THE EFFECTS OF DECREASING TRACE METAL CONCENTRATIONS ON BENTHIC COMMUNITY STRUCTURE

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by

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CERTIFICATION OF APPROVAL

I certify that I have read *The Effects of Decreasing Trace Metal Concentrations on Benthic Community Structure* by Michelle K. Shouse, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirements for the degree: Master of Arts in Biology: Marine Biology at San Francisco State University

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THE EFFECTS OF DECREASING TRACE METAL CONCENTRATIONS
ON BENTHIC COMMUNITY STRUCTURE

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The loading of dissolved trace metals (copper and silver) in water treatment plant effluents in South San Francisco Bay have decreased following the passage of the Clean Water Act in 1977, due to the implementation of advanced (tertiary) treatment of wastewater. The present study shows community responses to the decreased loading of copper and silver. An intertidal benthic community near one water treatment plant showed the following shifts in dominant functional groups; (1) increased abundance of subsurface deposit feeders, oviparous species, and species with mixed reproductive strategies, and (2) decreased abundance of species that brood their young. This dataset is remarkable in that it is from a long-term biological study that was conducted coincidently with environmental contaminant monitoring. This study shows a positive ecosystem response to regulatory control of contaminants.

I certify that the Abstract is a correct representation of the content of this thesis.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICIES

INTRODUCTION

Estuaries are complex, dynamic and biotically rich environments that are dominated by physical forces (Day et al. 1989). Beginning at an inlet of the sea, an estuary reaches back into a river valley as far as the upper limit of the tidal rise. Fairbanks (in Day et al. 1989) identifies three regions of an estuary: (1) a marine or lower estuary, in free connection with the sea; (2) a middle estuary that is subject to mixing of salt and fresh water and (3) an upper estuary that is predominantly fresh water, but still subject to daily tidal fluctuations. Most estuaries are characterized by deep channels with strong currents, surrounded by shallow subtidal areas with slow moving waters, all of which is surrounded by intertidal wetlands. Estuaries are areas of dynamic mixing of salt and fresh waters and are subjected to tidal influences. Along the eastern coast of the Pacific Ocean the tides are mixed and semidiurnal, meaning there are two cycles each day (two low and two high tides) with daily highs and lows unequal in height (Conomos 1979), with spring and neap tidal cycles.

Human settlements at or near estuaries have impacted the environment from their beginning. Settlements prospered and grew rapidly and led to increased pressures on the biological resources (Kennish 1998) and alterations in the natural state of the estuary (Day et al. 1989). Alterations in the environment make estuaries vulnerable to introductions, loss of species and habitat destruction. San Francisco Bay is more heavily impacted by anthropogenic activities than most estuaries because of its long history of urban and industrial development, mining along its shores and those of its freshwater inputs, and diversion of its freshwater inputs (Kennish 1998). The impact of the above human activities has increased San Francisco Bay's sensitivity to natural disturbances.

San Francisco Bay has been described as two estuaries (reaches), North Bay and South Bay, which connect to the Pacific Ocean at a region called the Central Bay (Conomos 1979). The northern reach receives 90 percent of the Sacramento-San Joaquin drainage basin water through the Delta (Conomos 1979). This inflow is highly seasonal and is comprised of rainfall runoff during the winter and snowmelt during the spring. The southern reach receives little freshwater inflow in the form of river input. Flows from Coyote Creek, the primary source of freshwater in the South Bay, were reduced with the construction of a dam and a reservoir (late 1940's), except during years with exceptionally high rainfall and runoff in the winter months (Conomos et al. 1985). The South Bay does receive low salinity waters from the Delta during wet winters. During the summer months however, the primary source of freshwater input is from the sewage effluents, which introduce low salinity water at the South Bay's southern boundary (Conomos et al. 1985). Although the two reaches share similar bathymetric features, such as a central boating channel and broad shallows, they have distinct differences in circulation patterns (Walters et al. 1985). The northern reach is a partially well mixed estuary characterized by temporally and spatially variable stratification (Monismith et al. 1996). The southern reach on the other hand, has a sluggish, transient three dimensional circulation giving it the characteristics of a tidally-oscillating lagoon for most of the year (Gross 1997). The distinct differences between the two reaches, in circulation patterns and currents, leads to differences in salinity, suspended sediments and nutrients (Conomos et al. 1985). These physical differences in turn lead to differences in biological communities.

In addition to the physical factors stated above, the presence of trace metals, in the sediment or in the water, can affect benthic community structure in estuaries. Effects on community structure by the presence of trace metals rely on the species-specific tolerances to the metals present (Luoma and Carter 1991). Community structure changes as sensitive species numerically decrease or are removed from the community. This effect is more pronounced when the species removed is one whose presence influences the abundance of other species.

Trace metals are a small portion of the dissolved constituents in estuarine water which is a mixture of river water and sea water. The major constituents of sea water are globally uniform, with the dominant ones being chloride, sodium, sulfate and magnesium (Day et al. 1989). River water on the other hand varies tremendously depending on the local environment. The dominant constituents of river water, based on a global average, are bicarbonate, calcium, silicon and sulfate (Day et al. 1989). River water has been shown to be the source of biologically important compounds that enter the estuary. These compounds are silicon, iron, nitrogen and phosphorous. In addition to being dissolved constituents of estuarine water, trace metals may enter an estuary as particulate material (Day et al.1989). Trace metals occur in very low concentrations, but can have dramatic biological effects in organisms even at normally occurring low concentrations (Rainbow 1993). Some of the dominant, normally-occurring trace metals in estuaries are: boron, silicon, fluoride, nitrogen, phosphorus, zinc, iron, copper, manganese and nickel (Day et al. 1989). All metals are toxic above a threshold of bioavailability (Rainbow 1993). Trace metals are taken up and accumulate in the tissues of benthic organisms most often by diffusion of metals from solution and from food (Rainbow 1993, 1996). Animals deal with the accumulation of metals in two ways (Kennish 1998). They can be considered bioaccumulators in which the metal concentration will be affected by growth dilution, changing concentrations in food or sediment, and their ability to regulate the metal. Or, they can be biomagnifiers in which the metal concentration will be affected by same factors as bioaccumulator, but they don’t regulate concentration of the metal to a maximum. Metals can be metabolically damaging if maintained in a metabolic form (Rainbow 1996). Luoma and Carter (1991) state that the uptake of trace metals in a benthic invertebrate can effect its reproductive processes, feeding rates, respiration, and protein utilization. Reproductive processes show the greatest sensitivity to metals. In addition, metal uptake can also cause morphological abnormalities, and histological problems in adult invertebrates (Luoma and Carter 1991).

Trace metals that have been noted to be of concern in San Francisco Bay are copper, cadmium, mercury, selenium and silver (Kennish 1998). These metals are naturally occurring but have been increased due to anthropogenic affects, such as discharges from wastewater treatment plants and industrial facilities, or as runoff from mine spoils. Their temporal and spatial distribution is heterogeneous as a result of localized inputs and variable physical and geochemical processes.

Inputs of metals, both natural and anthropogenic sources can contribute to a pollution problem where concentrations are considered to be potentially harmful to the ecosystem or to human health. The Federal Water Pollution Control Act (FWPCA), a law, was originally enacted in 1948. This act regulates the anthropogenic portion of pollution activities of the nation's streams, lakes and estuaries because that was the portion most easily controlled. Over the years the law was amended to include federal financial assistance to wastewater dischargers, federal enforcement programs for dischargers and water quality standards in 1965 (Kennish 2000). In 1972 the law was reauthorized establishing the basic structure for regulating discharges of pollutants. In 1977 the law was further amended to form what is now called the Clean Water Act (CWA) (USEPA 2002). The CWA set up programs and goals with deadlines to improve water quality throughout the nation, including the structure for regulating point source discharges of pollutants, focusing on toxic pollutants. Municipal dischargers were required to upgrade their facilities to include secondary treatment of wastewater. Later amendments directed states to include pollution management from nonpoint sources and encouraged them to pursue groundwater protection activities. The amendments to the CWA have advanced as technology advanced initially requiring dischargers to use the best practicable control technology and then later requiring that they use the best available technology. The continued improvements in pollution abatement have moved the nation closer to the goal of zero discharge of pollutants into the waters of the United States.

Improvements in point source discharges since the CWA legislation have led to improvements in water quality of estuaries and coastal waters regardless of the continuing population growth in those areas (Kennish 2000). These improvements include the reduction of contaminant loading from point sources resulting from the tighter federal and state regulations and improved industrial controls. The establishment of the National Estuary Program (NEP) under the U.S. Environmental Protection Agency (USEPA), in 1987 as part of the CWA, provided the structure for conserving and managing estuarine resources

(Kennish 2000). Individual management groups were set up under the NEP to identify and implement solutions to problems identified for estuaries selected. The management group for the San Francisco Bay-Delta Estuary is the San Francisco Estuary Project, which was established in 1987 (Kennish 2000).

Despite the establishment of management boards, very little research links changes in estuaries with point source pollution changes resulting from the CWA. Some research has documented long-term improvements in water quality and sediments, for example, indicating decreasing levels of nutrients, and dissolved metals in estuaries (Sañudo-Wilhelmy and Gill 1999, Hornberger et al. 2000, Morgan and Owens 2001 and Santschi et al. 2001). Changes in individual species may relate to improvements in water quality (Hornberger et al. 2000 and Arvai et al. 2002). However, few studies have investigated long-term changes in entire communities related to improvements in water quality. There has been some research documenting the changes in communities as a result of sediment contamination. Gradients of contaminated sediments have been correlated with patterns of community structure (Roper et al.1988). Copper-treated sediments have been found to impact benthic fauna in various ways depending upon the taxa, when compared to untreated sediments (Morrisey et al. 1996). Sediments heavily contaminated with metals from industrial effluents have been shown to impact intertidal benthic communities (Ahn et al. 1995). The communities present in the heavily contaminated sediments were inhabited by different infauna than previously observed and measurements of species in those sediments revealed high levels of bioaccumulation.

Contaminated sediments affect benthic communities, however, regulatory decisions are often made based on laboratory results on individual species instead of whole community responses. On the one hand, relationships between sediment toxicity tests on organisms in laboratory tests and the abundance and diversity of organisms in field research indicate a high degree of correspondence between the reduced survival of amphipods in laboratory toxicity tests and the reduced abundance and diversity of benthic infauna in the field (Long et al. 2001). However, the responses of estuarine communities to improvements in water quality can take place over long periods of time. Therefore, the use of long-term datasets is critical to support laboratory toxicity tests for water quality management and regulatory decisions. Verification of laboratory obtained results with field research should be an important part of the management and regulatory processes.

Patrick and Palavage (1994) used long-term data to compare species abundance and species diversity changes as a result of the CWA in estuaries. They found it was impossible to compare data through time due to differences in collection methods. They suggest that researchers consider the pollution tolerance of a species, and compare ratios of pollution tolerant species to species characteristic of non-polluted waters. The use of the ratio will allow for comparisons of community response to water quality improvement through time.

Relative abundance of species and species diversity are common methods of exploring changes in community structure using spatial data (Morin 1999). However, the applications of these techniques to complex systems, such as estuaries, over long periods of time, do not always produce clear results. The methods used to determine community response to stressors should be guided by the question of interest, the scales relevant to the question, and the nature of the variability that affects the stressor and the response variables (Luoma et al. 2001).

Study Area

The site of the present study (Figure 1) is located on the Palo Alto shoreline in the southern reach of San Francisco Bay, approximately 1 km south of the point of discharge of the Palo Alto Regional Water Quality Control Plant (PARWQCP). The tides in the South Bay are affected by the bathymetry of the local area, with tides being stronger in the deep central channel and weaker in the broad shallow shoals (Conomos 1979) and are the strongest advective force in the South Bay (Thompson 1999). The area is characterized by a moderate climate that varies from west to east, a coastal climate with a small annual variation in temperature to an inland climate with large annual variation in temperature. The interaction of the maritime and continental air masses are responsible for the seasonal weather patterns as well contributing to the circulation patterns in the South Bay (Conomos 1979).

South San Francisco Bay is heavily influenced by wind, especially during the summer months. The winds in the winter are typically consistent in direction, from the east to southeast. However, in the summer, the winds are normally from the west to northwest and there is no rain. Summer winds are increased over those in the winter due to elevated differential between the continental temperatures inland and the oceanic temperatures. The high summer winds interact with the surface of the water, creating waves. The waves serve to oxygenate the water, resuspend sediments and set up wind driven circulation (Conomos 1979). The flow patterns created by the winds supplement the circulation patterns set up by density differences brought about by estuarine circulation as stated. High winds in the summer also increase evaporation in the South Bay, contributing to the high salinities during the summer in the surface waters (Conomos 1979).

As mentioned above, the South Bay currently receives very little freshwater input from natural sources except during extreme winter storm events when fresh water is imputed from local creeks and marshes (Conomos 1979 and Thompson 1999). High flows of $1100 m^3/sec$ or greater from the Delta can reduce the salinity in the South Bay (Thompson 1999). However, these pulses of freshwater are rapidly mixed out of the area. During dry winters and summers, the only source of freshwater to the South Bay is from the local waste water treatment plant effluents. Therefore, the constituents of their effluents greatly affect the water quality of the South Bay.

The PARWQCP influences the study area (Thomson et al. 1984). It completed upgrades to the facility in 1972 to include secondary treatment of wastewater, following the reauthorization of the FWPCA. By 1978, the facility had upgraded to tertiary treatment, which included fixed film reactors and dual media filters. These upgrades gradually decreased the concentrations of dissolved metals in the effluent, while the volume of the effluent remained relatively constant (Figure 2) (Hornberger et al. 2000). Another large waste water treatment facility in the South Bay, San Jose/Santa Clara Water Pollution Control Plant upgraded to secondary treatment in 1964, followed by an upgrade to tertiary treatment in 1979. Together, the two water treatment plants provide the southern end of South San Francisco Bay with the majority of its freshwater input (Hagar and Schemel 1996).

Monitoring of the PARWQCP wastewater effluent has shown decreases in copper (Cu) and silver (Ag) concentrations (Hornberger et al. 2000). Copper concentrations in surface sediments decreased by half between 1977 and 1998, while silver concentrations decreased by three-fold during the same period. In addition, concentrations of the metals (Cu and Ag) were monitored in the tissues of the clam *Macoma balthica*. Results found by Hornberger et al. (2000) show a strong trend of declining concentrations from the 1970's through 1991. Bioaccumulation of the metals correlated significantly with concentrations of the metals in the sediment and with the declining metal loads from the local wastewater treatment plant. Uptake of the metals into the tissues of *M. balthica* affects the reproductive output (Figure 3) of the clam, demonstrating that as metal concentrations decreased reproduction increased.

Historical benthic community information from the local environment is sparse. The majority of research on estuarine benthos is from the east coast of the United States or from Europe. However, recent work in South San Francisco Bay, has provided some community knowledge as well as for individual species. Nichols (1977) investigated the biomass and production of mudflat infauna at the same site of the current study. His results showed that the total biomass of the infauna showed little variation between seasons and that bivalves dominated it. He speculated that the dominance was due to the abundance of food for the bivalves and the high amount of disturbance due to resuspension of the sediments, contributing to the transport and mortality of smaller and more fragile species. Nichols and Thompson (1985a) found the same community to be persistent over a 10 year time scale. Fluctuations in total community abundance were found to be within finite bounds with no clear long-term trends. It was found to be persistent due to the domination of the community by opportunistic species whose rapid response to disturbances were on the same time scale as the disturbances themselves. They also noted that the number of species in the present community was lower than similar communities throughout the United States. This was thought to be predominantly due to the availability of only a few potential colonizing species in the Bay and the soft mud substrate that is inhabitable to only a select number of species.

Two species, both of which are bivalves, from the present mudflat have been studied in greater detail, *M. balthica* and *Gemma gemma*. Nichols and Thompson (1982) compared the growth of the population of *M. balthica* in San Francisco Bay, the southern limit of its' range to populations in the higher latitudes. Their results revealed that the populations of *M. balthica* in San Francisco Bay are faster growing than in other locations, but the growth is controlled by temperature, as in other locations. The consequence of their rapid growth appeared to be animals that are narrower, with thinner shells. Results additionally showed that the spawning in the population occurred in the winter during periods of the coldest water temperatures. Growth of the *M. balthica* populations were further explored by Thompson and Nichols (1988) focusing on several sites within San Francisco Bay by comparing growth rates with that of chlorophyll *a* concentrations in the sediment and in the water column. Results showed that temperature remains a controlling factor in the growth of *M. balthica*, but that food availability is also a controlling factor. The growth of *M. balthica* was correlated to chlorophyll *a* concentrations (either benthic or planktonic or both) as well as tissue-weight changes, but varied among locations and months and years. There is currently some discussion regarding the species of *Macoma* in San Francisco Bay. Cohen and Carlton (1995) identify the current species as *M. petalum*. For the purposes of this study the synonym of *M. balthica* will be used to represent the species of *Macoma* in South San Francisco Bay.

The population structure of the clam *G. gemma* was investigated by Thompson (1982) and compared to populations on the eastern coast. Results showed that San Francisco Bay populations are very successful. Their success was related to the warm climate allowing for longer periods of reproduction, which in turn provides more recruits into the population, than populations in found in northeastern United States. Findings of the study additionally showed water-borne transport to be important in dispersion of animals into new areas. Results also demonstrated that competition with the bivalve *M. balthica* was important in controlling population size. Weinberg (1985) performed an investigation of the population structure of *G. gemma* on the northeastern coast of the United States. Results showed that the population cycled annually and was controlled by intraspecific competition between juveniles and adults and by low salinities that reduced the numbers of juvenile survivors. Additionally, it was thought that predation affected their size and structure.

In addition to research on benthic communities and some of the animals that inhabit those communities, there is also some information available on their food resources. A majority of the animals that have been shown to inhabit the present community are either filter feeders, removing food particles from the water column, or deposit feeders, removing food particles from the sediments. Measurements of chlorophyll *a* provide an indication of the amount of both water column phytoplankton and benthic microalgae concentrations. Cloern et al. (1985) investigated the temporal dynamics of the phytoplankton community in the South San Francisco Bay. They found that phytoplankton biomass was low in the South Bay, falling short of calculated totals based on measured growth rates. The low levels of biomass were attributed to the high biomass of suspension (filter) feeding benthic bivalves in the area, which were thought to consume phytoplankton at a rate that was equal to the phytoplankton growth rate (from Cloern 1982). This was supported by the result that phytoplankton blooms did occur when the water was stratified, entrapping all of the algae in the surface layers, away from the benthic grazers (Cloern 1985). Thompson and Nichols (1988) measured benthic microalgae concentrations in the South Bay and found low levels of benthic chlorophyll *a*, similar to the low levels found in the water column of the previous study. Their results showed that the bivalve *M. balthica* in the South Bay utilized the planktonic source of phytoplankton over the benthic source. These results support the hypothesis that the benthic filter feeders are a major consumer of phytoplankton.

Previous work in the intertidal communities of South San Francisco Bay has provided general descriptions of the animals that live there and their food resources. It has been established that the communities are affected by natural disturbances in the environment. Also established is the lessening of a chronic stressor in the community (i.e. trace metals). The affect of lessening stressors on benthic communities is not so readily established.

The purpose of the present study is to explore trends in the benthic community data from a mudflat in South San Francisco Bay and relate the trends to decreasing trends observed in trace metal concentrations from the same area. This will be accomplished by using a seasonal benthic community timeseries, which spans over 16 years. The community data will be compared to a decreasing trace metal contaminant timeseries, spanning over 13 years, that is coincident to the community data. Decreasing trace metal loading from the local wastewater treatment plant coincides with the decreases observed in the trace metal data set.

Through the exploration of multiple community analysis tools, I will show how the community structure has changed as a function of time. More specifically, community change will be shown as changes in individual species abundances and as changes in the dominance of functional groups within the community.

METHODS

Environmental Data

The environmental data used in the present study were collected from a variety of local resources. The types of environmental data collected, their location, time period covered, frequency and source can be seen in Table 1. Several of the data types are represented twice in the data set, representing different sources. USGS Water Quality data used in the dataset are a combination of two South San Francisco Bay stations (Station 36 and 30, see Figure 1). Station 36 is closest to the benthic community sampling site, but is sampled less frequently than Station 30. Therefore, data from Station 30 were combined with Station 36 to create a more complete set of water quality data. Cross-correlation analyses of the environmental parameters using Pearson Pairwise Correlation in Systat (Version 10) were conducted to determine similarities between variables (Appendix 1), and to facilitate interpretation of future correlations between the environmental variables and the benthic community data.

The frequency of collection for the different types of environmental data varied within years. Therefore data were summarized into quarterly means to allow for comparison with the community data, using the Basic Descriptive Statistics option in Minitab (Version 12). This process created a three month running mean for each environmental variable, as well as a minimum, maximum, and standard deviation for each quarter. Hypotheses were established for each environmental variable (Table 2) as to how changes in that variable would affect the benthic community. From the hypotheses, summary statistics for each variable were chosen for analyses with the benthic community data.

Community Data

Data Collection

The community data used in the present research were collected by USGS from two intertidal stations (St. 45 & St. 46). Data span from February 1974 to December 1984 and then from February 1989 to March 1990, and contain a variable number of replicates (hauls) per sampling date (Table 3). Samples from 1974-1984 were collected and sorted by USGS. Samples from 1989-1990 were collected and stored by USGS, but sorted by the author.

Samples were collected using two different sizes of cores. The majority of the samples were collected using 57 cm^2 diameter cores (standard cores) to a depth of 20 cm. These samples were divided into two 10 cm deep portions when extruded from the core for ease of sorting. Other samples used for analysis were collected using rectangular cores (can cores) measuring 16.5 x 10 cm to a depth of 23 cm (see Table 3 for dates used). All samples were washed on 0.5 mm screens, and then fixed in 10% buffered formalin in seawater for a period no shorter than 2 weeks. For storage and sorting, the samples were transferred to 70% ethanol and stained with Rose Bengal. Additional descriptions of the sampling methodology can be found in Nichols (1977) and Nichols and Thompson (1985a). Samples were sorted and individuals were identified, down to species when possible, and enumerated. In the case of annelids and amphipods, animals were enumerated only if the anterior end was present. USGS researchers that identified the 1974-1984 taxa verified taxonomic identifications by the author. Due to the varying frequency of benthic sampling, the present analysis utilizes quarterly data, when available, to provide a consistent timeline.

Data Treatment

Before beginning to manipulate the data, it was necessary to standardize the size of the samples taken by the two different types of cores. This was done by multiplying the can core species abundances by 0.344 (the ratio of the surface area of the standard cores to the surface area of the can cores). Corrected can core data were then combined with the standard core data for analysis.

Data for both stations (St. 45 & St. 46) were summarized using the Basic Descriptive Statistics option in Minitab. Species abundance data from replicate samples for each sampling date were averaged. Dates without replicates were reported as raw species abundance. For both stations, total animal abundance and species richness (the number of taxa present) were calculated for each sampling date. Station 45 data were used for comparison with the environmental data because this station is nearest to the trace metal contaminant collection site.

Station 46 data were used to verify species trends found in the St. 45 data. Species abundances for St. 45 were cross-correlated using Pearson Correlation analysis to identify relationships between species and to facilitate interpretations of future analyses (Appendix 2).

Initial data analysis was conducted using cluster analysis in Statistica (Version 5.5). Cluster diagrams for each station were created from a Bray Curtis similarity matrix (Equation 7.57, Legendre, P. & L. Legendre, 1998) using an unweighted pair-group average. The cluster diagrams, using winter and summer data, were used to explore similarities between sampling dates as well as similarities in species abundance distributions. Rare species (species consisting of less than 1% of the total abundance over the entire study period) were eliminated from the analyses to allow patterns of association to be more easily observed.

Changes in community structure were explored in two ways using species rank and abundance data. Species diversity indices, Shannon Weiner Index (Equation 6.1, Legendre, P. & L. Legendre, 1998), were calculated using all seasonal data and for each season (St. 45 only). Species for each sampling date at St. 45 were ranked in descending order based on the log (n+1) of their abundance. By plotting the abundance of the top 10 species versus the ranking for each species, changes in community structure through time could be explored. The changes observed were verified by comparing species abundances between years through the use of chi square analysis. The abundances used in the analysis were combined totals, summed from seasonal data for the particular years.

To investigate possible community patterns, the species from St. 45 were combined into functional groups. Four groups were established: feeding type, habitat type, reproductive type and barrier type. Feeding types were based on the method of feeding utilized by the organism and the location of their feeding; filter feeder, mixed feeding species, deposit feeders and carnivores. Physical location within the sediment determined the habitat type; burrowers, tube dwellers and surface dwellers. The reproductive types were based on where the larvae developed; brooders, spawners, oviparous and mixed reproductive species. The type of exterior protective covering of the organism determined the barrier type; tissue, calcium carbonate ($CaCO^3$).

