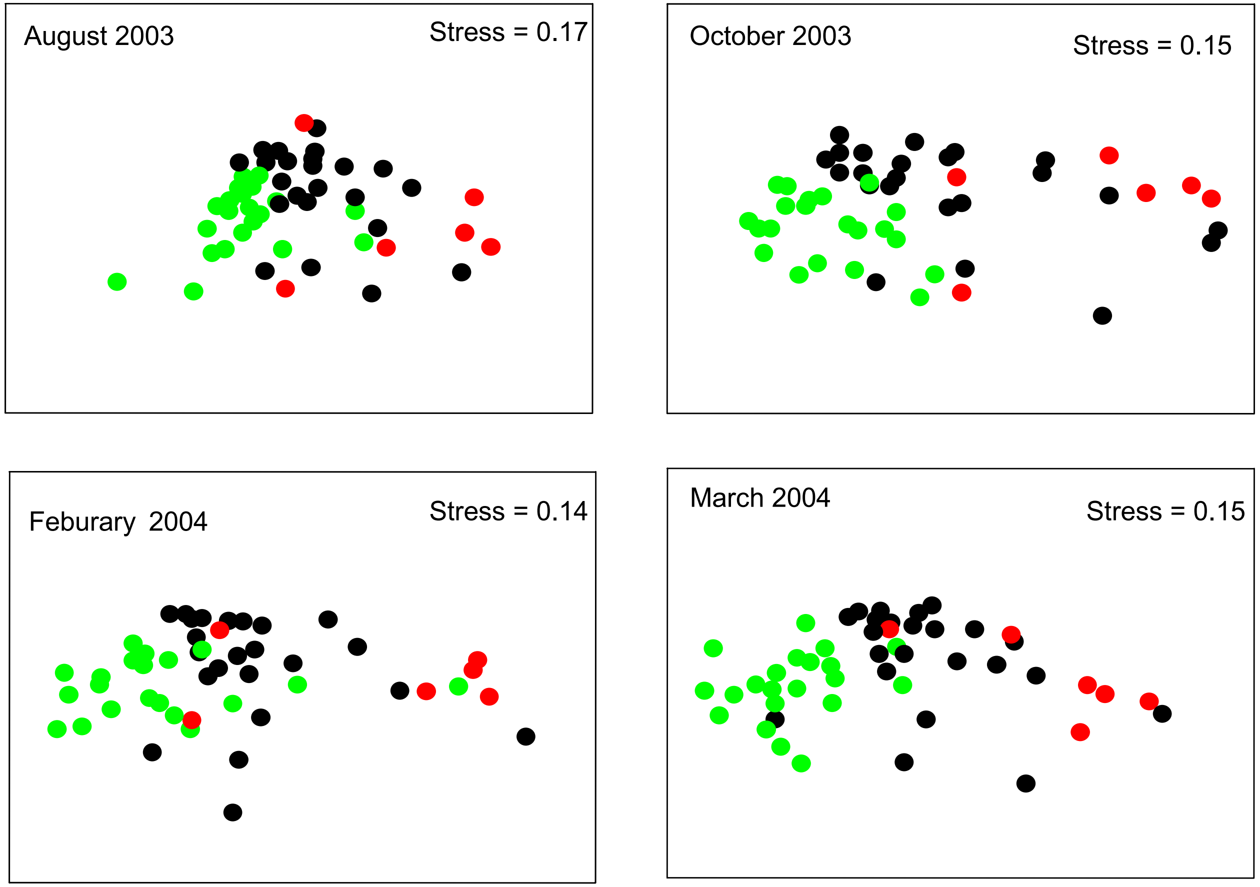

Figure 10. MDS plots of assemblage data at each sampling time showing different hydrodynamic energy groupings (obtained from environmental data). The analyses were based on the Bray-Curtis dissimilarity measure calculated from *ln* (*y* + 1)-transformed species data. Observations were pooled at the site level (*n*=6). High-energy sites are shown by red dots, medium-energy sites by black dots and low-energy sites by green dots.