The functional groups were cross-correlated using Pearson Correlation analysis to elucidate any group interactions. The groups were also used to investigate the possible relationships with the environmental data. The relationships were tested by Pearson Pairwise Correlation analysis using Systat (Version 10). Functional groups, along with total animal abundance and number of taxa, for each sampling date were compared to the environmental data using correlation analyses. Functional groups were combined to create multi-dimensional functional groups (e.g. brooders that are deposit feeders, burrowers that are oviparous, tube dwellers that have a chitin barrier, etc.) and compared to the environmental data to explore effects of the environment on species with two functional group traits in common that might lend them to more exposure to the elements.

RESULTS

Environmental Data

Strong seasonal and inter-annual differences in salinity were seen with all salinity data examined (Figure 4), reflecting the increase in freshwater flow in winter and spring of each year and the longer time-scale flood and drought events. Delta outflow (mean daily flow of water past Chipps Island to San Francisco Bay) was compared to two different sources of salinity data, water found inside *Macoma balthica* collected at a nearby site and water collected by USGS South Bay water-quality program in the nearby channel (Figure 5). A visual comparison of the salinity measures and the volume of delta outflow show a strong negative relationship, with maxima in delta outflow occurring with declines in salinity. The delta outflow data are reported daily, producing an extensive data set, and thus are not statistically comparable to other environmental variables reported as monthly data. Based on visual inspection, I will assume the relationship is strong enough to allow the use of salinity in further correlations as the measure of freshwater input to the study area. There is a strong positive correlation between the two measures of salinity (Pearson $r=0.835$, $p<0.001$). Local precipitation measurements were compared to salinity (based on USGS water-quality data) and clam water salinity showing a significant negative relationships, Pearson $r=-0.435$, $p<0.001$ (Figure 4), Pearson $r=-0.405$, $p<0.001$ respectively.

Water and air temperature, like salinity, showed a strong seasonal pattern with peak temperatures occurring in mid to late summer and minimums occurring in winter, but there was less inter-annual variation in these data than in salinity. A comparison of air temperature and water temperature (Figure 6) shows a tight correlation ($r=0.947$, $p<0.001$).

Calculated chlorophyll *a* was used as a measure of the biomass of phytoplankton present in the water column (Figure 7). Seasonal fluctuations are seen, as well as bloom events (measurements of >10 mg/m^3 in the South Bay) each spring, with abnormally large blooms occurring in 1980, 1983, 1985, 1986 and 1988. Baseline, or non-bloom chlorophyll a values have remained consistent (1-2 mg/m^3) throughout the study period.

The percentage of total organic carbon in the mudflat surface sediments, as analyzed by Hornberger et al. (2000), reflects all organic carbon in the sediment (Figure 8). Thus, it is not a measure of bioavailable carbon, which is likely to have much lower concentrations. TOC is seasonal, low in the summer months, presumably due to less input/runoff from freshwater sources. The TOC has remained relatively stable through time.

The water treatment plants measure biological oxygen demand (a measure of the potential oxygen to be removed from the water column by bacterial action on organic matter). The BOD data used for analyses in this study (Figure 9) are from the San Jose/Santa Clara Water Pollution Control Plant

(SJ/SC WPCP) that produces 80% of the wastewater volume into the lower portion of South San Francisco Bay (Hagar, S.W. pers. comm.). A dramatic drop in BOD is seen in January 1981 following the implementation of tertiary treatment at the facility. Prior to 1981 the seasonal peaks and annual minimums in BOD had been increasing. Following the change in treatment methods, BOD has remained low and very stable.

Trace metal data copper (Cu) and silver (Ag), as reported by Hornberger et al. 2000) from the study site have been reported as concentrations of the metals in the sediment as well as in the tissues of the clam *M. balthica*. A comparison of the time series data for Cu shows a general similarity between the concentration of trace metals in the sediment and uptake of Cu into the tissues of the clam (Figure 10); this similarity is reflected in a significant correlation between the two variables ($r=0.451$, $p<0.001$). The trends in these data are similar initially, increasing in concentration through the late 1970’s, then decreasing in the early 1980’s. But in 1988 the decreasing trend in the sediment concentration ceases and levels out, while the concentration in the tissues of the clam continues to decrease. A trend of increasing initially then decreasing, is also seen when comparing the same two measures of Ag concentrations (Figure 11). The Ag concentration in the tissues of the clam follows the concentration seen in the sediment up to 1987 when the sediment Ag concentration data stopped being collected. There is a strong correlation between the two measures of Ag ($r=0.413$, $p<0.001$) during the period prior to 1987.

Community Data

Total animal abundance per sampling date through time has decreased at both stations (Figure 12). The decreasing trend (demonstrated by the linear trendline) was stronger for Station 46 than for Station 45. The communities were markedly different in their abundance at the beginning of the dataset. Following a dramatic drop in abundance in 1975, due to the anaerobic conditions created by the decay of a mat of macro-algae on the mudflat in August (Nichols and Thompson, 1985), the communities slowly recovered, and maintained similar abundances and similar seasonal patterns until 1979. Following 1979, the seasonal patterns were not as consistent between stations. Despite the differences between the two stations, a regression reveals ($R^2=0.562$, $p<0.001$) the data are mostly coherent.

The timeseries of the number of taxa present for each sampling site begins with an increase following the first year, 1974 (Figure 13). There is a slight decrease, or alteration of the normal seasonal pattern in 1975 due to the presence of the algal mat, as mentioned earlier. The fluctuations in the data are irregular throughout the timeseries, demonstrating no patterns or trends. Both stations follow a similar pattern with St. 46 initially showing more extreme increases and decreases in the timeseries ($R^2=0.3356$, $p<0.001$).

Similarities in the structure of the benthic communities throughout the study period at Stations 45 and 46 were explored using Cluster Analysis, which incorporates species presence/absence data and total animal abundance data into one analytical tool. Cluster tree-diagrams show the level of similarity between the variables being tested, with shorter linkage distances demonstrating a greater degree of similarity. Clustering of sampling dates for St. 45 reveals several organizing factors for the benthic community that control similarity (Figure 14). The first branch in the tree isolates two dates (Jan 1976 and Aug 1974), which were periods of extremely low abundance of all species, from the rest of the dates. The second branching separates two large groups, one set of dates has low abundance of the bivalve *Gemma gemma* (the group on the left) and the other set has high abundance of *G. gemma* (the group on the right). Sub branches within these large groups cluster sampling dates by season or wet and dry years. An example of these groupings can be seen in the cluster for St. 46 (Figure 15). The cluster containing March 1979 through March 1978 are all winters, and the cluster containing August 1976 through August 1979 are all summers, and the cluster containing March 1980 through February 1974 are all wet winters with high Delta outflow. There are several instances where a drought winter community is grouped with a summer community. At St. 45 the cluster containing August 1984 through February 1989 is summer or drought winter sampling dates. At St. 46 the cluster containing August 1989 through January

1976 are summers or drought winters. Branchings within the more related dates are driven by the abundance of other numerically dominant species.

Similar patterns of branching can be seen in the cluster tree diagram for St. 46 (Figure 15). Two dates branch off first (Feb 1989 and Aug 1983), again, periods with extremely low abundance overall. The second point of branching again separates dates with low *G. gemma* abundance (on the left) from a group of dates with high *G. gemma* abundance (on the right). Similar to the cluster tree diagram for St. 45, additional clusters are driven by the amount of freshwater entering the system and differences in the dominant species present in the community.

Temporally consistent species relationships were also found in the community. At St. 45, the first branching isolates the three species (*Streblospio benedicti, G. gemma* and *Ampelisca abdita*) from the remaining species (Figure 16). Isolation of these same three species is also seen at St. 46 (Figure 17). Overall St. 46 has fewer dominant species (rare species were removed from the analysis, see Methods) defining the community than at St. 45. Similarities did occur between the station species clusters. *Heteromastus filiformis* and Oligochaeta spp. also cluster at both stations. The crustaceans *Corophium* spp. and *Grandidierella japonica* are in their own separate group at St. 45, whereas *Corophium* spp. stand alone at St. 46.

There were 29 species present throughout the timeseries at St. 45 (Table 4). Of the species present, 48% were annelids, 24% were arthropods, 24% were molluscs and 4% were cnidarians. Introduced species dominate the community (Cohen and Carlton 1998). The bivalve *M. balthica,* a cryptogenic species, was the only species present that is not clearly identified as an invasive species (Cohen and Carlton 1995). The most abundant species throughout the time series were: the filter feeding, burrowing bivalve *G. gemma*; the filter feeding, tube dwelling amphipod *A. abdita*; and the surface deposit feeding, tube dwelling polychaete *S. benedicti* (Figure 18). These three species account for 80% of the total animal abundance in the timeseries. The abundance for all three species peaks late 1976 or early 1977 following low abundances, they then display seasonal fluctuations, with no apparent long-term trends.

A few of the species that make up the remaining 20% of the total animal abundance did show trends. The species *Corophium* spp. seems to show a decreasing trend in the seasonal peaks (Figure 19) at the beginning of the timeseries, ending in extremely low abundances. Other dominant species (species consisting of greater than 1% of the total abundance over the study period), *Grandiderella japonica*, *M*. *balthica,* and *Eteone* sp., demonstrated seasonal patterns, but also lack trends through time (Figure 19). Trends were exhibited by two other dominant species, the subsurface deposit feeding burrowers, Oligochaeta spp. and *Heteromastus filiformis*. These two species

(Figure 20) show an increasing trend through the data series (for FN 45), especially in the case of *H. filiformis*. One species, a cumacean (a small arthropod), was omitted from the data set due to its' small size and shape relative to the size of the screen used for sorting. The size of the cumaceans that were enumerated by the author was inconsistent with those enumerated by USGS previously. Therefore, the species was removed from the current dataset.

Changes in community species diversity throughout the study period were explored by calculating a diversity index for each sampling date at St. 45. The results showed seasonal fluctuations and no trend (Figure 21). The indices were sorted by season to better reveal trends. Fluctuations in diversity were still present throughout the timeseries for each season, and no trends became evident (Figure 22).

Station 45 data from 1977, prior to the implementation of tertiary treatment in South San Francisco Bay, were compared to data from 1989, after tertiary treatment began. These two years were chosen for comparison because both years are considered to be dry years with antecedent dry years, and thus salinity, shown to be an important organizing variable in the time-series cluster analyses is likely to be similar in magnitude and seasonality. Rank abundance curves were created using winter and summer log (n+1) abundance data for 1977 and 1989. Comparison of the winter months for each year reveals two distinct curves (Figure 23). The curve for the 1977 winter community was dominated by a top ranked species (number one) followed by a logarithmic decline in species two, three and four. The remaining six species had similar abundances. The initial slope of the curve reflects the dominance in abundance of the top four species. The curve for the 1989 winter community is a shallower curve reflecting a community that was composed of species more equal in abundance than in 1977. The 1989 community was dominated by two groups of similar abundance, ranks 1 through 5 and ranks 6 through 10.

The comparison of the curves for the summer months of 1977 and 1989 shows similar differences between years (Figure 24) as seen in the winter data. The curve for 1977 summer was highly dominated by the three most abundant species. The remaining seven species had relatively similar abundances, slightly decreasing through the ranks. The top two ranked species for 1989 slightly dominated the community, followed by similar abundances of ranks 3 through 6, then followed by lower abundances of species ranked 7 and 8 and then 9 and 10. The step function of decreasing abundances in the 1989 curve produces a flatter curve than was seen in the summer of 1977.

Comparing the two seasons of 1977 reveals that abundances in the summer months were much greater for all species displayed. The summer community, in 1977, was more highly dominated by the top three species than was seen with the top four species in the winter. The curve for winter is smoother than the curve for summer of 1977. A comparison of the two seasons of 1989 shows the summer and winter curves as equally shallow: the community is dominated by six species followed by decreasing abundances of the remaining four species. There is a slight difference in the abundance of species, higher in the summer, but not as dramatic as that seen in 1977. Additionally, there is a bit more dominance of the first two species over the species ranked three, four five and six.

The rank abundance for all seasons is compared using data from 1976 and 1989. Data for 1976 (also a dry year) was used to allow for all four seasons to be compared to those of 1989. The curves for winter and summer of 1976 were similar to those of 1977. Data for 1977 consisted of only two seasons (winter and summer) but was chosen for the prior analysis due to the increased time it allowed the community to recover from the die off resulting from the algal mat decay that occurred in August of 1975. The 1976 curves show significant differences between the seasons (Figure 25). The summer had the highest abundances, and a smooth curve. The curve decreases gradually through the top 10 species. The second highest season for abundance was fall. The fall curve shows a steep decline initially, dominated by the first two species, followed by a gradual decrease in abundance through the rest of the species. Winter and spring have curves that are equally low in abundance and less steep than the other two seasons. The winter and spring curves show no dominance of species, with a gradual decrease through the rank of species.

The comparison of seasonal rank abundance curves for 1989 reveals much more similarity between seasons (Figure 26) than was seen in 1976. The fall community is numerically dominant, followed by spring, then summer and then winter. The curve for fall is initially steep (but much less so than seen in summer or fall of 1976), for the top five ranked species, then drops down to a lower abundance for the remaining five species. The spring rank abundance curve shows dominance by the top ranked species, followed a plateau at ranks two, three and four, and a gradual decrease through the remaining six species. Two species slightly dominate the summer community, followed by equal abundances of ranks three through six, and a much lower abundance for the remaining four species, decreasing through the remaining ranks. Overall, the 1989 curves showed less seasonal differences and little domination by a few species than was seen in 1976.

Chi square analysis revealed similarities and differences between the 1977 and 1989 summary statistics (total animal abundance and number of taxa present for each sampling date) and species abundance data (Table 5). Significant increases abundances of Oligochaeta spp. (21.33 vs. 94.66 mean #/57cm^2), *H. filiformis* (6.33 vs. 43.33 mean #/57cm^2), and *Eteone* sp. (9.32 vs. 22.66 mean #/57cm^2) were seen from 1977 to 1989. There was a significant decrease in the total abundance of animals present from 1977 to 1989. Lower abundances in 1989 for *G. gemma* (548.33 vs. 89.66 mean #/57cm^2), *S.*

benedicti (403 vs. 38.32 mean #/57cm^2), *A. abdita* (242.33 vs. 48.33 mean #/57cm^2), *G. japonica* (20.33 vs. 0.66 mean #/57cm^2), *Odostomia* spp. (18.33 vs. 3.99 mean #/57cm^2), and *N. succinea* (21.33 vs. 2.33 mean #/57cm^2) were found to be significantly different from 1977. There was no significant difference found between the abundance of the remaining species in 1977 and 1989, as well as the number of taxa present for the two years.

The species present in the community were classified into functional groups (Table 6). Of the different feeding types present in the benthos, 48% of the species were filter feeders, 17% were carnivores, 24% were deposit feeders, and 28% used mixed (multiple) methods of feeding (mixed feeding type). The deposit feeders were further divided into those that fed exclusively on the surface sediments (Deposit1), and those that fed on sub-surface sediments (Deposit2). Of the deposit feeders, Deposit1 feeders made up for 57% and Deposit2 feeders made up for 43%. The mixed feeding type group was divided into species that surface deposit fed and filter fed (Mixed1), encompassing 62.5%, and species that surface deposit fed and were scavengers (Mixed2), encompassing 37.5%. The species in the community lived in a range of locations within the sediment. Burrowers made up 48% of the species, tube dwellers (tubicolous species) made up 24%, and surface dwellers composed 28% of the community. Reproductive types were also diverse, with 38% of the species being classified as brooders, 31% as spawners, 14% as oviparous species (egg laying species), and 17% as capable of using multiple methods of reproducing (mixed reproductive type). Three different types of organism protective barriers were present in the community. Fifty-two percent of the species had a tissue barrier, 24% had a calcium carbonate ($CaCO_3$) barrier and 24% had a chitinous barrier.

The four different feeding groups: filter feeders, carnivores, deposit feeders, and mixed feeding species demonstrated seasonality (Figure 27), but showed no clear trends between years. The different habitat groups: burrowers, tube dwellers and surface dwellers also showed seasonal fluctuations (Figure 28). A slight downward trend for the time series is seen in the tube dwellers, but no trends were observed in the other groups. The reproductive groups: brooders, spawners, oviparous species, and mixed reproductive species, again showed seasonal fluctuations (Figure 29). There was a gradual upward trend in the abundance of oviparous species and in the mixed reproductive species. Of the time series for the three different organism barrier types: tissue, $CaCO_3$ and chitin, only chitin showed a slight decreasing trend through time (Figure 30). However, no seasonal trends were apparent in all three of the barrier type time series.

The functional groups were used to further explore differences between 1977 and 1989 (Table 7) using Chi Square analysis. A significant increase in abundance of mixed reproductive (22.99 vs. 97.32 mean #/57cm^2) and oviparous species (25.66 vs. 47.32mean #/57cm^2) was found between 1977 and 1989.

Significantly lower abundances were seen from 1977 to 1989 for brooders (1219.65 vs. 184.61 mean #/57cm^2), filter feeders (792.66 vs. 139.31 mean #/57cm^2), tube dwellers (647.32 vs. 89.97 mean #/57cm^2), burrowers (616.3 vs. 240.95 mean #/57cm^2), deposit feeders (432.99 vs. 181.63 mean #/57cm^2) and mixed feeding species (37.97 vs. 9.98 mean #/57cm^2). Increases in abundance seen from 1977 to 1989 for spawners, carnivores and surface dwellers were not significant. Significant decreases in abundance were seen for all three barrier types from 1977 to 1989: tissue (452.63 vs. 207.28 mean #/57cm^2), $CaCo_3$ (570.65 vs. 99.64 mean #/57cm^2) and chitin (267.99 vs. 53.31 mean #/57cm^2).

To assist in understanding the relationships within the community, cross correlations of the functional groups were analyzed to see if any patterns emerged, to aid in the discussion of the results. Many groups were significantly positively correlated (Appendix 3). Species with traits in common were combined, creating multi-dimensional functional groupings. These groupings were also cross-correlated to reveal several significant relationships (Appendix 4), which will also be used to aid in understanding the trends in the community.

Environmental vs. Community Data

Possible relationships between the benthic community (summary statistics and functional groups) and the environmental parameters (seasonal summary statistics) were examined using Pearson correlation. Relationships were found with all environmental variables.

The two basic descriptive statistics (total animal abundance and number of taxa) and the functional groups (eighteen groups) were tested against the environmental data (Table 8). Of the salinity summary statistics tested (minimum, maximum and standard deviation of clam salinity and water salinity), only standard deviation was not correlated to any community groups. Significant positive relationships were found between minimum and maximum salinity measures and total animal abundance, number of taxa, the abundances of filter feeders and chitinous species.

All summary statistics for air and water temperature (mean, minimum, maximum, and standard deviation) were significantly correlated to some biological parameter. All temperature relationships were positive except for abundances of mixed2 feeding type, which was negatively correlated with the standard deviation of air temperature. Positive relationships were found with total animal abundance, number of taxa, the abundances of filter feeders, all mixed feeders, mixed1 feeding type, tube dwellers, brooders, chitinous species.

Of the chlorophyll *a* statistics tested, only one significant relationship was found; spawners were positively correlated to maximum chlorophyll *a*. Significant negative relationships were found between TOC and total abundance, the abundances of all deposit feeders, deposit feeders1, filter feeders, all mixed feeders, mixed1 feeding type, burrowers, tube dwellers, brooders, chitinous species and tissue barrier species. BOD summary statistics showed positive significant relationships with total abundance, the abundances of filter feeders, all mixed feeders, mixed1 feeding type, tube dwellers, brooders, and chitinous species.

Metal summary statistics tested were mean and maximum for clam and sediment metals (Ag and Cu). There were no significant relationships found with maximum clam Ag, but the remaining metal parameters were significantly, positively correlated with the abundances of carnivores, filter feeders and species with chitin barriers. Number of taxa, and the abundances of all deposit feeders, deposit2 feeders, surface dwellers, mixed reproductive type species, and tissue barrier species had significant negative relationships with metals.

The multi-dimensional functional groups were correlated to the environmental data as well to enable better understanding of the relationships when more than one life history trait was considered (Appendix 5). These correlations will be brought into the discussion of observed trends when appropriate.

DISCUSSION

The estuarine environment is extremely dynamic. It is characterized by extreme fluctuations in physical factors, such as: temperature, salinity, turbidity, and water movement (Day et al. 1989). Estuaries are inhabited by species that reflect this environmental variability, with individuals exhibiting a broad range of tolerance to changes in physical factors. In addition to natural variation, estuaries are heavily modified and affected by anthropogenic activities. The presence of man-induced variation can provide additional stress on organisms already dealing with stress from the natural environment. The presence of multiple stressors can make it difficult to evaluate effects of a single stressor on an organism or a community (Clements et al. 2001). The stressors must be identified and quantified before interrelationships can be determined. This can be complicated when the community is exposed to a chronic stressor, over a long period of time. The presence of a chronic stressor can make the community more susceptible to natural variations in the environment (natural stressors), which can then delay the recovery of the community or alter the community altogether (Paine et al. 1998). Communities with chronic exposure to pollutants often are dominated by species that have enhanced tolerance to the pollutants relative to species from unexposed areas (Luoma 1977). These tolerant species can replace more sensitive species, creating a community that as a whole is more tolerant, but usually less diverse (Clements et al. 2001).

The present study investigates a mudflat community in South San Francisco Bay that has been exposed to chronic pollutants, namely high concentrations of the trace metals copper and silver, from a local water treatment plants. Trace metal uptake and accumulation into the tissues of organisms is known to negatively affect benthic invertebrate physiological processes such as reproduction, feeding, respiration and protein utilization (Luoma and Carter 1991). As a result of the implementation of tertiary treatment in the South Bay water treatment plants by 1980, removal of the metals from the effluents resulted in the decline of the metals in the sediments on the mudflat, as well as in the tissues of the biosentinal clam *Macoma balthica* (Hornberger et al. 2000). In addition to the changes observed in the sediments and tissues of *M. balthica*, the benthic community on the mudflat was expected to respond to the lower concentrations of metals. That is, the removal of a chronic stressor would make the environment more stable for the organisms inhabiting it, by lessening the toxicity of the sediments.

In classical ecology, a more stable environment, brought about by removing unpredictable and unstable stressful physical factors, would create a more diverse community (more species) that use the environment in more refined ways (Connell 1978). Connell (1978) challenged this “stability-diversity” hypothesis by proposing that increased diversity in many environments was due to the presence of an intermediate level of disturbance. An intermediate level of disturbance would prevent competitively dominating species from excluding new immigrants and thus allow the community to become more diverse. These two competing hypotheses have one thing in common; both predict that when physical (non-biological) factors are reduced in a community, biological factors (i.e. competition, predation, etc.) will become more important in shaping community structure. Therefore, based on both hypotheses, the community that developed, as heavy metal pollution was reduced, was predicted to be less physically stressed and more biologically influenced.

The organisms that make up the present community are predominantly introduced opportunistic species (Nichols and Thompson 1985a and Cohen and Carlton 1998). These species are characterized by short life spans, rapid development to reproductive maturity, many reproductive periods per year, the presence of larvae in the water column most of the year and high death rates (Nybakken 1997). By their very opportunistic nature they are frequently very abundant one season or year and then gone or diminished in very short time frames. Opportunistic species dominate in areas that are subjected to frequent disturbance due to their high availability in the water column, rapid growth and development once settled and the potential for postlarval dispersement (Lenihan and Micheli 2001 and Nybakken 1997). Early successional stages in a community are dominated by high abundances of opportunistic species. The presence of these species can delay the successional process of a community due to competition between species (Whitlatch and Zajac 1985). Their success in a community is predicted by the variability of the estuarine environment (Connell 1978, Odum 1985 and Paine et al. 1998), especially in the presence of multiple stressors.

Based on these theories, I predicted: an increase in the abundance of animals, an increase in the number of species present, and an increase in diversity representing changes in the structure of the community.

Changes in the benthic community structure in this study were explored by examining the trends in the biological and environmental data (Luoma et al. 2001); trends in the community data were identified and compared to trends in the environmental data. Once associations were made, mechanisms for the trends were explored using the hypothesized effects of the measured environmental variables on the benthic community (Table 2). The relationships were then compared to results from other studies.

Variability of temperature and salinity are inherent to an estuary and are common organizing stressors in estuarine communities (Day et al. 1989 and Geyer et al. 2000). Therefore, almost all data are related directly or indirectly to temperature and salinity. This can be seen in the present community in the cluster analysis of sampling dates (Figures 14 & 15). The dates are organized by dominant species abundances first, and then by similarities in temperature and salinity (i.e. wet and dry years, summers and winters clustered together). In addition to temperature and salinity, maximum BOD was related to a majority of the data. BOD never reached critical levels in South San Francisco Bay, so therefore it is assumed to have no detrimental affect on organisms in the bay. In addition, BOD is closely related to temperature, with highest levels of BOD occurring with maximum temperatures. Therefore, BOD's associations to the community data are most likely due to the relationship between the community structure and the temperature. As a result of the expected and established associations of the data to temperature, salinity and BOD, the association of the trends in the community data will focus on the trends of other environmental parameters.

Investigations of total animal abundance at Station 45 revealed high abundances in the early 1970's, then a drastic drop in abundances due to a die off caused by the presence of an algal mat on the mudflat in 1975 (Nichols and Thompson 1985a). The community recovered to high abundances in 1977 and then exhibited a decreasing trend through the early 1980's. This pattern was supported by a simultaneous, stronger decreasing trend in abundance at Station 46, due in part to a higher abundance at Station 46 prior to the algal mat die off. The reason for the differences in abundance between the two stations prior to 1975 is unknown. Following the die off, the two stations remained fairly similar in abundances through the remaining years of data collection. Of the variables expected to be related to the trends in abundance (decreasing concentrations of

Cu and Ag in the sediment and in the tissues of *M. balthica*), none were significant. The decrease in total animal abundance of the community following the decreasing concentrations of metal was opposite to what was predicted. In fact, the decreasing trend in community abundance could be due to any one, or a combination of a number of biotic or abiotic influences. Possibly, declining abundance was due to influences other than metals, masking any responses resulting from the declines in metal concentrations. The decrease in abundance observed could be a related to the reduction of physical controlling factors on the community, allowing biological controlling factors (i.e. competition, predation and recruitment) to structure the community (Connell 1978).

None of the other community summary statistics, number of taxa, cluster analysis or species diversity index comparisons showed predicted community trends. An increase in diversity of species was predicted in the absence of high metal concentrations. Instead, seasonal fluctuations dominated the timeseries (i.e. within year fluctuations were greater than between year fluctuations).

Changes were found in community structure and these changes were consistent with predictions. The rank abundance curves, displaying the comparative abundances of the top 10 ranked species for specific years, reflect a benthic community responding to changes in an environmental stressor over an extended period of time. A visual comparison of a full year of data (four seasons) prior to tertiary treatment (1976) to a full year post tertiary treatment (1989) using rank abundance curves (Figs. 25 and 26), shows seasonal fluctuations in species abundances throughout the dataset for both years. Increased abundances in the summer are a result of late spring/early summer reproduction and recruitment of species. Summer and fall months are warm with little to no fresh water input into the system, which may present an environmental stressor to some organisms. Winter often presents an excess of fresh water and lower temperatures that can also be stressful to animals.

Large differences between the seasonal abundances of the top ranked species in 1976 (Figure 25) indicate a community responding to multiple stressors throughout the year. The seasonal curves for 1976 are similar in slope, but vary considerably in abundances between seasons. As predicted the highest abundances were found in the summer followed by the fall. The large differences in abundance between the seasonal curves during 1976 could reflect a community that is struggling to survive and recruit in the presence of environmental stressors amplified by high metal concentrations in the sediment and water column. The distinctly high abundances in the summer could reflect stressed organisms' increased reproductive effort.

In contrast, the 1989 rank abundance seasonal curves (Figure 26) reveal a community that has little seasonal variability. Highest abundances are seen in the fall, possibly due to a late or additional reproductive period. Spring abundances are also high, reflecting the spring reproductive period. The four curves have similar slope with little to no domination of the community by extremely high abundances of a few species. The curves are those of a community that is stable throughout the year and maintaining lower abundances in the absence of the metal stressors.

The effect of metal stressors can also be seen when comparing the rank abundance curves for the summer months of 1977 and 1989 (Figure 24), due to the similarities of those years in other stressors. Summer months can be stressful to intertidal animals due to increased temperatures and salinities. The addition of a stressor, such as trace metals, to a community that is already stressed by the natural environment can cause drastic changes in the structure of the community. Such changes are suggested in the comparison of the summer communities. The numerical dominance of the top three ranked species in 1977, *Gemma gemma, Streblospio benedicti* and *Ampelisca abdita,* results from their ability to be successful in an extremely stressful environment, while other species struggle to survive at much lower numbers. The community present in 1989 has greater species evenness, i.e. species exist in more equal numbers than those seen in 1977. This would suggest that the environment present in 1989 is more favorable for a majority of species present in the community.

One species that has increased in abundance with the reduction of heavy metals is the polychaete *Heteromastus filiformis*. The increasing trend in their abundance is correlated with the decreasing trend in trace metals. A comparison of *H. filiformis* abundance to data for copper and silver concentrations in the sediment revealed a strong significant negative relationship (R^2=-0.666, $p<0.001$) with the silver data (Figure 31). There was no such relationship with copper in the sediment. An investigation of the worm's natural history suggests possible mechanisms for this relationship. *H. filiformis* is a subsurface deposit feeder, known to turn over the sediment quite rapidly as a result of its feeding habits (Cadee 1979, Gillet and Gorman 2002). It ingests the sediment and passes it through its body, removing food particles from the sediment granules. They inhabit vertical burrows in the sediment with an open end to the surface. They are hermaphroditic egg layers (oviparous species) that deposit their eggs and sperm into egg cases that are then deposited on the surface of the sediment outside the adults' burrow. The larvae develop within the egg cases for a short period and are then released into the water column for a period up to one month, allowing for distribution of the larvae. While in the plankton, the larvae subsist on the yolk mass within their body (lecithothropic). The larvae then settle to the bottom and metamorphose into the bottom stage (Rasmussen 1956). Biological effects of silver in polychaetes have not been identified, but limitation of reproduction in the bivalve *M. balthica* has been reported by Hornberger et al. (2000). Silver is rapidly sorbed into sediments and easily bioaccumulated and amplified in the tissues of invertebrates due to the complexes that it forms with natural particles in sediments and the neutral chloro complex of Ag ($AgCl^0$). The chloro complex has been shown to facilitate the diffusion of Ag across biological membranes (Engel et al. 1981). Therefore, low concentrations of silver in the sediments are considered toxic to organisms (Lumoa et al. 1995).

Another species category that has increased in abundance post tertiary treatment is the oligochaetes. Like *H. filiformis*, oligochaetes are subsurface deposit feeders, ingesting deep sediments by passing them through their body and, they often live in burrows. However, these organisms have the ability to reproduce asexually or by laying their eggs in the sediment (Brusca and Brusca 1990). Although there was an increase in abundance when comparing 1977 to 1989, there were no clear trends over the course of the study. This is possibly due to extreme seasonal fluctuations in oligochaete abundance (Figure 20). This lack of trend could be due to the seasonal shifts in reproductive method.

Examining community changes as well as individual species changes can identify general shifts and the associations related to the shifts, but do little to identify the mechanisms behind the changes. To better detect the influences of the environmental variables, the community was reorganized into functional groups (Luoma et al. 2001) to look at the community with a higher level of organization. This approach allows a comparison of relative abundances of groups, which are based on organisms' traits (Weiher and Keddy 1999). Functional groups can be organized along a number of axes, including type of feeding mechanism or food source, type of sub-habitat utilized or type of reproductive life history. The present study identifies four different functional groups; feeding type, habitat type, reproductive type and barrier type. Applying this level of organization to community results may make the mechanisms causing community change clearer.

The comparative analysis of the species rank abundance curves for the summers of 1977 and 1989 revealed that the community had undergone a definite shift, suggesting that the environment in 1989 was more favorable. To help understand this shift, functional group information (Table 6) was added to the summer rank abundance curves.

The addition of feeding type information (Figure 32) shows a shift from a community dominated by filter feeders and surface deposit feeders to one that is dominated by sub-surface deposit feeders and filter feeders. The 1977 community was dominated by species that filter feed from the water column, *G. gemma* and *A. abdita*, a species that ingests food particles from the surface sediment, *S. benedicti*, and a species that feeds using both of these methods, *G. japonica*. The decrease in trace metals in the sediment provides species with cleaner, less toxic sediments and may allow species that ingest the sediments to thrive and increase in abundance. In 1989, two such species, Oligochatea spp. and *H. filiformis*, rose in the ranks. The deposit feeder *S. benedicti* dropped in the ranks, but still remained in high abundance. The mixed feeder *G. japonica*, present in high numbers in 1977 was not considered a dominant species in 1989. Possibly, the lack of metals in the sediment supports more species that ingest sediment. However, the negative correlation of all deposit feeders to TOC (Total Organic Carbon) seems to suggest that this is not the case.

The curves with habitat type information added (Figure 33) reveal a community that has shifted from one that was dominated by species that live in and above the surface sediments to one that includes species that live below the surface. The 1977 community included species that burrow shallowly in the sediment, *G. gemma* and *G. japonica*, and those that live inside a tube on the surface of the sediment, *S. benedicti* and *A. abdita*. The 1989 community, in addition to the species living on or in the sediment, includes species that live below the surface in the sediments, Oligochaetea spp. and *H. filiformis*. Based on the previous discussion, the presence of the Oligochaetes and *H. filiformis* could be due to the cleaner habitat or the less toxic food sources, or both. The present research is not able to differentiate.

The addition of reproductive strategies (Figure 34) onto the rank abundance curve exhibits that in 1977 the community was dominated by species that brood their young. Of theses species, *G. gemma, S. benedicti, A. abdita,* and *G. japonica* make up the first four ranks in the community. The resulting high abundances of these populations are a result of their localized release and possibly due to the protective nature of brooding. The developing larvae are protected from the external environment and potential toxins by the brood sac, and released as juvenile stages, allowing for the repopulation of the local environment as juveniles near the parent. This could facilitate greater survivorship of juveniles than other species, which have larvae that need to survive plankton and settling stresses (i.e. predation and exposure as smaller animals). The first four ranks in 1989 reveal a community consisting of brooders, *G. gemma* and *A. abdita*, in ranks two and three, but also by species that lay their eggs in the sediment. The top ranked species, Oligochaeta spp. can lay their eggs in the sediment, as well as reproduce asexually. The species in the fourth rank, *H. filiformis*, is an oviparous species exclusively. A more favorable environment would accommodate species whose developing young are more exposed to the local environment than species that brood their young. The species abundance curve for 1989 also shows a spawning species, *Eteone* spp., high in the ranks. The larvae of spawning species develop in the water column, and settle out in new habitats as juveniles. The rise of spawning species in the ranks reflects that the competent larvae of these species are finding the mudflat habitat suitable for settlement and metamorphosis. The species that dominate the community in 1989 were more diverse in reproductive strategies, suggesting an environment that was more conducive to juvenile survival and successful recruitment. It is however interesting to note that the eurytopic, introduced species *Potamocorbula amurensis*, a spawning species, did not recruit in high numbers to the mudflat community, despite high abundances in other locations (deep channel) in the South Bay beginning in the fall of 1988 (Schemel et al. 1990). Perhaps the pool of larvae transported onto the shoals in South San Francisco Bay is limited to species already inhabiting the shoals in that area.

The addition and application of functional group information to the rank abundance curves reveals shifts in the structure of the community. These shifts suggest that the cleaner sediments have enabled several groups/species, which previously were unable to reproduce and survive in great numbers, to thrive and increase in abundance.

In order to better understand the shifts that have occurred in the community, functional groups that exhibited trends throughout the data set were investigated. The trends explored were also supported by significant differences in the abundance of the groups between the 1977 and 1989 Chi Square analysis (Table 7). By looking for trends in the functional group data, and making associations to the trends found in the environmental data, mechanisms for the associations may become clear (Weiher and Keddy 1999 and Luoma et al. 2001). Within the community, there were four functional groups that exhibited a trend in their timeseries data: tube dwellers, brooders, oviparous species and mixed reproductive species.

There was a noted decrease in the abundance of tube dwellers and brooders through the data set (Figures 28 & 29, respectively). Of the environmental variables expected to affect the abundance of these groups, none were significant. There was however a significant negative relationship to the percent of TOC in the sediment for both groups. This was opposite of what was expected if these groups included deposit feeders. However, when correlating tube dwellers that are deposit feeders and brooders that are deposit feeders (i.e. *S. benedicti*) to TOC, we see a significant negative relationship to minimum TOC (Table 8). Since TOC is cross-correlated to temperature, these relationships may reflect the strong negative relationship between all species and groups with temperature. It should be noted that, in all cases, the correlations of the functional groups are confounded by the fact that individual species are potential members of many functional groups by virtue of their diverse natural histories.

Oviparous species abundance, which increases over the course of the timeseries (Figure 29), might be expected to be driven by decreases in variables that would create a stressful environment. However, there were no direct correlations of the oviparous species functional group to any of the environmental variables. Oviparous species that are mixed feeding type2 species were correlated to temperature, TOC and metals significantly, but these relationships were driven by an extremely rare species in the dataset (*Ilyanasa obsoleta*), and are therefore statistically biased. Significant negative relationships were found between deposit feeding2 oviparous burrowers (i.e. *H. filiformis*) and BOD as well as metals, as expected. High levels of BOD mean low levels of oxygen in the water, suggesting higher abundances with low levels of BOD, which was the case. Higher concentrations of metals are more toxic, and can cause decreases in animal abundance. As was the case with multidimensional oviparous species groups, the groups were low in abundance when metal concentrations were high. Correlations between the community and BOD may be driven by the high degree of positive correlation between BOD and metals. The correlation between BOD and metals may be due to their improved levels due to the implementation of tertiary treatment in the South Bay.

Mixed reproductive species also exhibit an increasing trend throughout the data set (Figure 29). Mixed reproductive species are those that are known to switch between two forms of reproduction, usually one of which is egg laying. This group would also be expected to be affected by decreases in the values of environmental variables that are stressful to species in the community. Of the environmental variables that would cause such an increase, only a correlation to metals is significant. The relationship of mixed reproductive species to metals is a negative relationship for sediment concentrations of both silver and copper. Thus, these species are more abundant in sediments that have lower concentrations of the metals, as was predicted. No other correlations or cross-correlations explain the changes observed in these data.

The use of functional group data has allowed for the observation of community response to long-term environmental changes. Through their use, it has been possible to identify shifts within a community that has shown a gradual decrease in total animal abundance coincident with what first appears to be subtle shifts in community structure. The community was found to be primarily controlled by physical disturbance (resuspension and deposition of sediment) by Nichols and Thompson (1985b). Their results identified a collection of species that persisted throughout the dataset, demonstrating that the community never reached final successional stages, and was therefore probably controlled by the prevailing intermediate level of disturbance (Connell 1978). The severe disturbance in 1975 reduced the community to extremely low abundances, showing the effect of high levels of disturbance on the community. The present analysis has revealed a community that continues to be structured and maintained by intermediate levels of disturbance. However, the reduction of trace metal concentrations in the sediments, have allowed groups of species (functional groups) and individual species to increase in abundance. The increases in abundance of these species supports a hypothesis of a change in the community structure due to the reduction of the chronic stress induced by metal contaminants. The present study demonstrates that the community is still made up of the same opportunistic species found by previous researchers (Nichols and Thompson 1985a). However, the change in the environment has caused a shift in functional group diversity, as well as in dominant species. The community could be partially structured by unmeasured biological forces (i.e.

predation, recruitment, etc.), but physical factors dominate the environment and appear to be the primary structuring force. Lenihan and Micheli (2001) show that biological factors become important in structuring the community only when physical disturbance exists at very low levels. Physical disturbance in the present community has remained at high levels (i.e. there has been no change in sediment resuspension and accretion). Therefore, biological forces exert at most, a secondary control on the present community.

It was hypothesized that the decreases in the concentrations of trace metals in the environment would be reflected in the community, as an increase in diversity. Initial investigations did not reveal such changes. The initial analysis performed were likely not the appropriate measures of change in a community and environment with such complex stressors in place. It may be more appropriate to explore the communities' response to changes in stressors through the use of functional groups. The present dataset is very unique (in length and with a gradual decrease in metals), and suggests a new way to look at community response to changes in stressors.

SUMMARY

The community that was present during low concentrations of metals differs from the community that was present when concentrations of the metals were high. The changes that resulted demonstrated that the community is structured primarily by physical disturbance, and secondarily by anthropogenic physical stressors. Evidence for physical disturbance as a structuring mechanism was seen in the associations of the community data to the salinity and temperature data, as well as previously established work on the effect of sediment resuspension and deposition. The effect of secondary structuring mechanisms could be seen in the shifts in the community that took place concurrent with the decreasing concentrations of metals in the sediment. Community changes were found through the examination of rank abundance curves with functional group information applied. Specifically, in the community there was an increase in oviparous species and species that utilized multiple reproductive strategies, and a decrease in species that lived in tubes and those that brooded their young. The data reported here support the hypotheses that biological changes observed, changes in the dominant reproductive strategies in the community, were in response to declining metal contamination in the sediment, a change brought about by upgrades made in wastewater treatment facilities in South San Francisco Bay as a result of the Clean Water Act (CWA) of 1972. Higher levels of pollution abatement have improved water quality in South San Francisco Bay allowing communities to be structured by natural physical stressors as they should be, instead of by anthropogenic stressors.

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Figure 1. The location of the present study is located on the Palo Alto shoreline in the southern reach of San Francisco Bay. The effluent of the local waste water treatment facility (Palo Alto Regional Water Quality Control Plant (PARWQCP)) is located approximately 1 km north of the sampling site. Water Quality of San Francisco Bay (USGS) sampling stations (Stations 30 & 36) are also located in South San Francisco Bay.

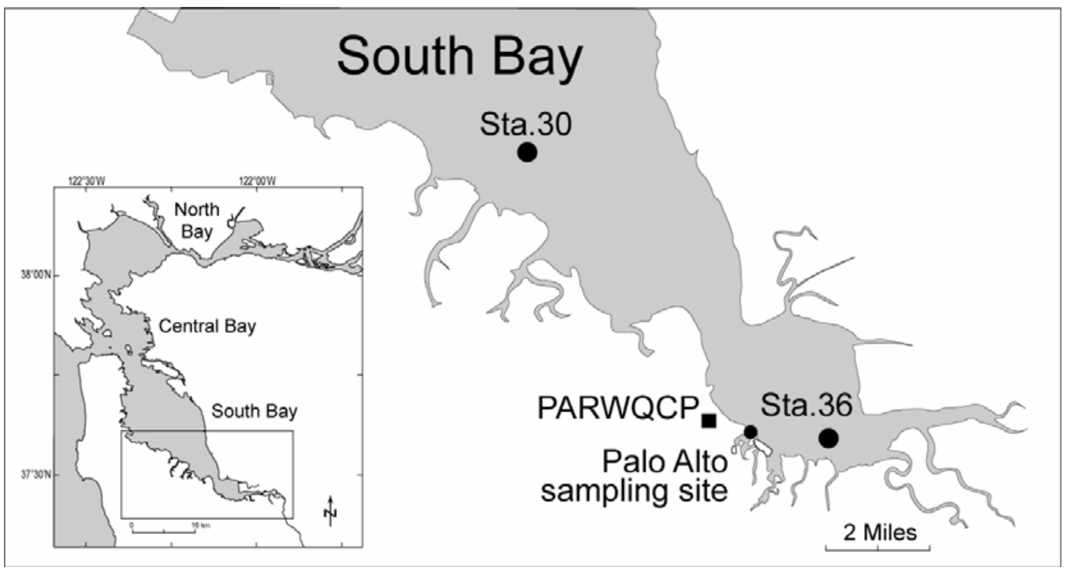

South Bay
Sta.30
PARWQCP
Sta.36
Palo Alto
sampling site
2 Miles
North
Bay
Central Bay
South Bay

Figure 2. The annual mean volume of effluent from the Palo Alto Regional Water Quality Control Plant remains relatively constant through time, while the loading of copper and silver decrease. Adapted from Hornberger et al. (2000).

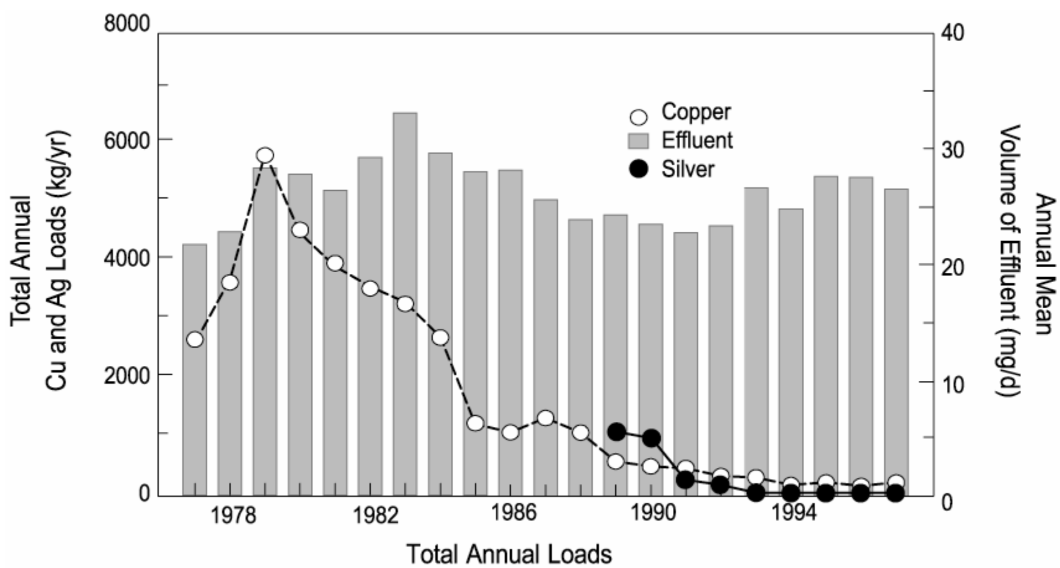

Total Annual
Cu and Ag Loads (kg/yr)
8000
6000
4000
2000
0
Annual Mean
Volume of Effluent (mg/d)
40
30
20
10
0
Copper
Effluent
Silver
1978
1982
1986
1990
1994
Total Annual Loads

Figure 3. Uptake of metals into the tissues of the bivalve *Macoma balthica* affects reproductive output of the clam. During periods when concentrations of metals were high in the environment, the percentage of clams that were reproductive were low, and the percent quiescent were high. As metal concentrations decreased in the environment, the percent that were reproductive increased and the percent quiescent decreased. Adapted from Hornberger et al. (2000).

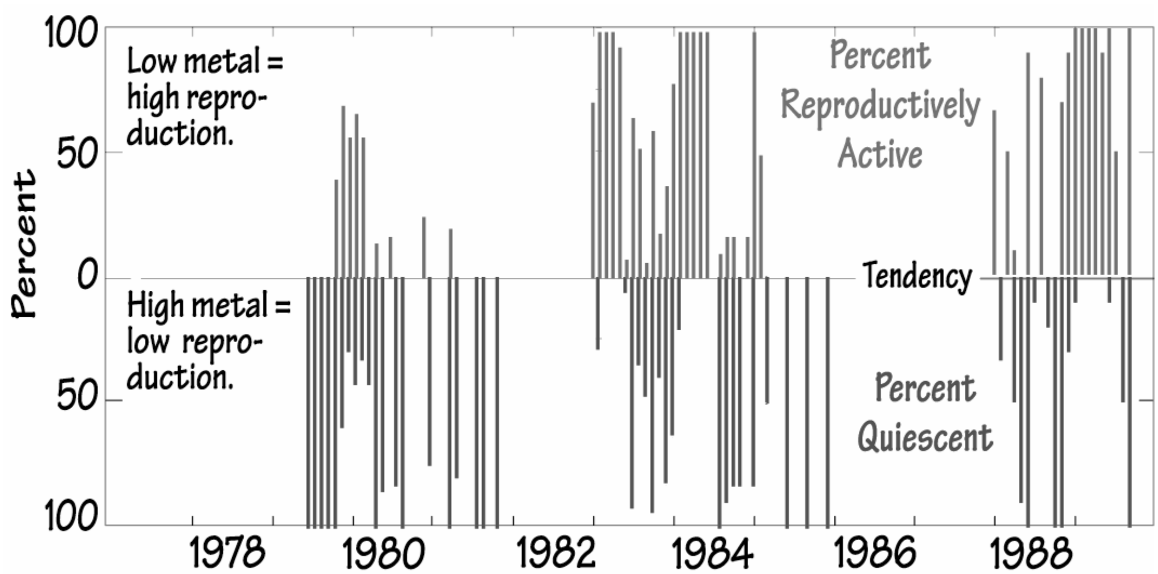

100
Low metal =
high repro-
duction.
Percent
Reproductively
Active
50
Percent
0
Tendency
High metal =
low repro-
duction.
50
Percent
Quiescent
100
1978
1980
1982
1984
1986
1988

Table 1. Types and sources of environmental data used for analysis.

Type	Location	Time Covered	Frequency	Source
Biological Oxygen Demand (BOD)	South Bay	1976-1990	monthly	Hagar, S.W. (2001)
Calculated Chlorophyll *a*	South Bay	1977-1990	monthly	Water Quality of San Francisco Bay - USGS *
Copper (tissues of *M. balthica*)	Sand Point	1977-1990	monthly	Hornberger, M.I. et al. (2000)
Copper (sediment)	Sand Point	1977-1990	near monthly	Hornberger, M.I. et al. (2000)
Delta Outflow	Delta	1973-1990	daily volume	Interagency Ecological Program: Dayflow Website ***
Precipitation	Palo Alto	1973-1990	monthly averages	Western Regional Climate Center - Climate Summary **
Salinity (field)	South Bay	1974-1990	monthly	Water Quality of San Francisco Bay - USGS *
Salinity (in clam)	Sand Point	1977-1990	monthly	Hornberger, M.I. et al. (2000)
Silver (tissues of *M. balthica*)	Sand Point	1977-1990	monthly	Hornberger, M.I. et al. (2000)
Silver (sediment)	Sand Point	1977-1987	near monthly	Hornberger, M.I. et al. (2000)
Temperature (air)	Palo Alto	1973-1990	monthly averages	Western Regional Climate Center - Climate Summary **
Temperature (water)	South Bay	1974-1990	monthly	Water Quality of San Francisco Bay - USGS *
Total Organic Carbon (TOC) Sediment	Palo Alto	1977-1989	monthly	Hornberger, M.I. et al. (2000)

* http://sfbay.wr.usgs.gov/access/wqdata/query/

** http://www.wrcc.dri.edu/summary/climsmsfo.html

*** http://iep.water.ca.gov/dayflow/

Table 2. The environmental variables used for analysis and their hypothesized effect on the benthic community. The types of summary statistics used for each environmental variable for analyses were determined by the stated hypothesis.

Environmental Variable	Hypothesis	Critical Summary Statistics to Test
Salinity	Salinities above and below the normal will cause a decrease in species abundance, as will rapid/extreme changes in salinities.	Minimum, Maximum, Standard Deviation
Precipitation	Increased precipitation decreases the salinity of the water. It also increases runoff and debris input into the system. Increases in precipitation could therefore cause a decrease in species abundance, particularly for intertidal species, due to drops in salinity and burial from debris.	Mean, Minimum, Maximum, Standard Deviation
Temperature	Extreme temperatures above and below the species tolerance, as well as drastic temperature fluctuations, can kill intertidal organisms.	Mean, Minimum, Maximum, Standard Deviation
Chlorophyll *a*	Decreases in chlorophyll *a* levels lowers food availability in the water, thereby decreasing the abundance in species.	Mean, Maximum, Minimum
Total Organic Carbon	Changes in TOC affect the chemistry of the sediment and its ability to absorb trace metals from the water. Increases in TOC could also reflect an increase in benthic diatom and microorganism biomass, therefore lower levels of TOC could indicate lower levels of food for deposit feeders and detritivores.	Mean, Minimum, Maximum
Biological Oxygen Demand	Lower BOD loading draws less oxygen out of the water in to which the effluent is released. A lower BOD loading value will result in more oxygen in the water available for organisms. Higher BOD values decrease oxygen and can decrease species abundance.	Mean, Maximum
Trace Metals	High levels of metals cause physiological problems in animals including problems in development, growth and reproduction, therefore potentially decreasing the abundance in species.	Mean, Maximum

Table 3. Community samples from Stations 45 and 46 utilized for data analysis. The numbers of replicates taken per sampling date are noted. Samples noted with an X* are can core samples.

Date	FN45			FN46		
	Haul 1	Haul 2	Haul 3	Haul 1	Haul 2	Haul 3
2/1/1974	X	X	X	X	X	X
5/7/1974	X	X	X	X	X	X
8/2/1974	X	X	X	X	X	X
11/11/1974	X	X	X	X	X	X
2/6/1975	X	X	X	X	X	X
5/29/1975	X	X	X	X	X	X
7/24/1975	X	X	X	X	X	X
11/13/1975	X	X	X	X	X	X
1/27/1976	X	X	X	X	X	X
4/5/1976	X	X	X	X	X	X
8/12/1976	X	X	X	X	X	X
12/16/1976	X	X	X	X	X	X
2/14/1977	X	X	X	X	X	X
8/30/1977	X	X	X	X		
3/2/1978	X	X	X	X		
8/18/1978	X			X		
3/22/1979	X			X		
6/13/1979	X*					
8/7/1979	X			X		
11/29/1979	X*					
3/12/1980	X			X		
5/20/1980	X*					
8/12/1980	X			X		
12/16/1980	X*					
3/10/1981	X			X		
4/23/1981	X*					
8/18/1981	X			X		
10/14/1981	X*					
2/3/1982	X			X		
5/11/1982	X			X		
8/19/1982	X			X		
2/22/1983	X			X		
5/18/1983	X			X		
8/10/1983	X			X		
12/16/1983	X*	X*				
2/21/1984	X*	X*				
5/18/1984	X*	X*				
8/14/1984	X*	X*				
12/20/1984	X*	X*				
2/27/1989	X	X	X	X	X	X
5/5/1989	X	X	X	X	X	X
8/2/1989	X	X	X	X	X	X
12/7/1989	X		X	X	X	X
3/28/1990	X	X	X	X	X	X

Figure 4. A comparison of monthly average precipitation in Palo Alto with monthly water salinity measurements from Stations 30 & 36 in South San Francisco Bay. Strong seasonal and inter-annual differences were observed, reflecting the increase in freshwater flow in winter and spring of each year and the longer time-scale flood and drought events. High values of precipitation correspond to low values of salinity.

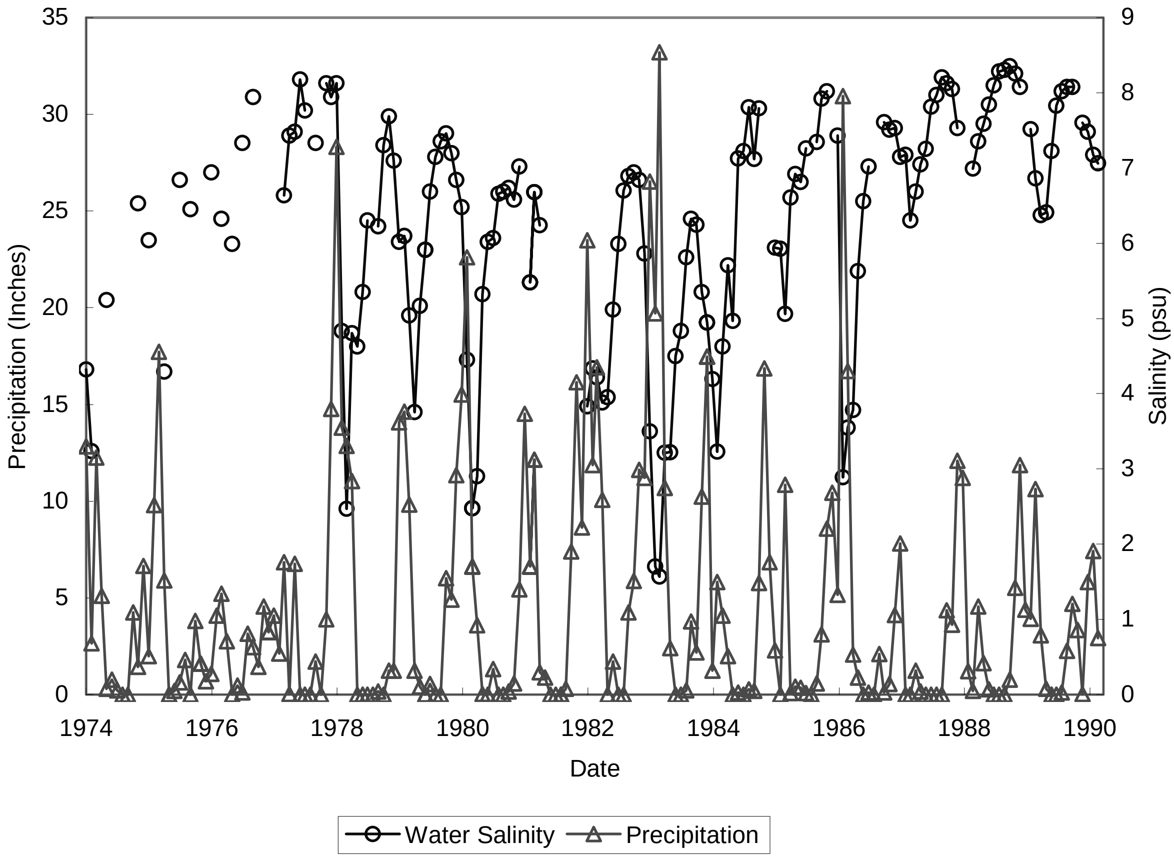
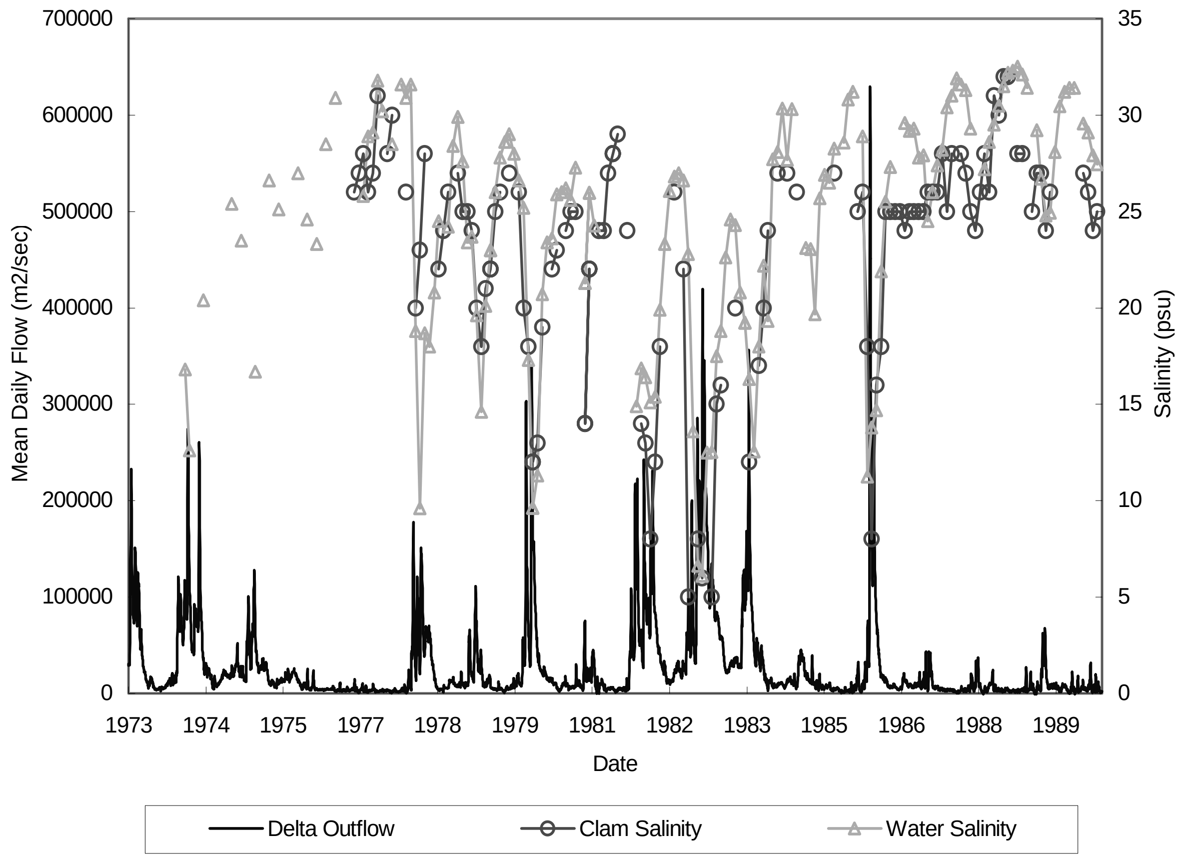

35
30
25
20
15
10
5
0
9
8
7
6
5
4
3
2
1
0
Precipitation (Inches)
Salinity (psu)
1974
1976
1978
1980
1982
1984
1986
1988
1990
Date
Water Salinity
Precipitation

Figure 5. A comparison of freshwater inflow (Delta outflow) from the Sacramento/San Joaquin Delta (mean daily flow of water past Chipps Island to San Francisco Bay) to two different sources of salinity data, water found inside *Macoma balthica* collected at a nearby site and water collected by USGS South Bay water-quality program in the nearby channel. A visual comparison of the salinity measures and the volume of delta outflow show a strong negative relationship, with maxima in delta outflow occurring with declines in salinity.



700000
600000
500000
400000
300000
200000
100000
0
35
30
25
20
15
10
5
0
Mean Daily Flow (m2/sec)
Salinity (psu)
1973
1974
1975
1977
1978
1979
1981
1982
1983
1985
1986
1988
1989
Date
Delta Outflow
Clam Salinity
Water Salinity

Figure 6. Monthly averages of air temperature from Palo Alto are compared to monthly water temperature samples from Stations 30 & 36 in South San Francisco Bay. There is a high degree of correspondence between the two temperature measurements. The timeseries are dominated by strong seasonal patterns, with peak temperatures occurring in mid to late summer and minimums occurring in winter. There is very little inter-annual variation in both measures.

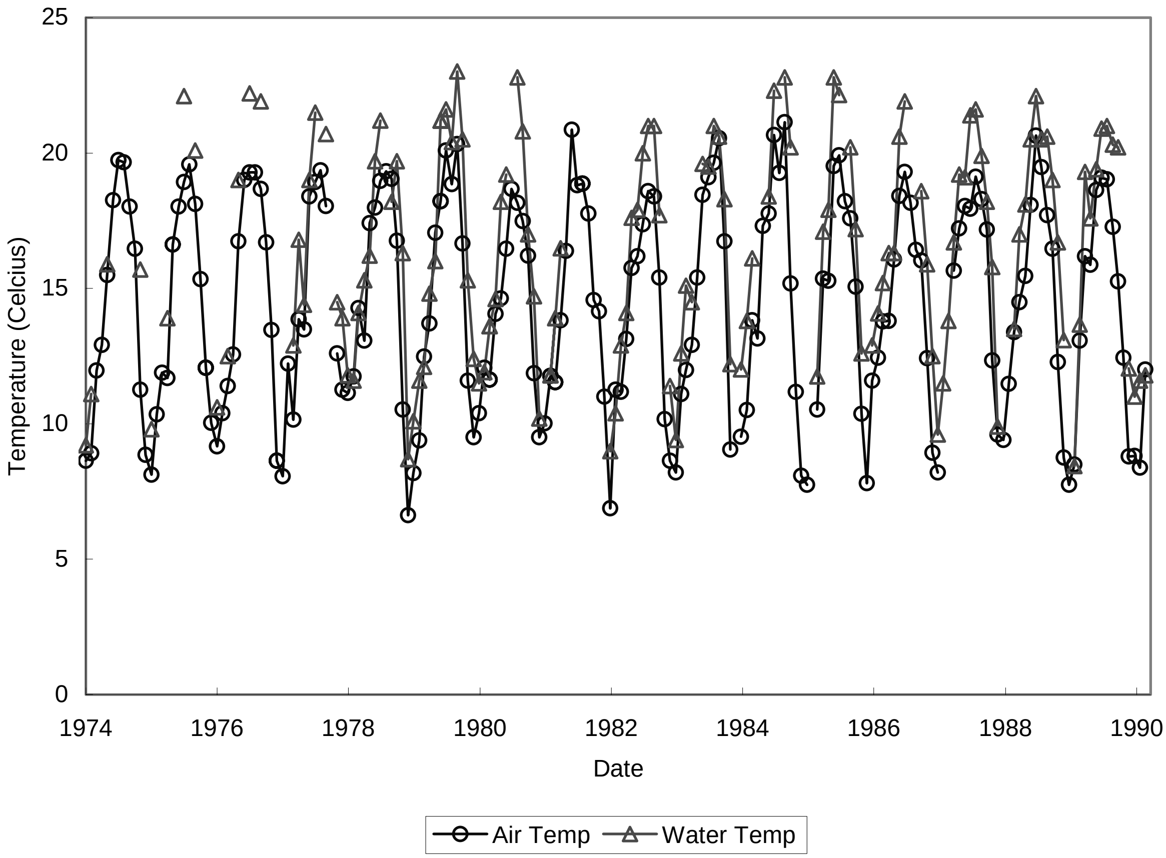
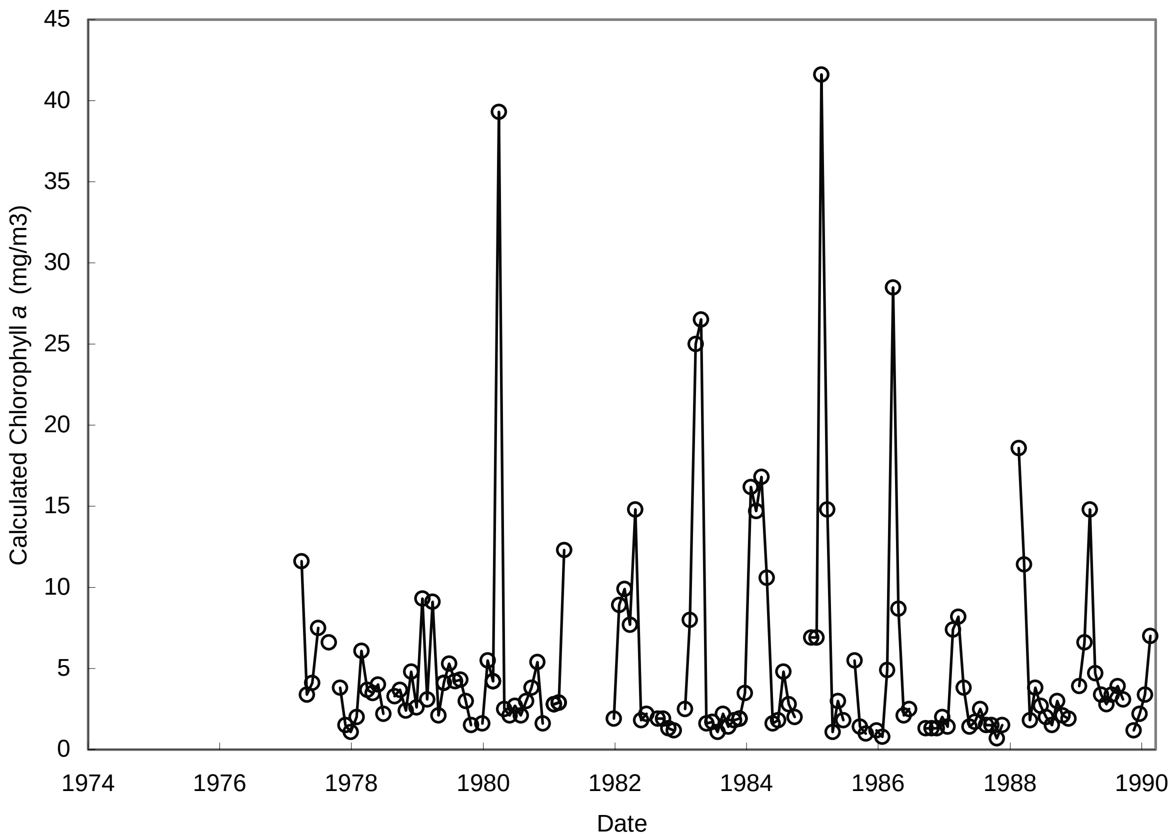

25
20
15
10
5
0
Temperature (Celcius)
1974
1976
1978
1980
1982
1984
1986
1988
1990
Date
Air Temp
Water Temp

Figure 7. Monthly calculated cholorphyll *a* measurements from South San Francisco Bay fluctuate seasonally. Bloom events (measurements of >10 mg/m^3 in the South Bay) occur in the spring. Abnormally large bloom events occurred in 1980, 1983, 1985, 1986 and 1988.



45
40
35
30
25
20
15
10
5
0
Calculated Chlorophyll *a* (mg/m3)
1974
1976
1978
1980
1982
1984
1986
1988
1990
Date

Figure 8. The percentage of Total Organic Carbon (TOC) in the sediments has remained relatively stable throughout the time series. TOC does show seasonal fluctuations, with lower values in the summer months.

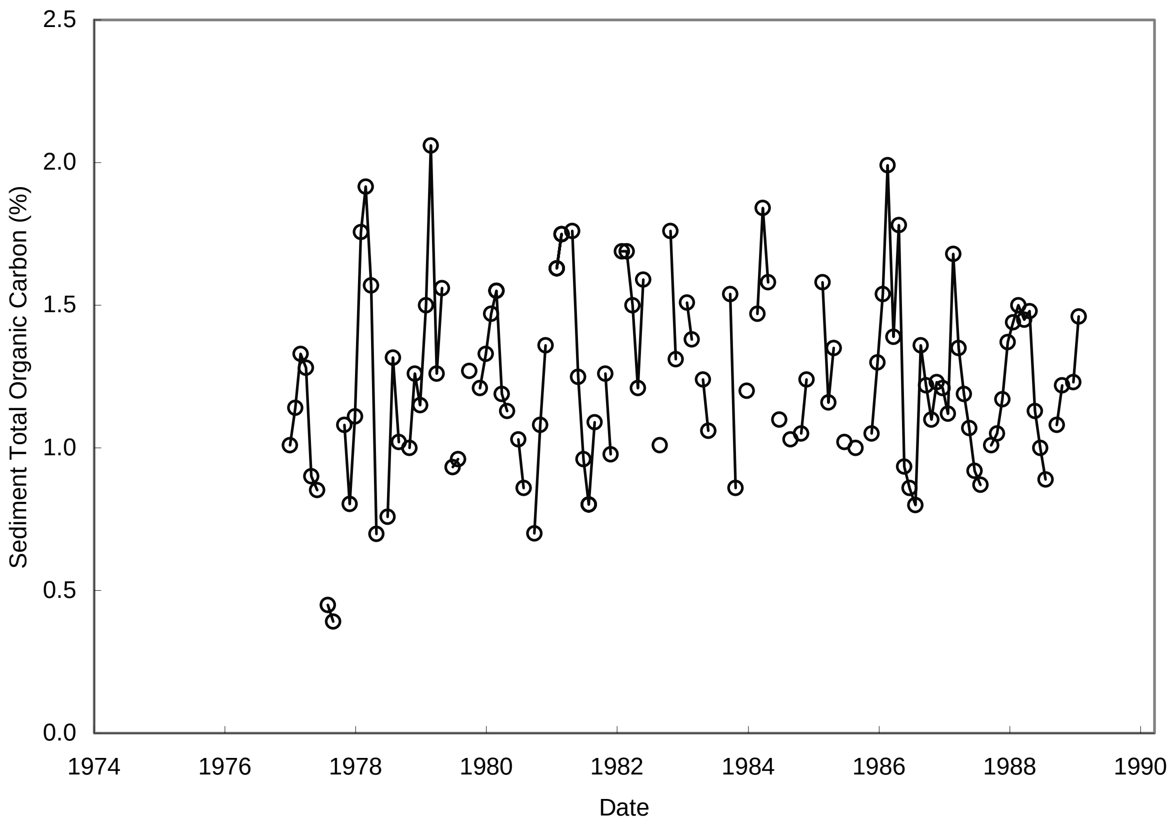

Sediment Total Organic Carbon (%)
0.0
0.5
1.0
1.5
2.0
2.5
1974
1976
1978
1980
1982
1984
1986
1988
1990
Date

Figure 9. Biological Oxygen Demand (BOD) from San Jose/Santa Clara Water Pollution Control Plant shows a step function drop in January of 1981. This is due to the implementation of tertiary treatment at the facility. Following the implementation of tertiary treatment, BOD levels remain very low and stable.

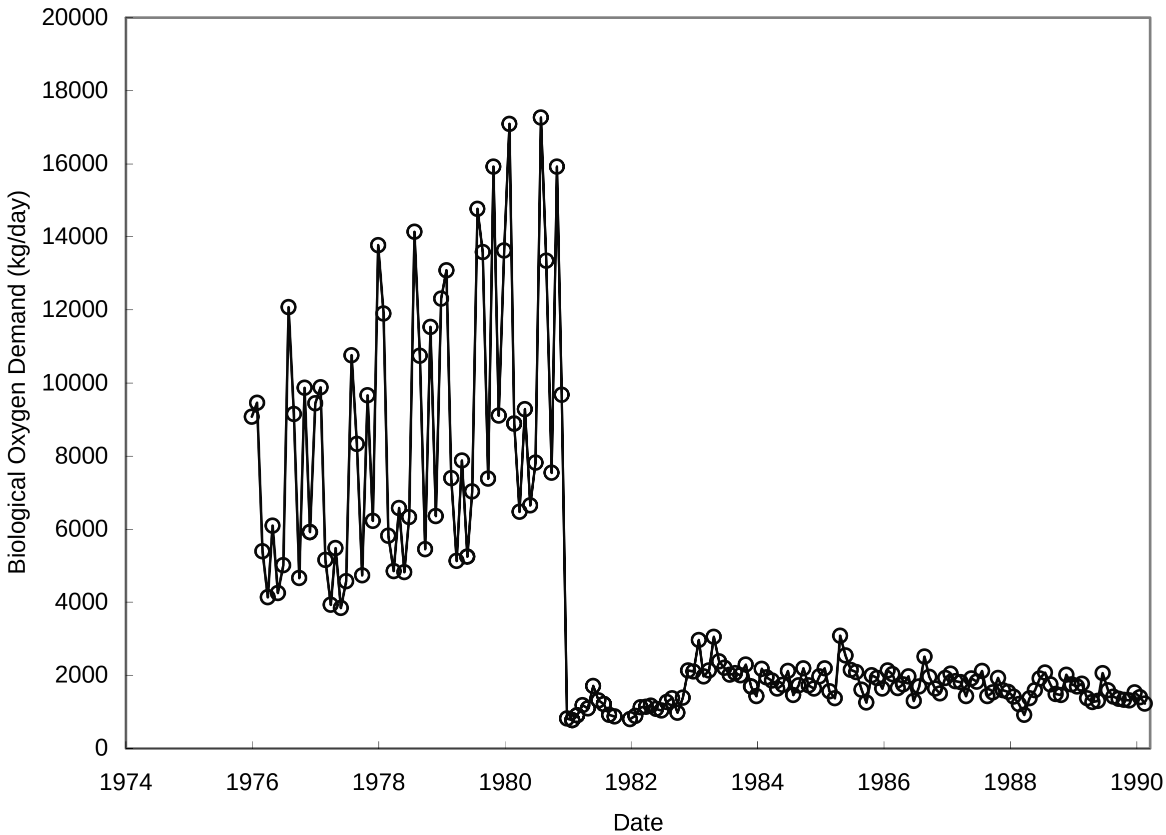

Biological Oxygen Demand (kg/day)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
1974
1976
1978
1980
1982
1984
1986
1988
1990
Date

Figure 10. Decreasing copper concentrations in the tissues of *M. balthica* are compared to decreasing concentrations found in the sediment. There is general similarity between the two measures. However, the concentrations in the sediment level off in the mid-1980's while the concentrations in the tissues of the clam continue to fall.

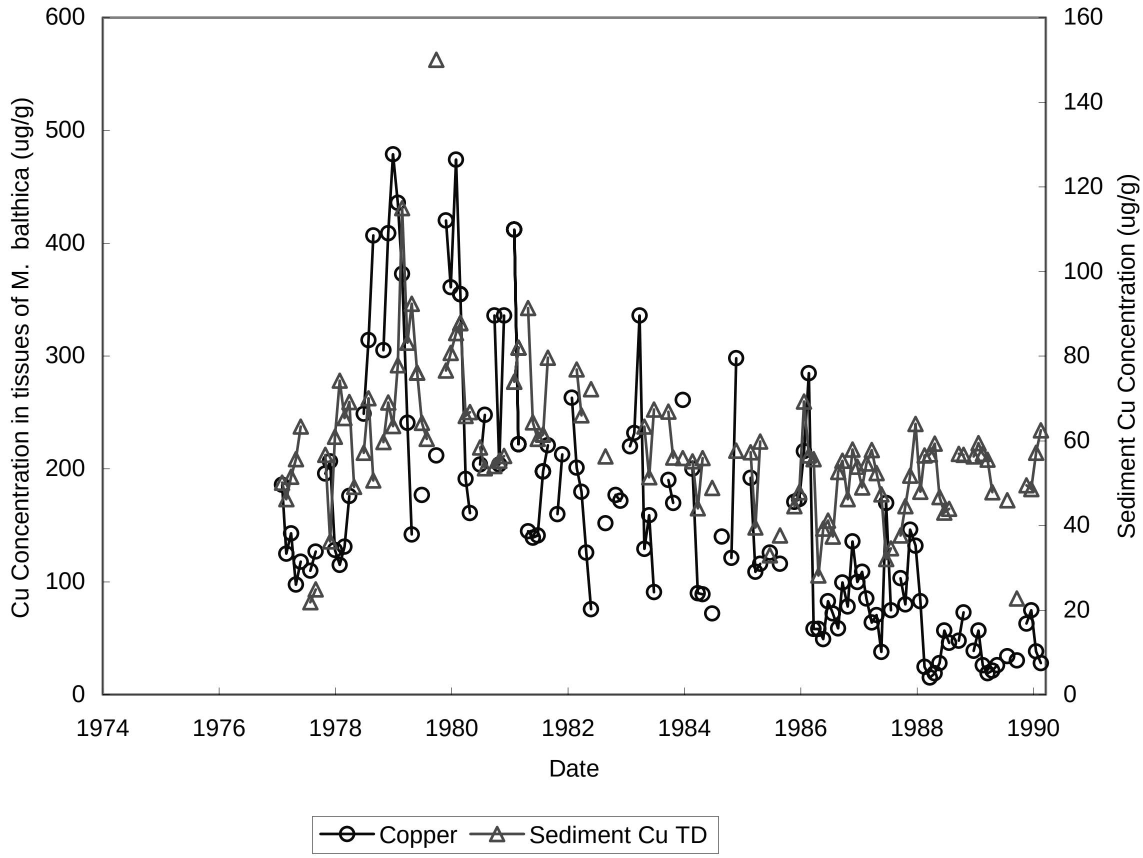
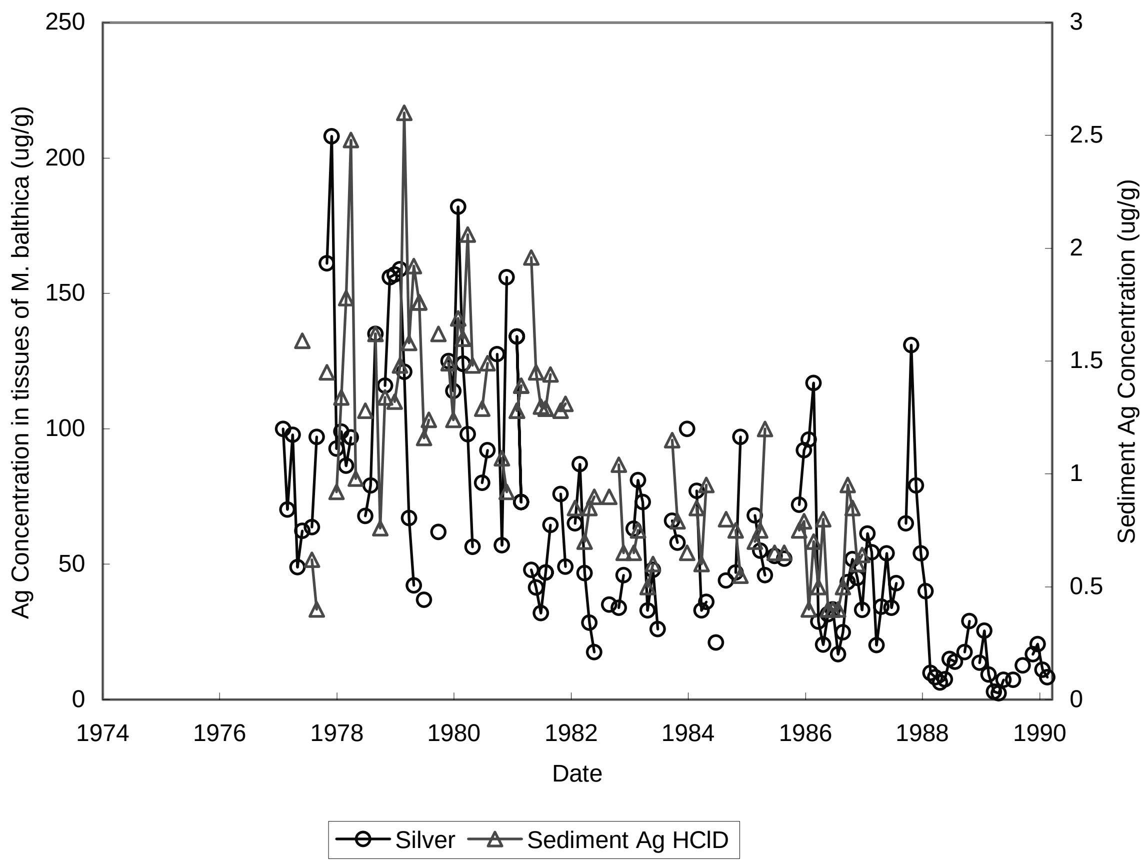

600
500
400
300
200
100
0
160
140
120
100
80
60
40
20
0
1974
1976
1978
1980
1982
1984
1986
1988
1990
Cu Concentration in tissues of M. balthica (ug/g)
Sediment Cu Concentration (ug/g)
Date
Copper
Sediment Cu TD

Figure 11. Decreasing silver concentrations in the tissues of *M. balthica* are compared to decreasing concentrations found in the sediment. The two timeseries are very similar up to 1987 when the silver concentrations in the sediment stopped being collected.



250
200
150
100
50
0
3
2.5
2
1.5
1
0.5
0
1974
1976
1978
1980
1982
1984
1986
1988
1990
Date
Ag Concentration in tissues of M. balthica (ug/g)
Sediment Ag Concentration (ug/g)
Silver
Sediment Ag HCID

Figure 12. Total animal abundance per sampling date decreased at both stations (45 & 46), as demonstrated by the linear trendlines applied to the timeseries. The trend for St. 46 is greater than the one seen for St. 45 due to the high abundances seen in 1974 and 1975

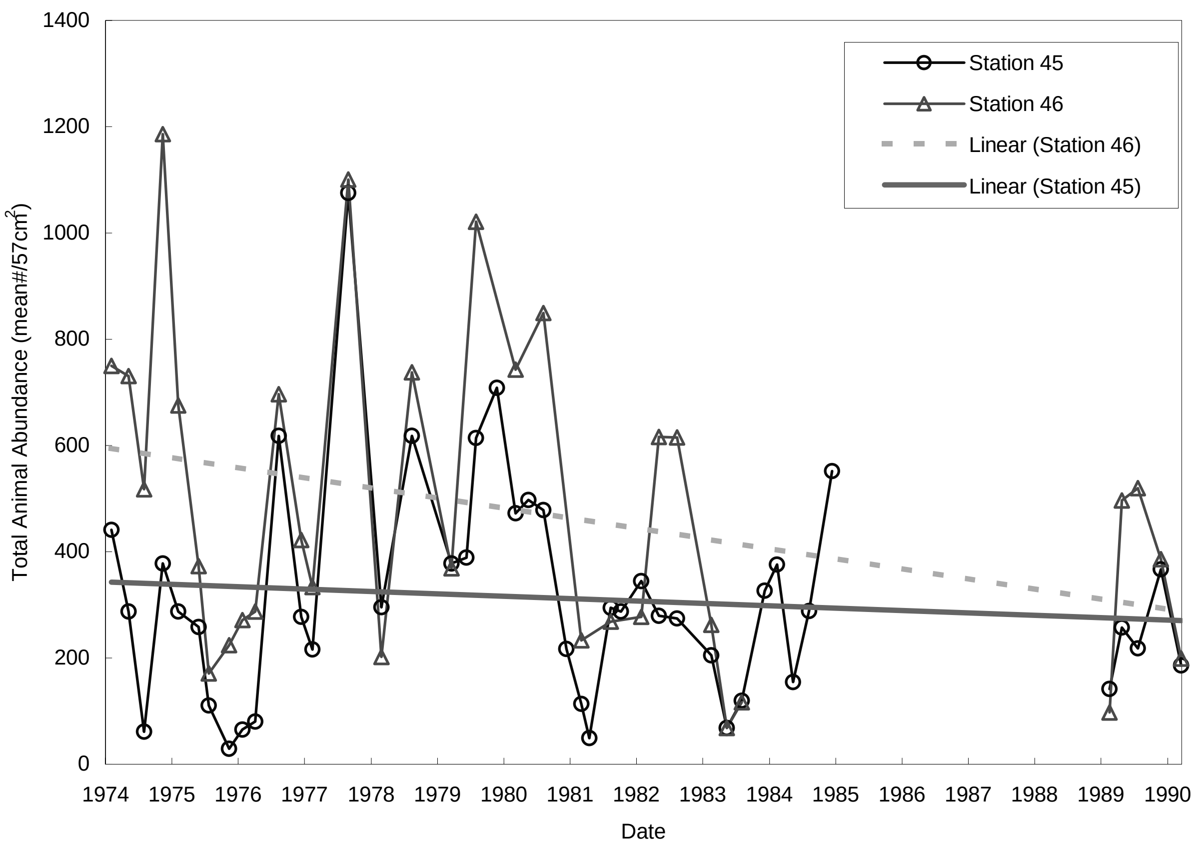

Station 45
Station 46
Linear (Station 46)
Linear (Station 45)
Total Animal Abundance (mean#/57cm^2)
Date
0
200
400
600
800
1000
1200
1400
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990

Figure 13. A comparison of the number of taxa at both stations (45 & 46) shows similarity between stations. Fluctuations occur in the data, but are not consistent.

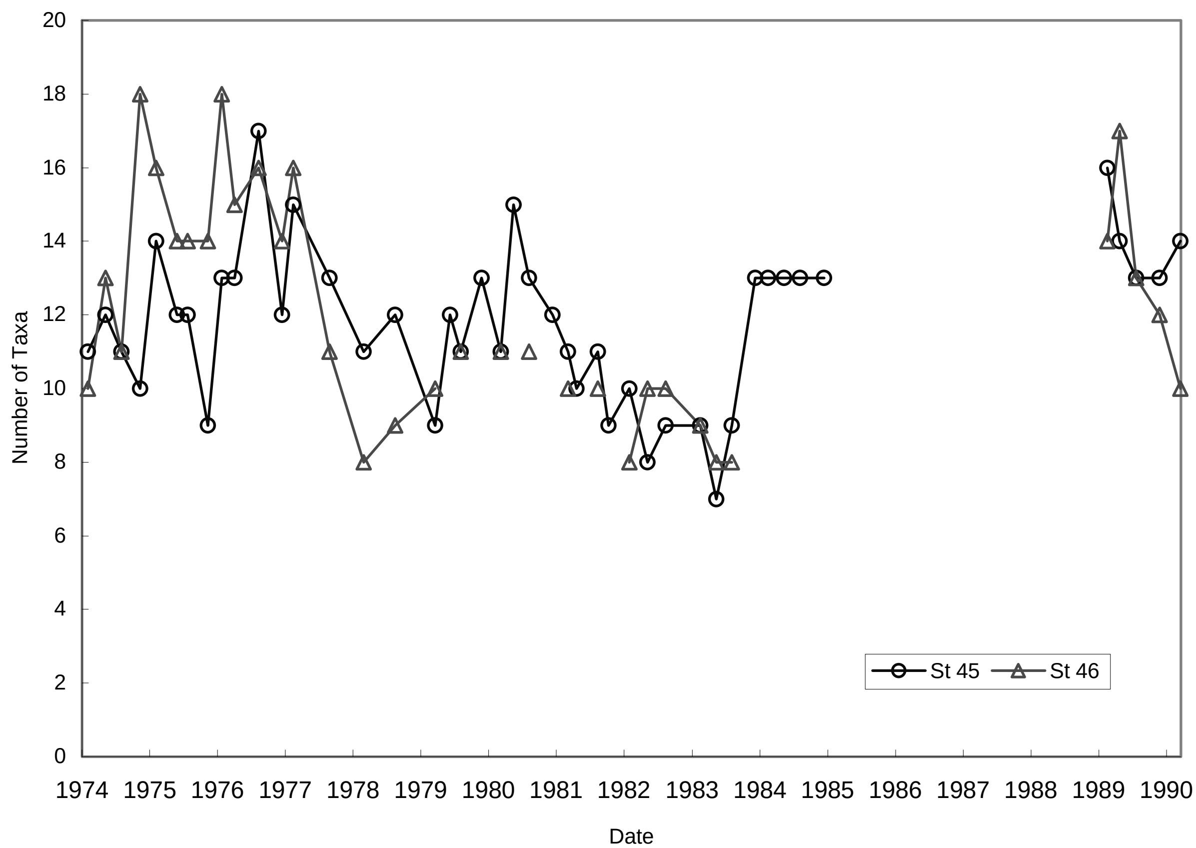
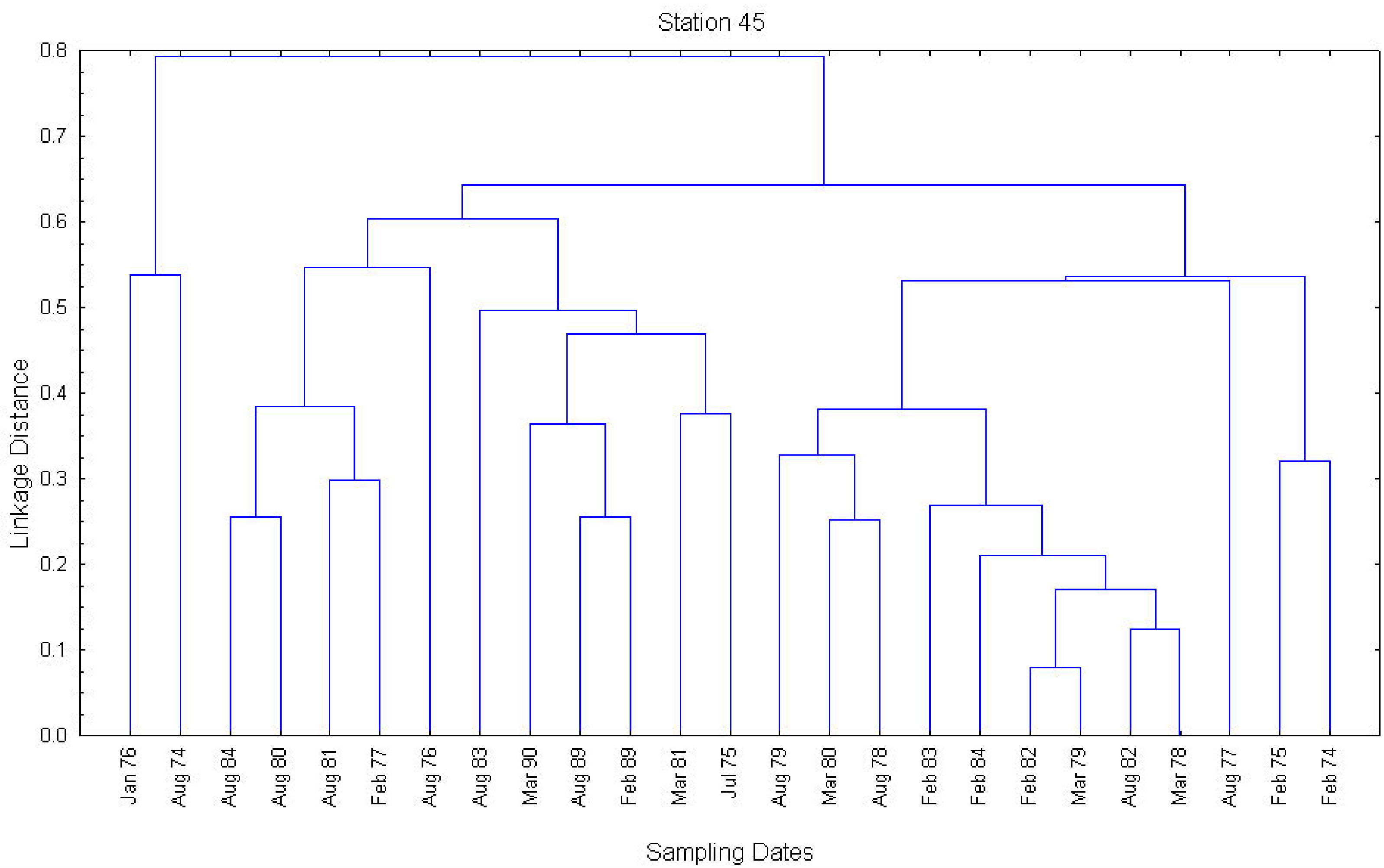
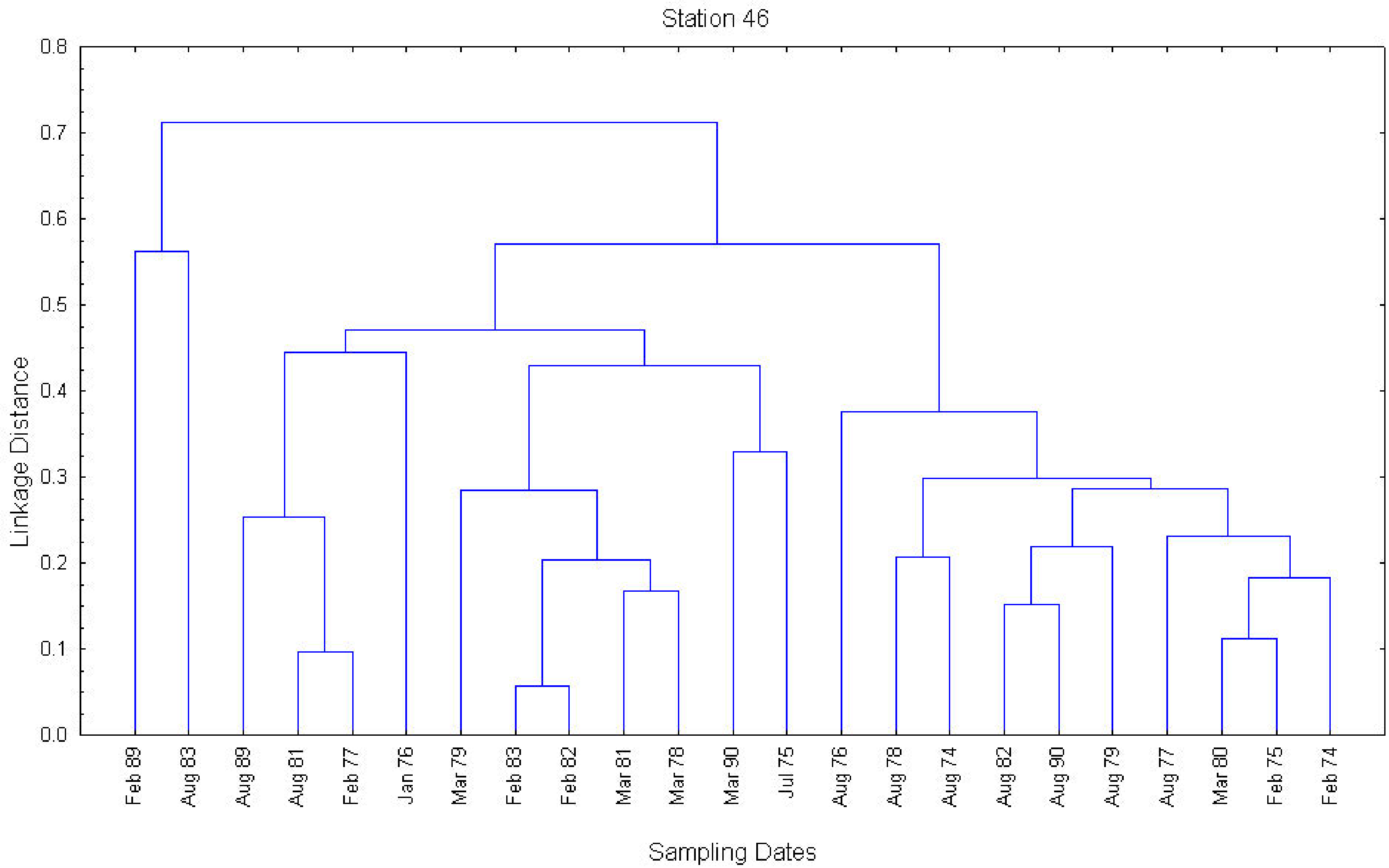

20
18
16
14
12
10
8
6
4
2
0
Number of Taxa
1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990
Date
St 45
St 46

Figure 14. Cluster tree diagram for sampling dates at St. 45. The cluster tree reveals a complex community. The first branching is driven by the extreme low abundances of all species for January 1976 and August 1974. The second branching separates sampling dates with low abundances of the bivalve *Gemma gemma* from sampling dates with high abundances of *G gemma*. Additional branchings in each group are driven by the seasons or by wet and dry years.



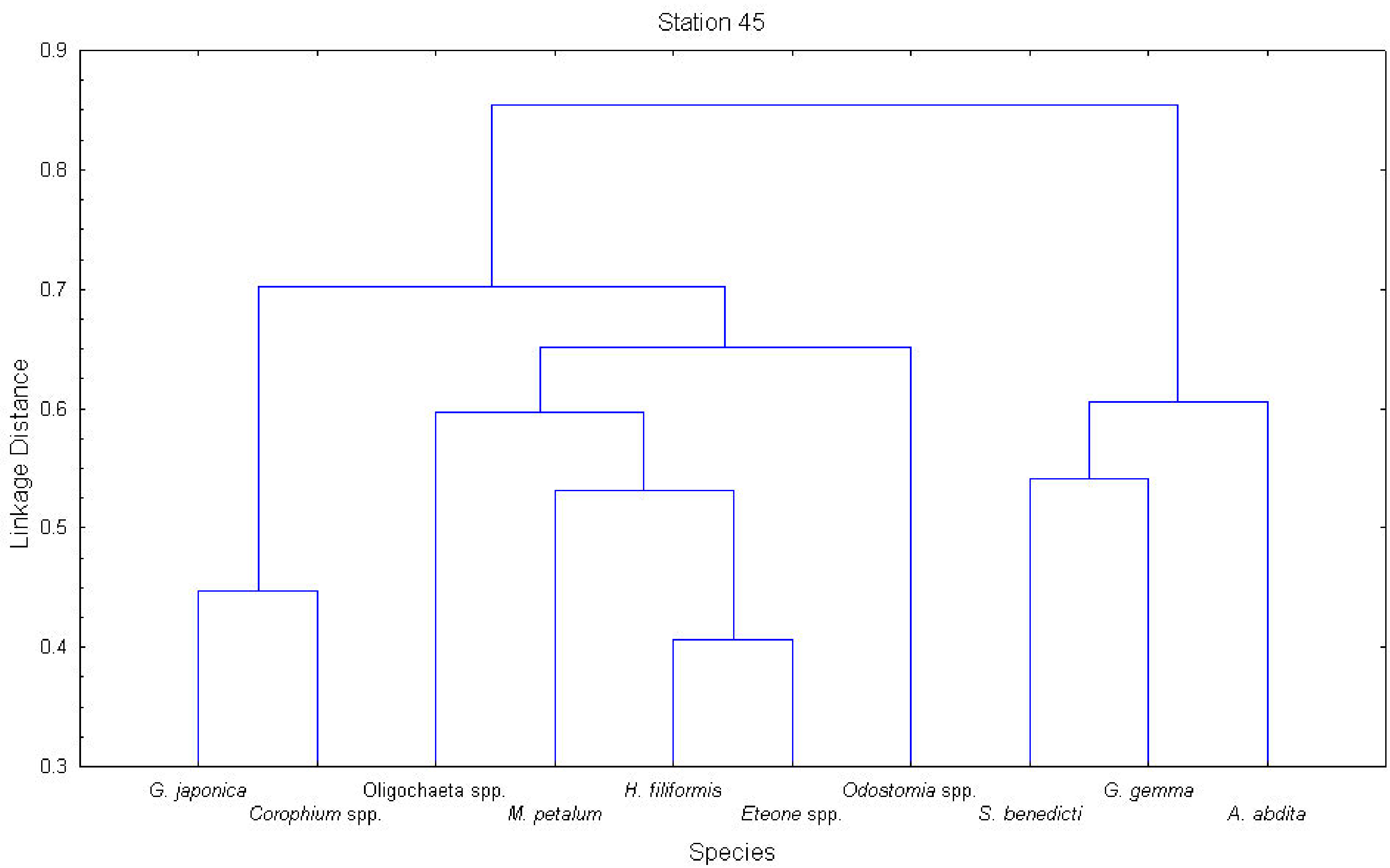
Station 45
Linkage Distance
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Jan 76
Aug 74
Aug 84
Aug 80
Aug 81
Feb 77
Aug 76
Aug 83
Mar 90
Aug 89
Feb 89
Mar 81
Jul 75
Aug 79
Mar 80
Aug 78
Feb 83
Feb 84
Feb 82
Mar 79
Aug 82
Mar 78
Aug 77
Feb 75
Feb 74
Sampling Dates

Figure 15. Cluster tree diagram for sampling dates at St. 46. The cluster tree reveals a complex community. The first branching is driven by the extreme low abundances of all species for February 1989 and August 1983. The second branching separates sampling dates with low abundances of the bivalve *Gemma gemma* from sampling dates with high abundances of *G gemma*. Additional branchings in each group are driven by the seasons or by wet and dry years, similar to the cluster trees for St. 45.



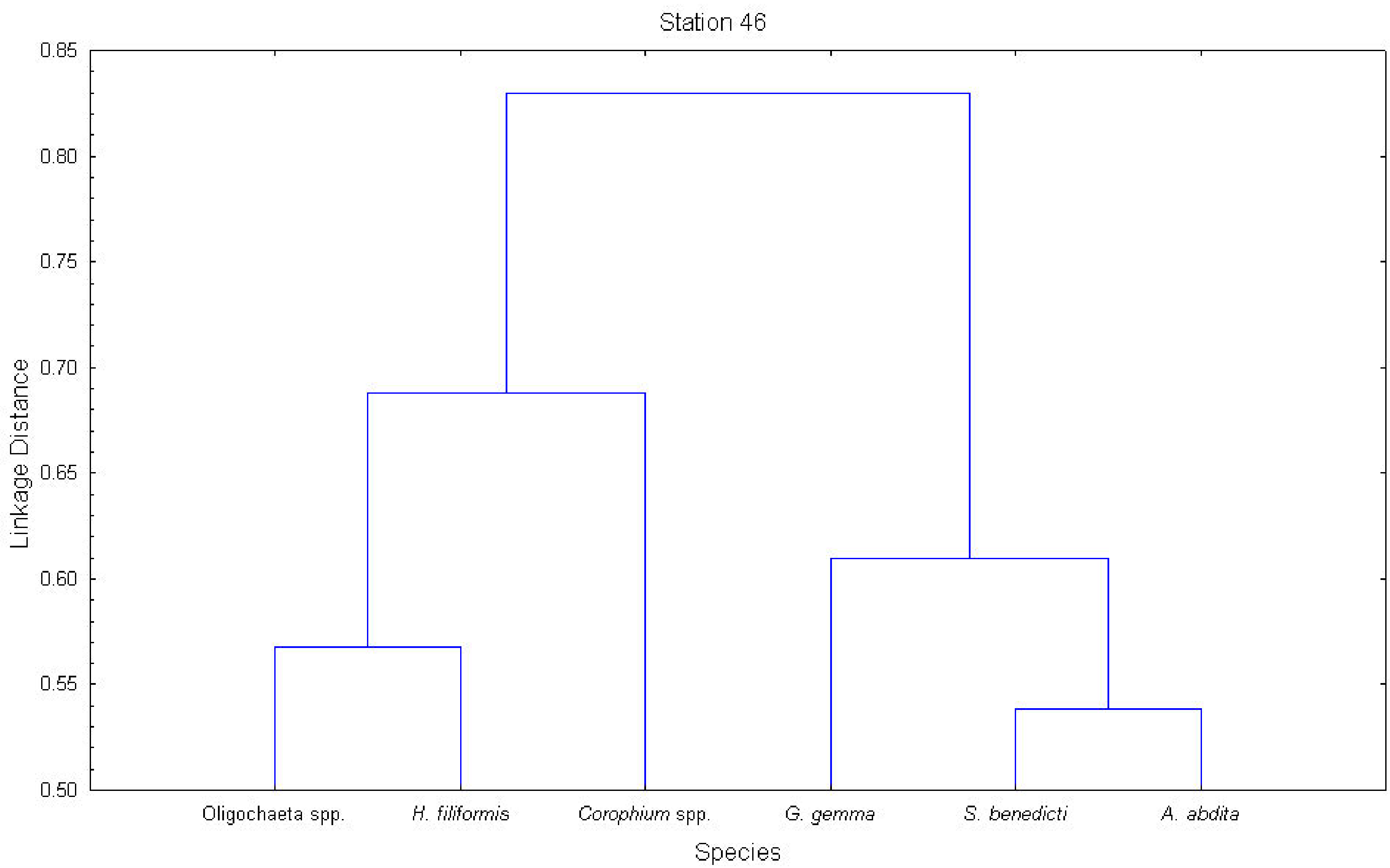
Station 46
Linkage Distance
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Feb 89
Aug 83
Aug 89
Aug 81
Feb 77
Jan 76
Mar 79
Feb 83
Feb 82
Mar 81
Mar 78
Mar 90
Jul 75
Aug 76
Aug 78
Aug 74
Aug 82
Aug 90
Aug 79
Aug 77
Mar 80
Feb 75
Feb 74
Sampling Dates

Figure 16. Cluster tree diagram for the dominant species relationships at St. 45. The first branching isolates three species (*Streblospio benedicti, G. gemma* and *Ampelisca* abdita) from the rest. The second branch isolates the crustaceans *Grandiderella japonica* and *Corophium* spp. from the remaining dominant species.



Station 45
Linkage Distance
0.9
0.8
0.7
0.6
0.5
0.4
0.3
G. japonica
Corophium spp.
Oligochaeta spp.
M. petalum
H. filiformis
Eteone spp.
Odostomia spp.
S. benedicti
G. gemma
A. abdita
Species

Figure 17. Cluster tree diagram for the dominant species relationships at St. 46. The first branching isolates three species (*S. benedicti, G. gemma* and *Ampelisca* abdita) from the rest. The second branching isolates the crustacean *G. japonica* from Oligochaeta spp. and *Heteromastus filiformis*.

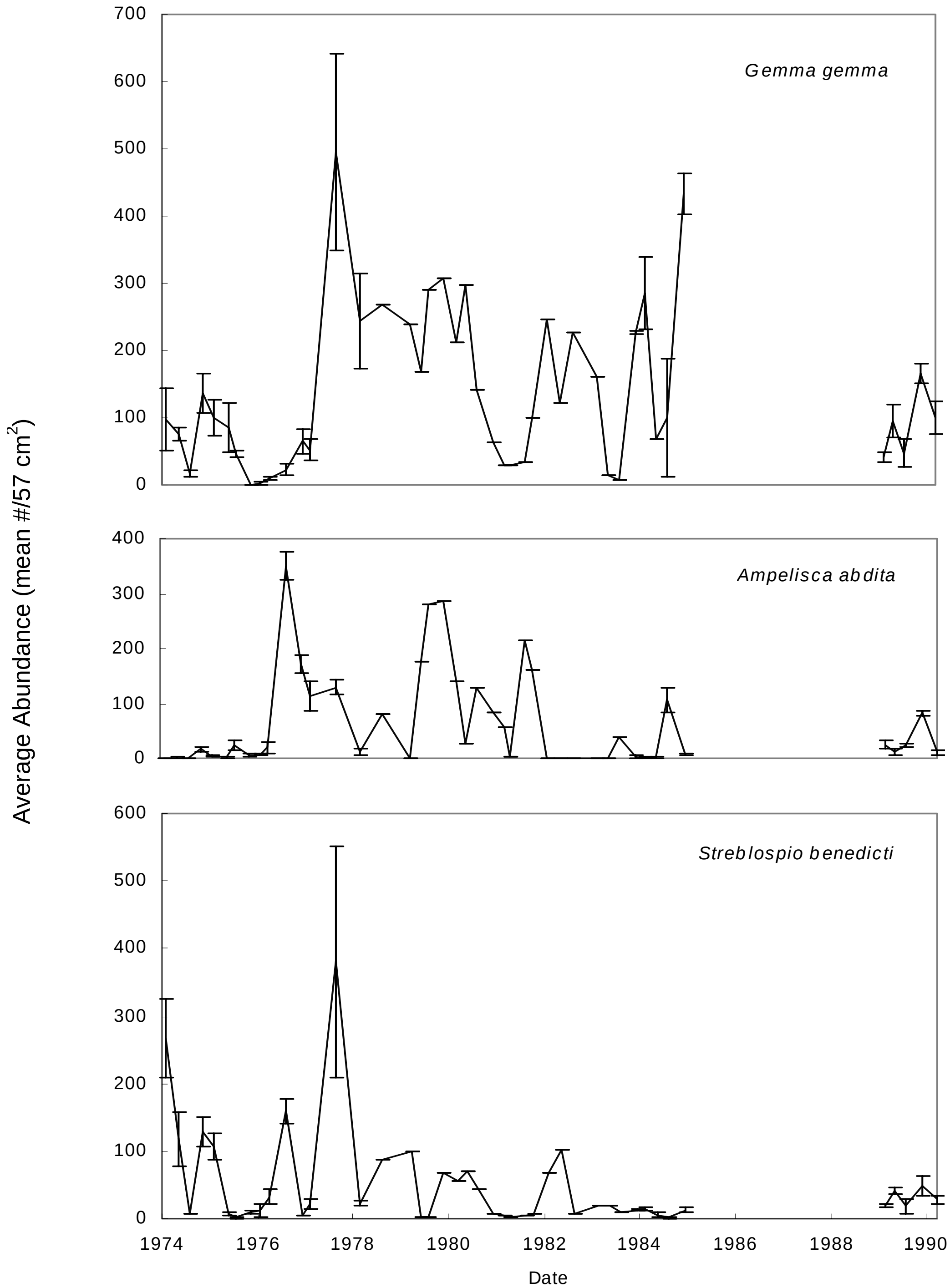


Station 46
Linkage Distance
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
Oligochaeta spp.
H. filiformis
Corophium spp.
G. gemma
S. benedicti
A. abdita
Species

Table 4. Species present at St. 45 throughout the timeseries. Species are grouped by taxonomic classifications. When the use of Order is not appropriate, the level of classification used is written in italics in the Order column.

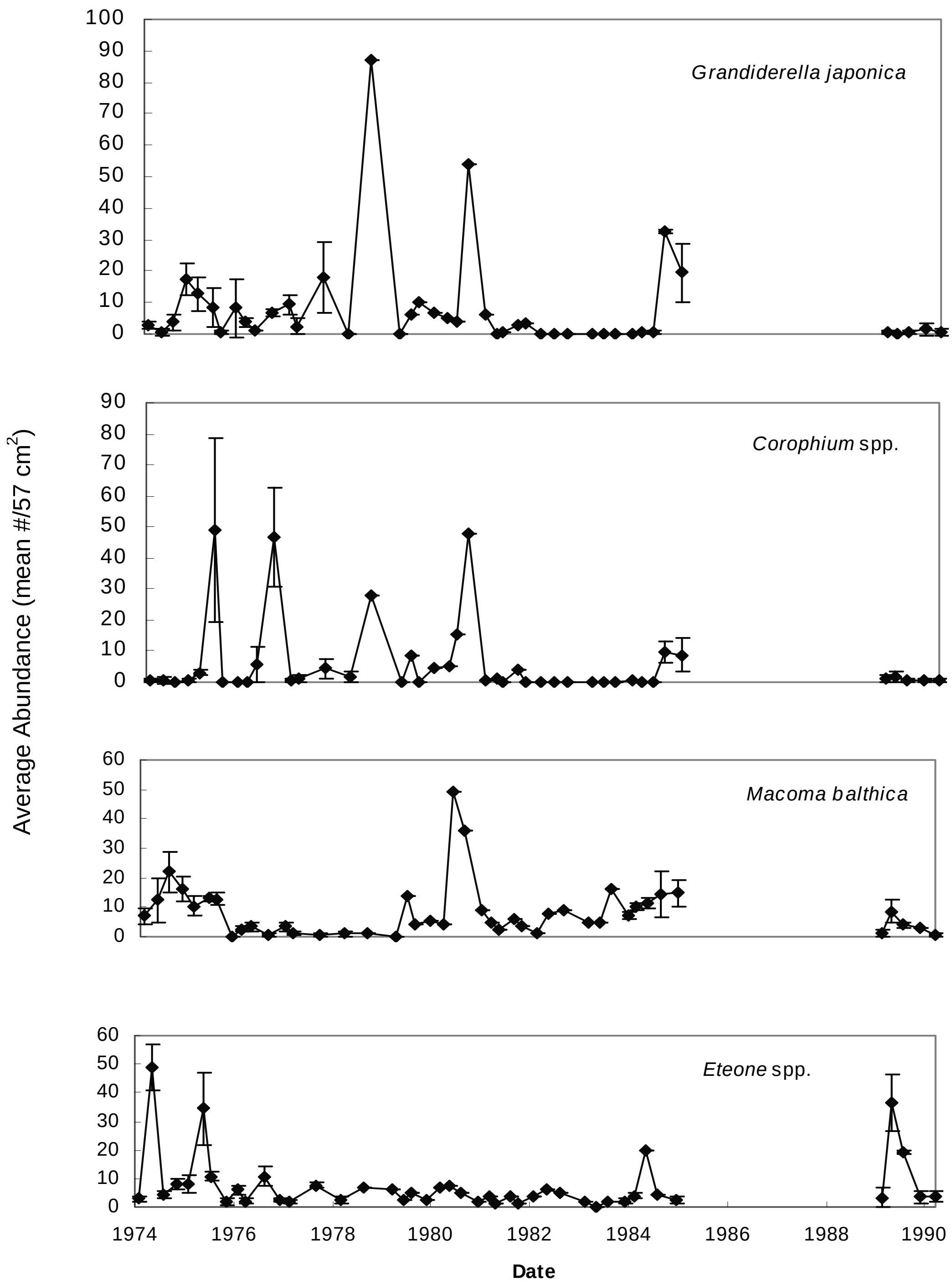
Phylum	Order	Species
Annelida	Oligochaeta	Oligochaeta spp.
	Polychaeta	*Capitella capitata*
		Eteone spp.
		Euchone sp.
		Glycera sp.
		Heteromastus filiformis
		Maldanidae
		Marphysa sanguinea
		Neanthes succinea
		Polydora cornuta
		Pseudopolydora kempi
		Sphaerosyllis sp.
		Streblospio benedicti
		Tharyx sp.
Arthropoda	Amphipoda	*Ampelisca abdita*
		Corophium spp.
		Grandiderella japonica
		Melita sp.
	Isopoda	*Sphaeroma quoyana*
		Synidotea laticauda
	Subclass Cirripedia	*Cirripedia* sp.
Cnidaria	*Class* Anthozoa	Anthozoa sp.
Mollusca	Bivalvia	*Gemma gemma*
		Macoma balthica
		Musculista senhousia
		Mya arenaria
		Potamocorbula amurensis
	Gastropoda	*Odostomia spp.*
		Ilyanassa obsoleta

Figure 18. Abundances of the three most abundant species, *G. gemma, A. abdita,* and *S. benedicti*. These animals account for 80% of the total animal abundance throughout the timeseries.



Average Abundance (mean #/57 cm^2)
700
600
500
400
300
200
100
0
Gemma gemma
400
300
200
100
0
Ampelisca abdita
600
500
400
300
200
100
0
Streblospio benedicti
1974
1976
1978
1980
1982
1984
1986
1988
1990
Date

Figure 19. Abundances of *G. japonica, Corophium* spp., *M. balthica* and *Eteone* spp. throughout the timeseries.



Average Abundance (mean #/57 cm²)
100
90
80
70
60
50
40
30
20
10
0
Grandiderella japonica
Corophium spp.
Macoma balthica
Eteone spp.
1974
1976
1978
1980
1982
1984
1986
1988
1990
Date

Figure 20. Abundances of the polychaetes Oligochaeta spp. and *H. filiformis* throughout the timeseries.

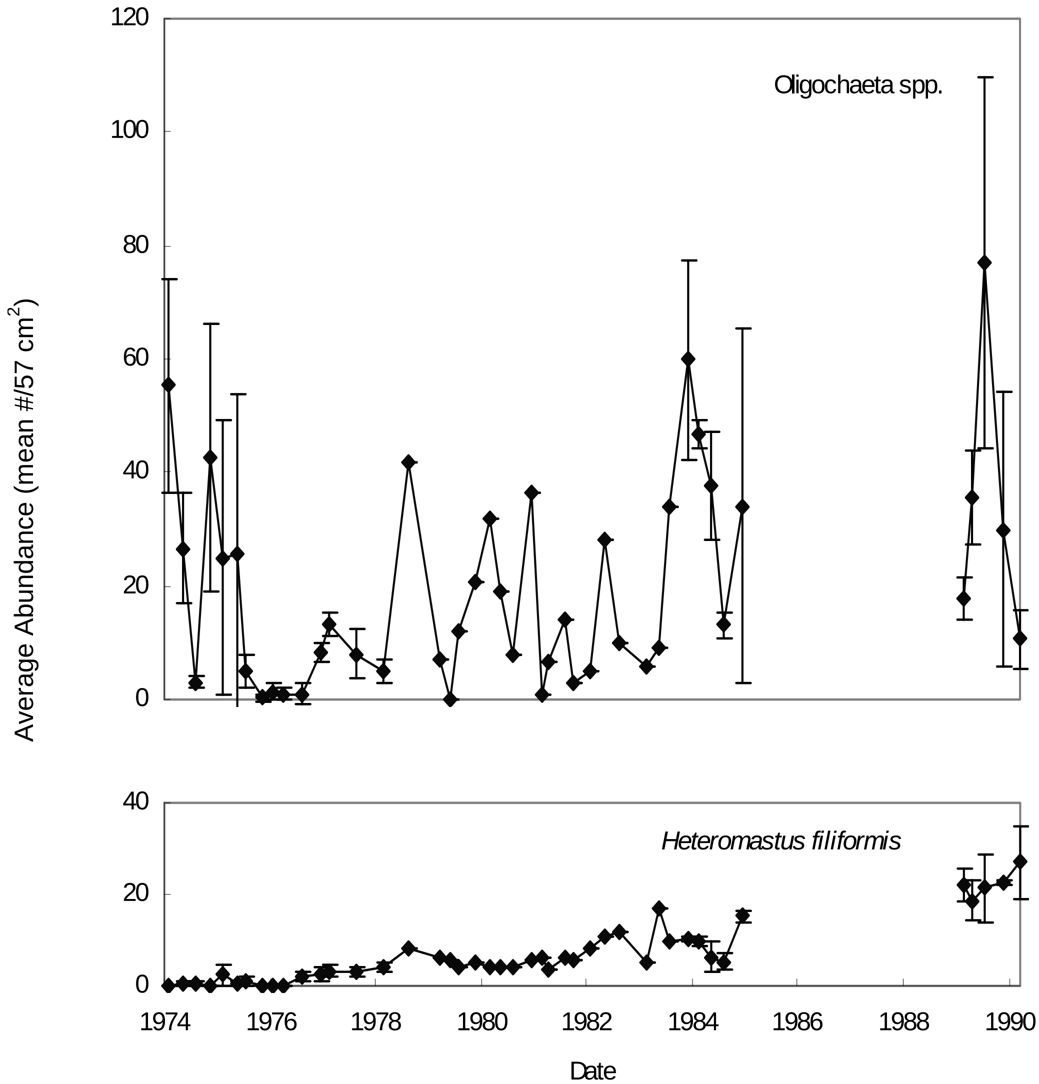
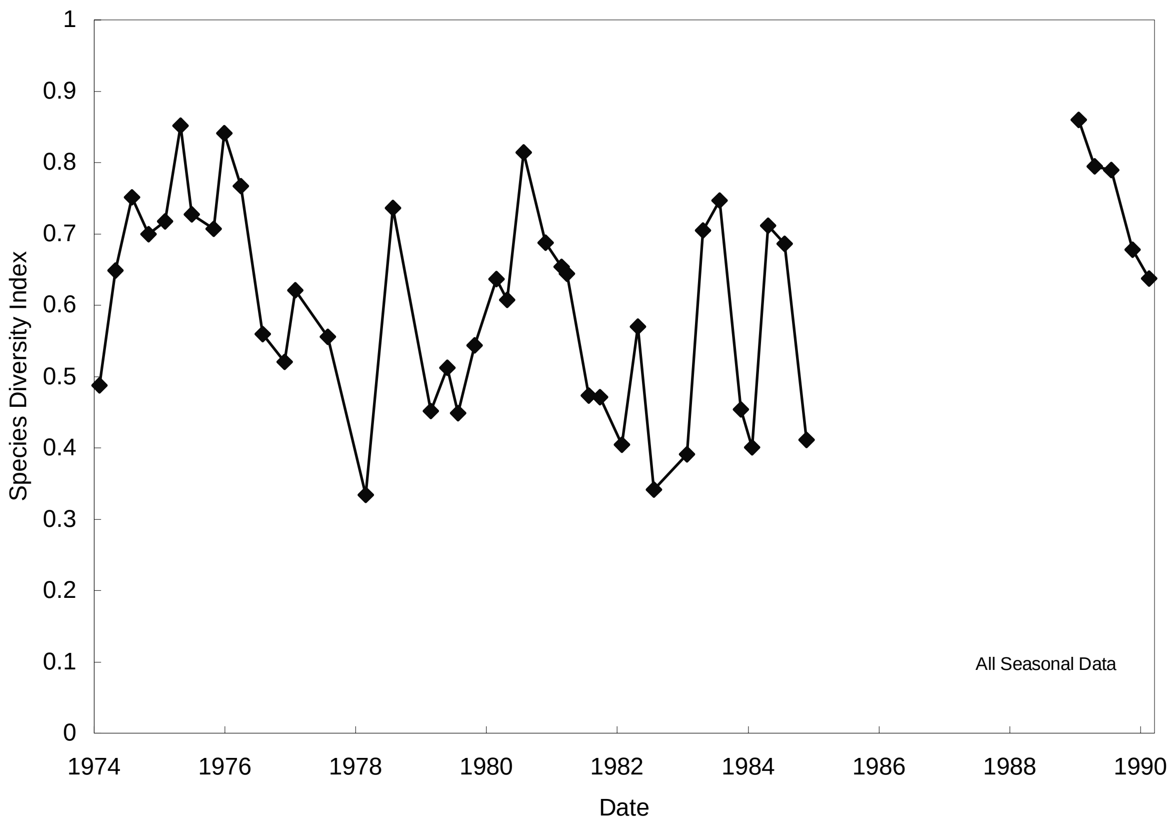

Average Abundance (mean #/57 cm^2)
Oligochaeta spp.
Heteromastus filiformis
120
100
80
60
40
20
0
1974
1976
1978
1980
1982
1984
1986
1988
1990
Date

Figure 21. Species diversity index (Shannon Weiner Index) for each sampling date in the timeseries. Fluctuations dominate the timeseries, with no trends.



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Species Diversity Index
1974
1976
1978
1980
1982
1984
1986
1988
1990
Date
All Seasonal Data

Figure 22. Species diversity indices separated by season. No seasonal trends are apparent.

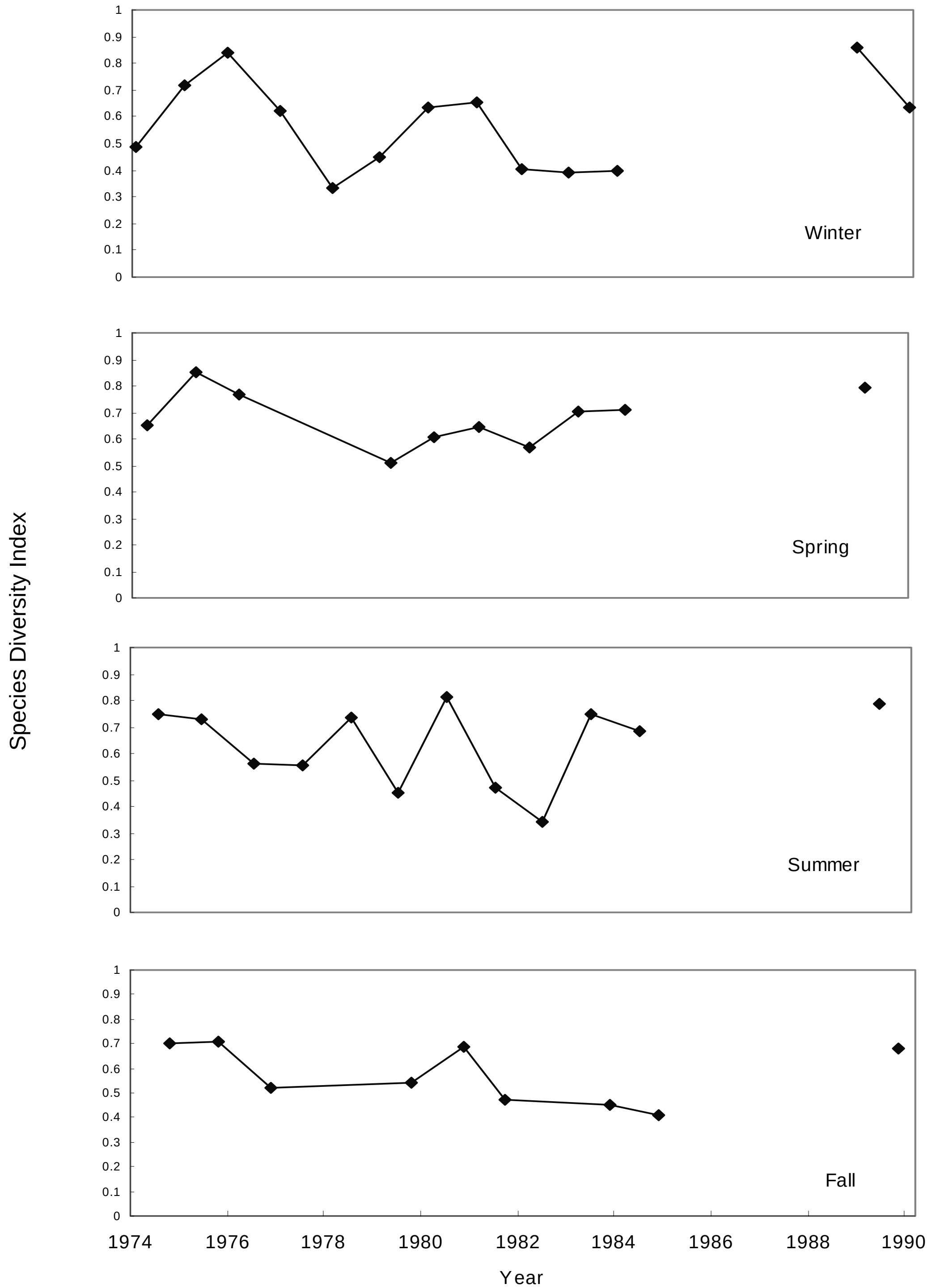

Species Diversity Index
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Winter
Spring
Summer
Fall
1974
1976
1978
1980
1982
1984
1986
1988
1990
Year

Figure 23. Species ranking by the log of their abundance. Curves reflect the relative similarities in species abundances between the ranks for the winter of two years. The year 1977 was prior to the implementation of tertiary treatment, and the year 1989 was post tertiary treatment implementation. The curve for 1989 is a shallower curve than is observed for 1977.

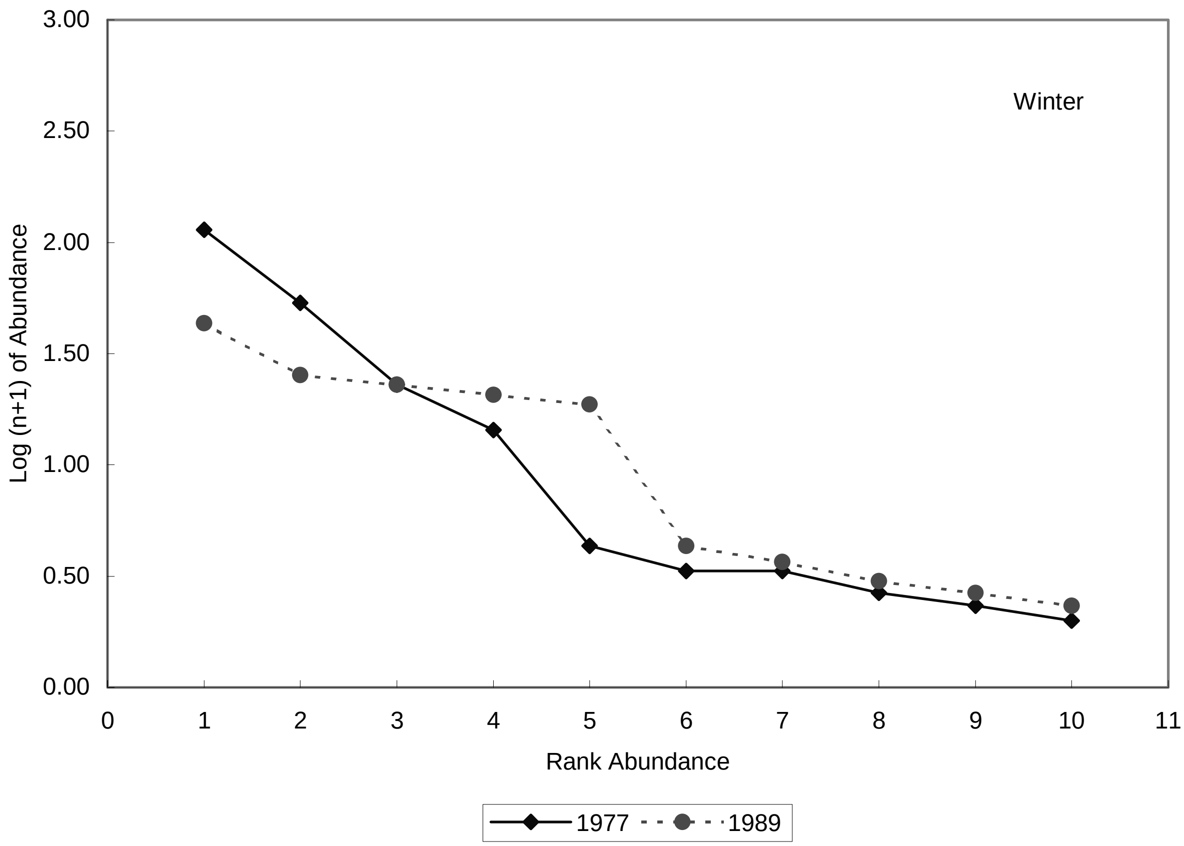

3.00
2.50
2.00
1.50
1.00
0.50
0.00
Log (n+1) of Abundance
Winter
0
1
2
3
4
5
6
7
8
9
10
11
Rank Abundance
1977
1989

Figure 24. Species ranking by the log of their abundance. Curves reflect the relative similarities in species abundances between the ranks for the summer of two years. The year 1977 was prior to the implementation of tertiary treatment, and the year 1989 was post tertiary treatment implementation. The curve for 1989 is much shallower than is observed for 1977. The curve for 1977 is highly dominated by the first three ranked species.

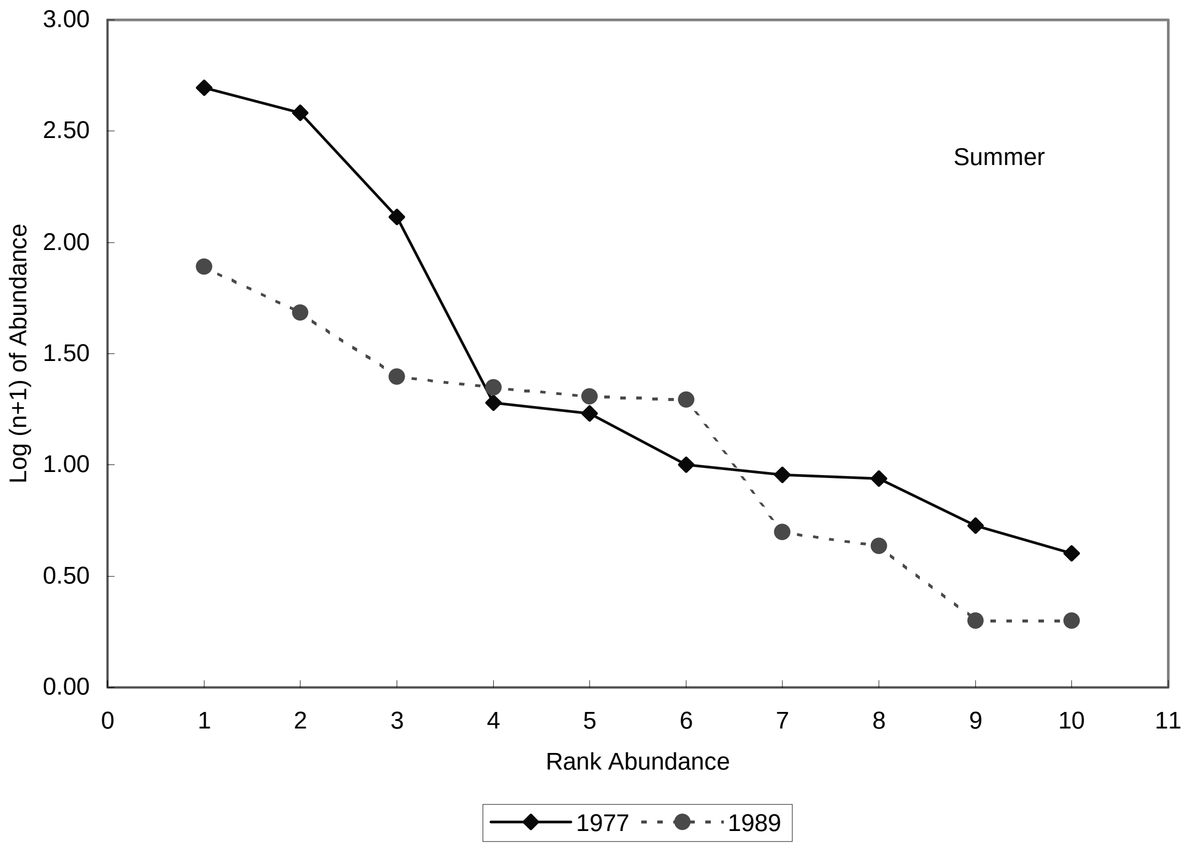

Summer
Log (n+1) of Abundance
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
1
2
3
4
5
6
7
8
9
10
11
Rank Abundance
1977
1989

Figure 25. Species rank abundance curves for the four seasons of 1976. Abundances between seasons vary greatly, with the highest abundances seen in the summer.

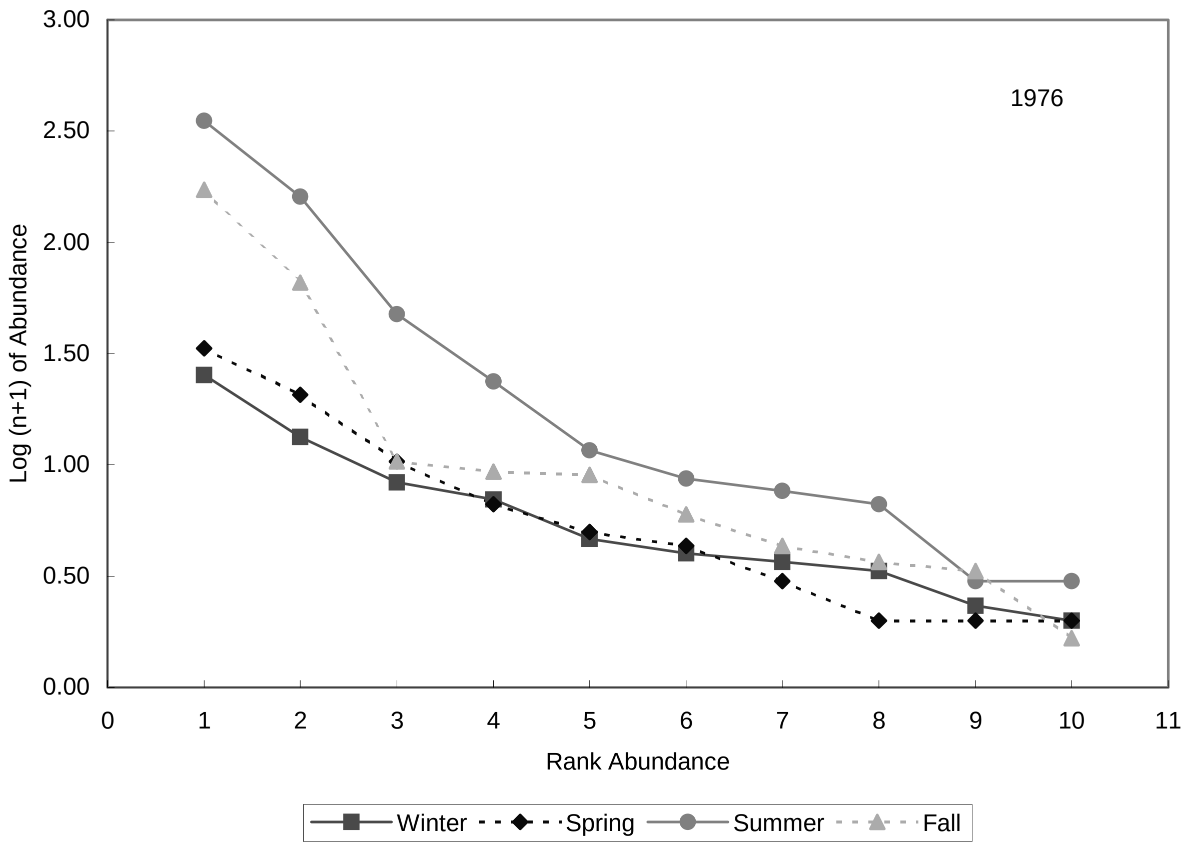

1976
Log (n+1) of Abundance
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
1
2
3
4
5
6
7
8
9
10
11
Rank Abundance
Winter
Spring
Summer
Fall

Figure 26. Species rank abundance curves for the four seasons of 1989. Abundances between seasons are fairly similar, with little domination of the community by the top ranking species.

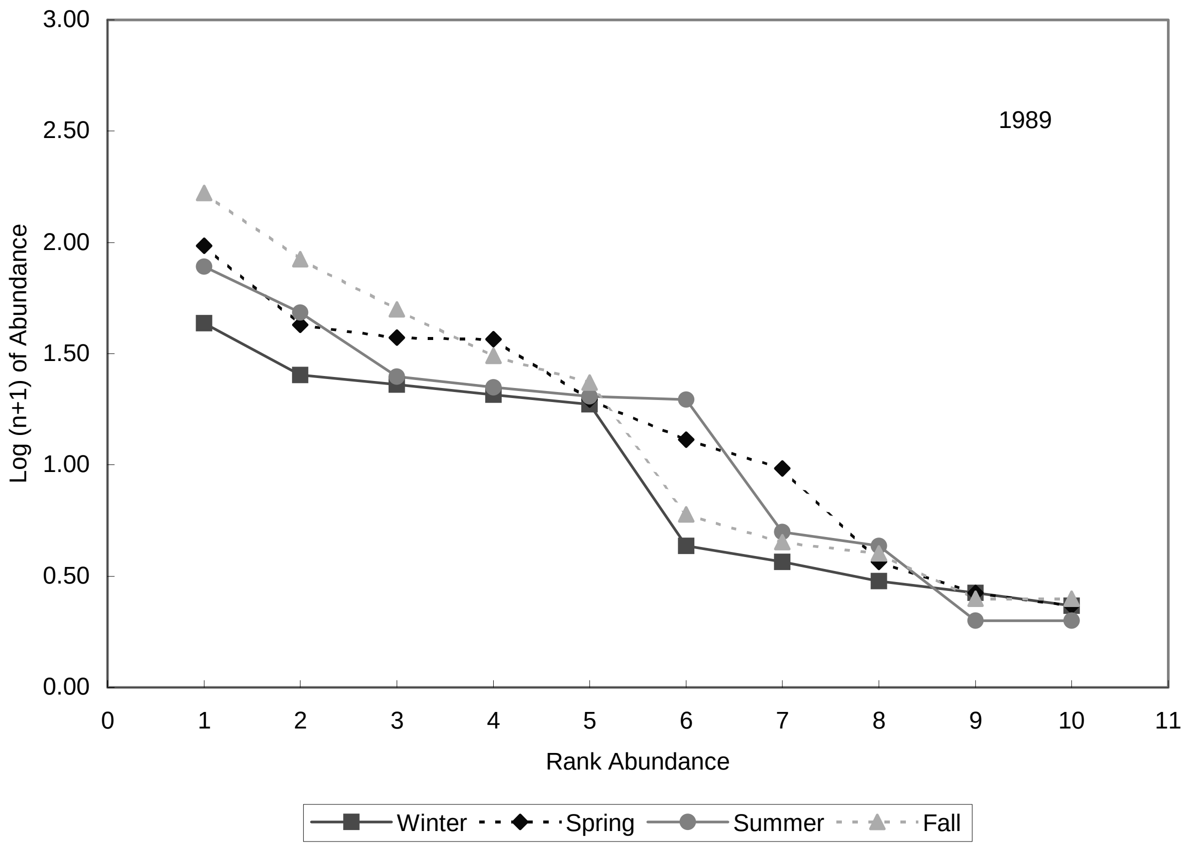

3.00
2.50
2.00
1.50
1.00
0.50
0.00
Log (n+1) of Abundance
1989
0
1
2
3
4
5
6
7
8
9
10
11
Rank Abundance
Winter
Spring
Summer
Fall

Table 5. Comparison of 1977 data to1989 data using Chi Square Analysis for summary statistics and species abundances. Direction of the change between the years is noted. Significance values are given only for categories with a significant difference between years.

Category	Direction of Change	Chi-Square Value	P-Value
Oligochaeta spp.	Increase	46.369	p<0.001
H. filiformis	Increase	27.567	p<0.001
Eteone sp.	Increase	5.565	p<0.02
Sphaerosyllis sp.	Increase	2.66	
M. balthica	Increase	1.523	
Tharyx sp.	Increase	0.443	
Number of Taxa	Increase	0.017	
Total Abundance	Decrease	524.877	p<0.001
G. gemma	Decrease	329.751	p<0.001
S. benedicti	Decrease	301.349	p<0.001
A. abdita	Decrease	129.484	p<0.001
G. japonica	Decrease	18.433	p<0.001
Odostomia spp.	Decrease	9.213	p<0.005
N. succinea	Decrease	4.481	p<0.05
M. arenaria	Decrease	2	
Corophium spp.	Decrease	1.926	
C. capitata	Decrease	1.000	
P. cornuta	Decrease	0.33	
I. obsoleta	No change	N/A	

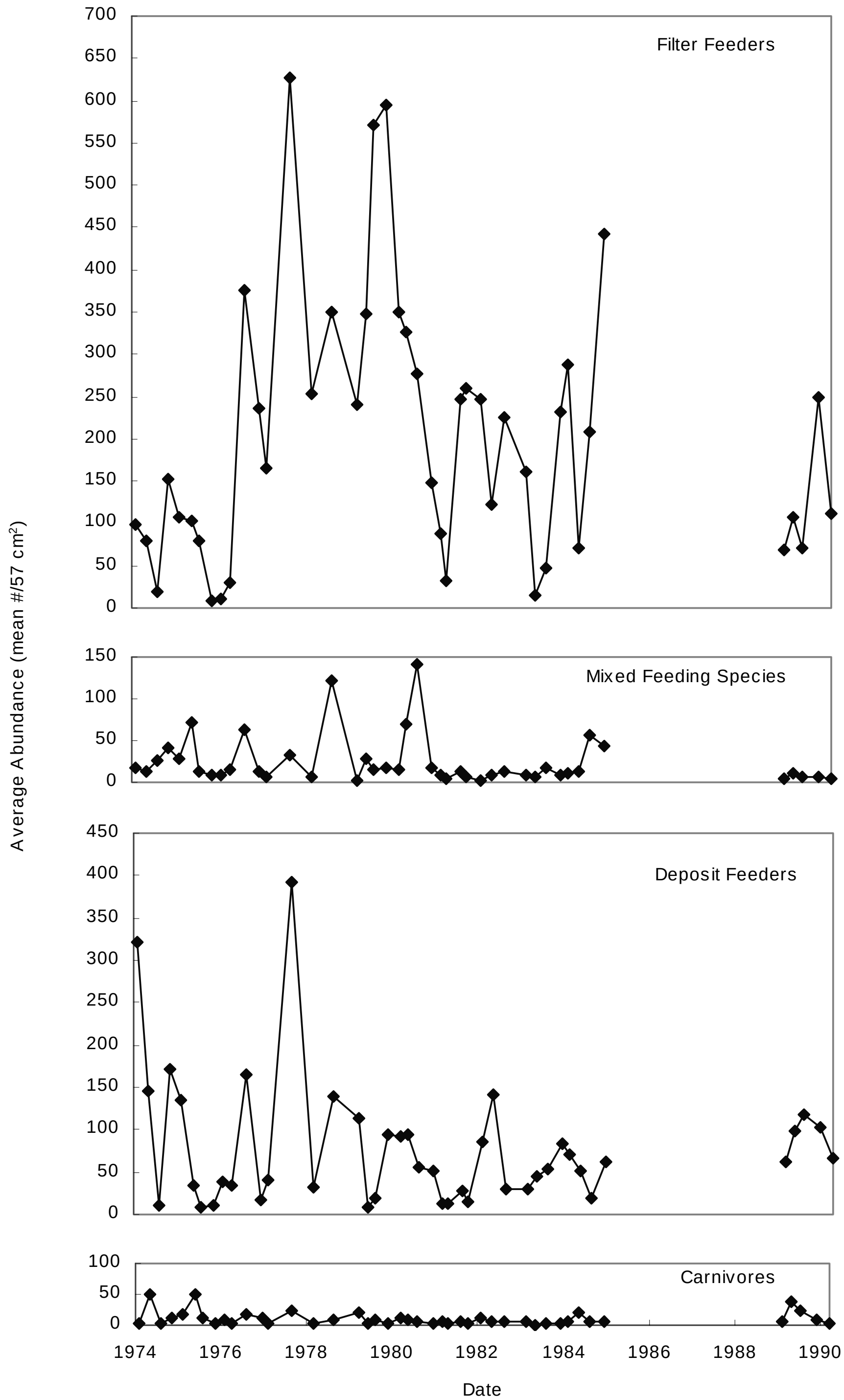
Table 6. Species natural history information used for the classification of species into functional groups. Functional groups were formed based on feeding type, habitat type, reproductive type and barrier type. The resources for the natural history information are noted. Feeding groups annotated with a number are explained at the bottom of the table.

Species	Feeding Type	Habitat Type	Reproductive Type	Barrier Type	References
Bivalves					
Gemma gemma	filter	burrower	brooder	$CaCO_3$	Thompson, J.K. (1982), personal knowledge
Macoma balthica	mixed1	burrower	spawner	$CaCO_3$	Stanley, S.M. (1970); Dankers, N.H. et al. (1981); Thompson, J.K. & F.H. Nichols (1988)
Musculista senhousia	filter	surface	spawner	$CaCO_3$	Morton, B. (1974); Wilan, R.C. (1987); Crooks, JA (1996)
Mya arenaria	filter	burrower	spawner	$CaCO_3$	Green, J. (1968); Stanley, S.M. (1970); Dankers, N.H. et al. (1981)
Potamocorbula amurensis	filter	burrower	spawner	$CaCO_3$	personal knowledge
Cnidaria					
Anthozoa sp.	filter	surface	spawner	tissue	Brusca, R.C. & G.J. Brusca (1990)
Crustacea					
Ampelisca abdita	filter	tubicolous	brooder	chitin	Mills, E.L. (1967)
Cirripedia spp.	filter	surface	mixed	chitin	Brusca, R.C. & G.J. Brusca (1990)
Corophium spp.	mixed1	burrower	brooder	chitin	Miller, D. C. (1984), Dixon, I.M.T. & P.G. Moore (1997), McCurdy et al. (2000)
Grandiderella japonica	mixed1	burrower	brooder	chitin	Chapman, J.W. & J.A. Dorman (1975), Niesen, T. (2002), Chapman, J.W. (2002)
Melita sp.	deposit1	burrower	brooder	chitin	Borowsky, B. et al. (1997)
Sphaeroma quoyana	filter	burrower	brooder	chitin	Green, J. (1968), Rotramel, G. (1972), Ricketts, E.F. et al. (1985)
Synidotea laticauda	carnivore	surface	brooder	chitin	Menzies R.J. & M.A. Miller (1972)
Gastropods					
Odostomia spp.	carnivore	surface	oviparous	$CaCO_3$	Fretter, V & A. Graham (1949); Kohn, A.J. (1983); White, M.E. et al. (1985)
Ilyanassa obsoleta	mixed2	surface	oviparous	$CaCO_3$	Scaefer (1969); Sastry, A.N. (1971), Ricketts, E.F. et al. (1985)
Polychaetes					
Capitella capitata	deposit2	burrower	oviparous	tissue	Rasmussen, E. (1956); Rasmussen, E. (1973); Fauchald, K. & P.A. Jumars (1979)
Eteone spp.	carnivore	surface	spawner	tissue	Rasmussen, E. (1973); Fauchald, K. & P.A. Jumars (1979); Rouse G. W. & F. Pleijel (2001)
Euchone sp.	filter	tubicolous	brooder	tissue	Fauchald, K. & P.A. Jumars (1979), Rouse G. W. & F. Pleijel (2001)
Glycera sp.	carnivore	burrower	spawner	tissue	Ockelmann, K.W. & O. Vahl (1970); Fauchald, K. & P.A. Jumars (1979)
Heteromastus filiformis	deposit2	burrower	oviparous	tissue	Rasmussen, E. (1956); Fauchald, K. & P.A. Jumars (1979), Shaffer, P.L. (1983)
Maldanidae	deposit1	tubicolous	mixed	tissue	Fauchald, K. & P.A. Jumars (1979), Rouse G. W. & F. Pleijel (2001)
Marphysa sanguinea	mixed2	burrower	spawner	tissue	Fauchald, K. & P.A. Jumars (1979), Cassai, C. & D. Prevedelli (1998)
Neanthes succinea	mixed2	burrower	spawner	tissue	Pettibone, M.H. (1963); Rasmussen, E. (1973); Fauchald, K. & P.A. Jumars (1979), Fong (1985)
Oligochaetes spp.	deposit2	burrower	mixed	tissue	Barnes, R.D, (1980)
Polydora cornuta	mixed1	tubicolous	brooder	tissue	Rasmussen, E. (1973); Zajac, R.N. (1991), Blake, J. A. & P. L. Arnofsky (1999)
Pseudopolydora kempi	mixed1	tubicolous	mixed	tissue	Taghon, G.L. & R.R. Greene (1992), Wilson, W.H., Jr. (1994), Blake, J. A. & P. L. Arnofsky (1999)
Sphaerosyllis sp.	carnivore	surface	brooder	tissue	Fauchald, K. & P.A. Jumars (1979); Kuper, M. & W. Westheide (1998)
Streblospio benedicti	deposit1	tubicolous	brooder	tissue	Dean, D. (1965); Fauchald, K. & P.A. Jumars (1979); Levin, L.A. (1984), Blake, J.A. & P.L. Arnofsky (1999)
Tharyx sp.	deposit1	tubicolous	mixed	tissue	Farke, H. (1979), Fauchald, K. & P.A. Jumars (1979); Rouse G. W. & F. Pleijel (2001)

Feeding Types

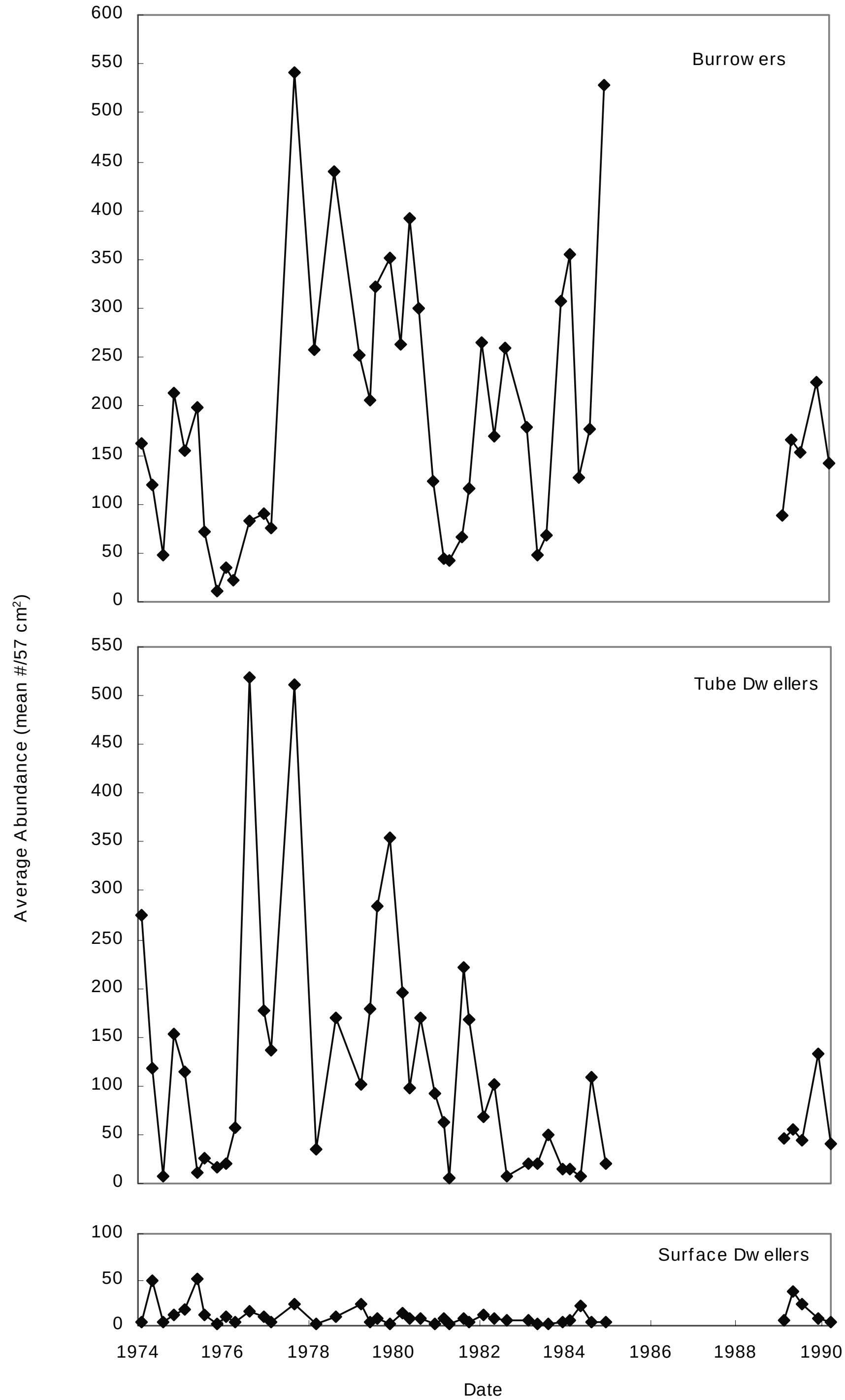
deposit1=surface deposit feeder
deposit2=sub-surface deposit feeder
mixed1=surface deposit feeder and filter feeder
mixed2=surface deposit feeder and scavenger

Figure 27. Abundances of feeding functional groups throughout the timeseries. Seasonal fluctuations were the dominant feature of the datasets.



Filter Feeders
Mixed Feeding Species
Deposit Feeders
Carnivores
Average Abundance (mean #/57 cm²)
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
1974
1976
1978
1980
1982
1984
1986
1988
1990
Date

Figure 28. Abundances of habitat functional groups throughout the timeseries. Seasonal fluctuations were the dominant feature of the datasets. There is a decreasing trend in tube dwelling species.



Burrow ers
Tube Dw ellers
Surface Dw ellers
Average Abundance (mean #/57 cm^2)
Date
0
50
100
150
200
250
300
350
400
450
500
550
600
1974
1976
1978
1980
1982
1984
1986
1988
1990

Figure 29. Abundances of reproductive functional groups throughout the timeseries. Seasonal fluctuations were the dominant feature of the datasets. There is a decreasing trend in brooding species, and an increasing trend in oviparous species and mixed reproductive species.

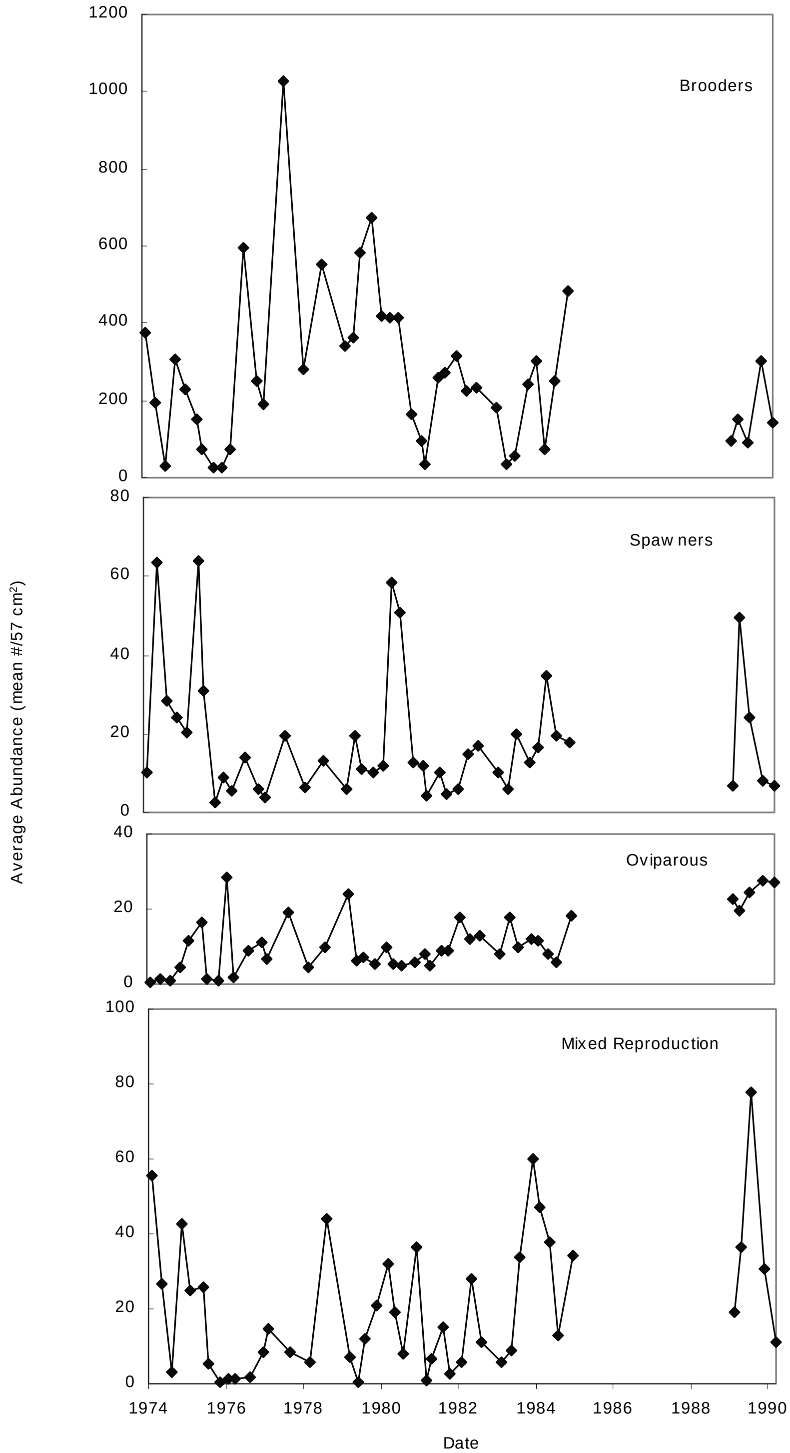

Brooders
Spaw ners
Oviparous
Mixed Reproduction
Average Abundance (mean #/57 cm²)
Date
1200
1000
800
600
400
200
0
80
60
40
20
0
40
20
0
100
80
60
40
20
0
1974
1976
1978
1980
1982
1984
1986
1988
1990

Figure 30. Abundances of barrier type functional groups throughout the timeseries. There are fluctuations in the dataset, but they do not seem to be seasonally related. There is a slight decreasing trend in the chitin barrier timeseries.

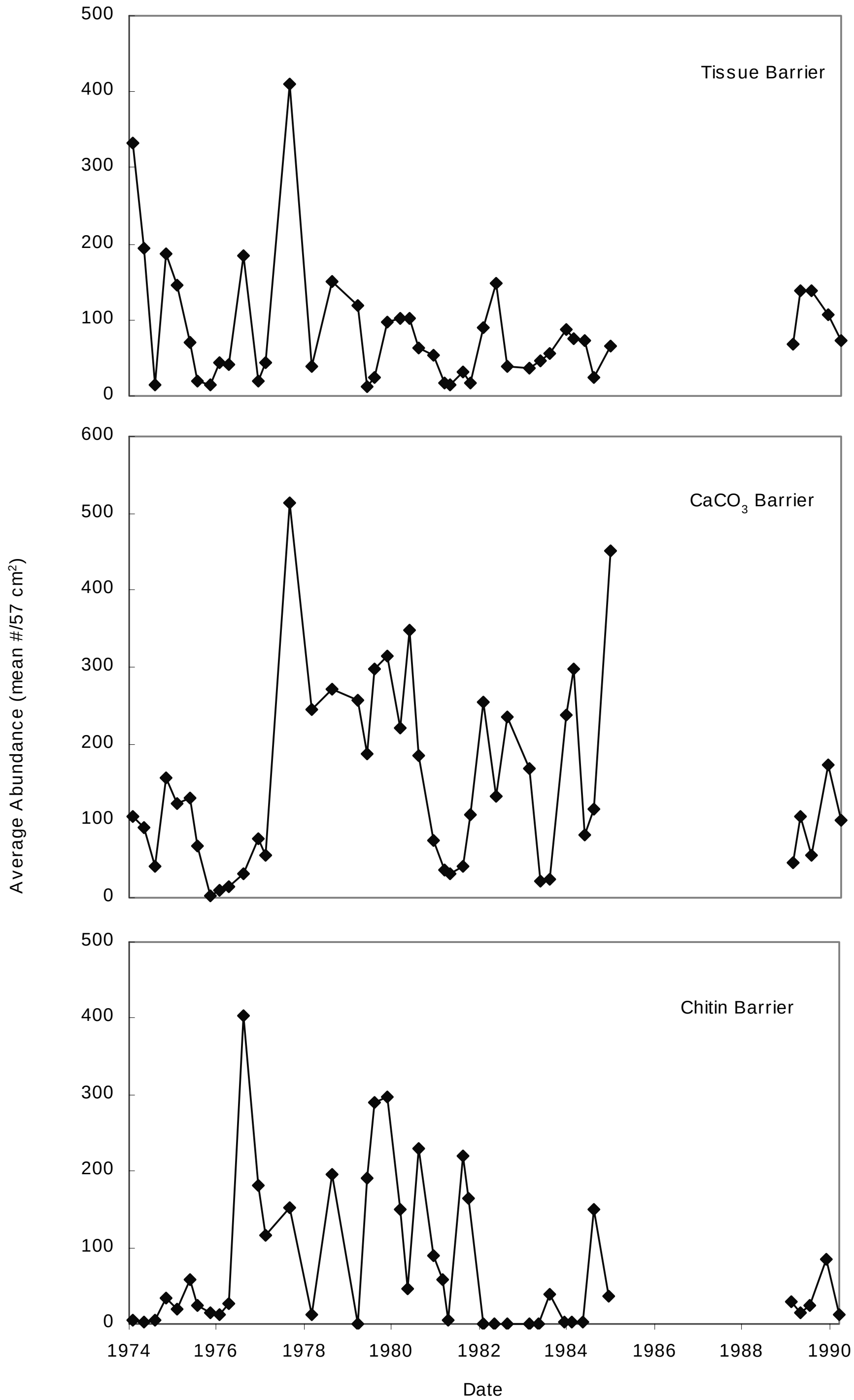

Tissue Barrier
CaCO$_3$ Barrier
Chitin Barrier
Average Abundance (mean #/57 cm^2)
Date
0
100
200
300
400
500
600
1974
1976
1978
1980
1982
1984
1986
1988
1990

Table 7. Comparison of 1977 data to1989 data using Chi Square Analysis for functional group abundances. Direction of the change between the years is noted. Significance values are given only for categories with a significant difference between years.

Category	Direction of Change	Chi-Square Value	P-Value
Mixed Reproductive Species	Increase	45.922	$p<0.001$
Oviparous Species	Increase	6.428	$p<0.001$
Spawners	Increase	1.189	
Carnivores	Increase	0.483	
Surface Dwellers	Increase	0.048	
Brooders	Decrease	762.898	$p<0.001$
Filter Feeders	Decrease	458.025	$p<0.001$
Tube Dwellers	Decrease	421.325	$p<0.001$
Shell Barrier	Decrease	330.9768	$p<0.001$
Burrowers	Decrease	164.348	$p<0.001$
Chitin Barrier	Decrease	143.4407	$p<0.001$
Deposit Feeders	Decrease	102.798	$p<0.001$
Tissue Barrier	Decrease	91.21944	$p<0.001$
Mixed Feeding Species	Decrease	16.338	$p<0.001$

Table 8. Significant correlations between community summary data and environmental data. Significance values are identified as:
* p<=0.05, ** p<0.02, *** p<0.01, **** p<0.005, ***** p<0.002, and ****** p<0.001

Salinity

	Min Clam Sal	Min H20 Sal	Max Clam Sal	Max H20 Sal
Total Abundance	0.374*		0.359*	
# of Taxa	0.55*****	0.503****	0.555*****	0.479***
Filter Feeders	0.414**		0.387*	.0318*
Chitin Barrier	0.493****			0.333*

Temperature

	Mean Air Temp	SD Air Temp	Min Air Temp	Max Air Temp	Mean H20 Temp	SD H20 Temp	Min H20 Temp	Max H20 Temp
Total Abundance					0.36*			0.39**
# of Taxa						0.433*		
Filter Feeders				0.316*	0.395**			0.454****
All Mixed Feeders	0.381**		0.379**	0.338*	0.418***		0.428***	0.386**
Mixed Feeding Type 1	0.379**		0.373**	0.341*	0.417***		0.429***	0.385**
Mixed Feeding Type 2		-0.315*						
Tube Dwellers	0.356**		0.344*	0.314*	0.343*			0.353*
Brooders					0.349*			0.379**
Chitin Barrier	0.520******		0.469*****	0.517******	0.552******		0.480*****	0.575******

Chlorophyll

	Max Chloro
Spawners	0.433**

Total Organic Carbon in the Sediment

	Mean TOC	Min TOC	Max TOC
Total Abundance	-0.547****	-0.542****	-0.435*
All Deposit Feeders	-0.393*	-0.488***	
Deposit Feeders1		-0.459**	
Filter Feeders	-0.485***	-0.442**	-0.427*
All Mixed Feeders	-0.396*		
Mixed Feeding Type 1	-0.388*		
Burrowers		-0.395*	
Tube Dwellers	-0.599******	-0.533****	-0.533****
Brooders	-0.537****	-0.532****	-0.431*
Chitin Barrier	-0.572*****	-0.412*	-0.600******
Tissue Barrier	-0.379*	-0.475**	

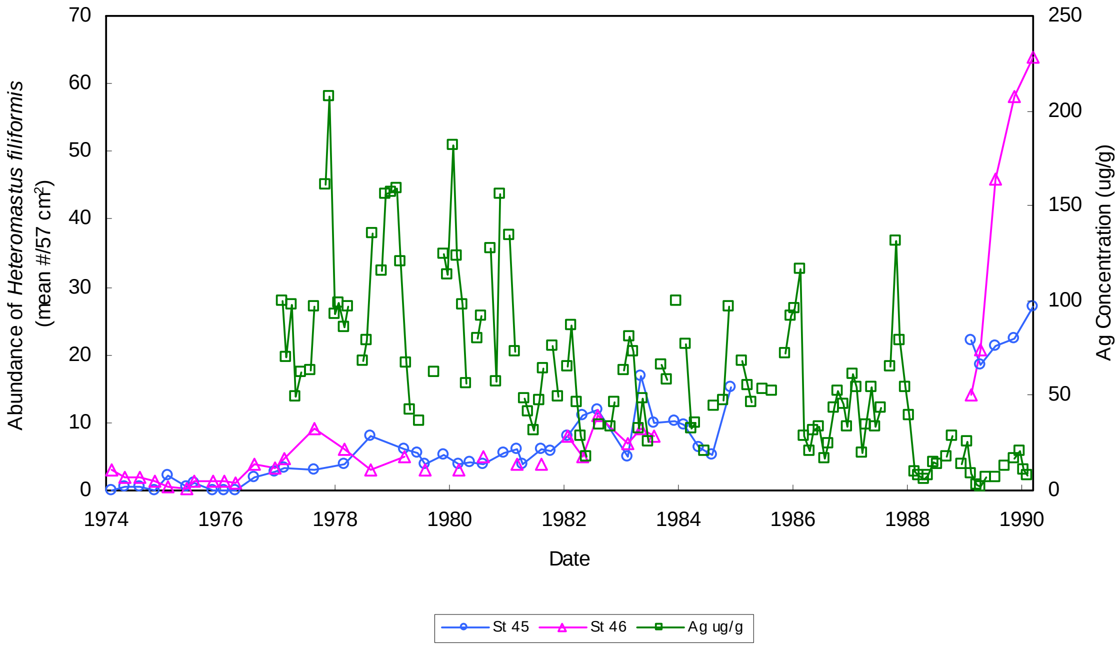
Biological Oxygen Demand

	Mean BOD	Max BOD
Total Abundance	0.409**	0.493****
Filter Feeders	0.427***	0.494*****
All Mixed Feeders	0.329*	0.434***
Mixed Feeding Type 1		0.427***
Tube Dwellers	0.423**	0.516*****
Brooders	0.432***	0.517*****
Chitin Barrier	0.452***	0.553******

Metals

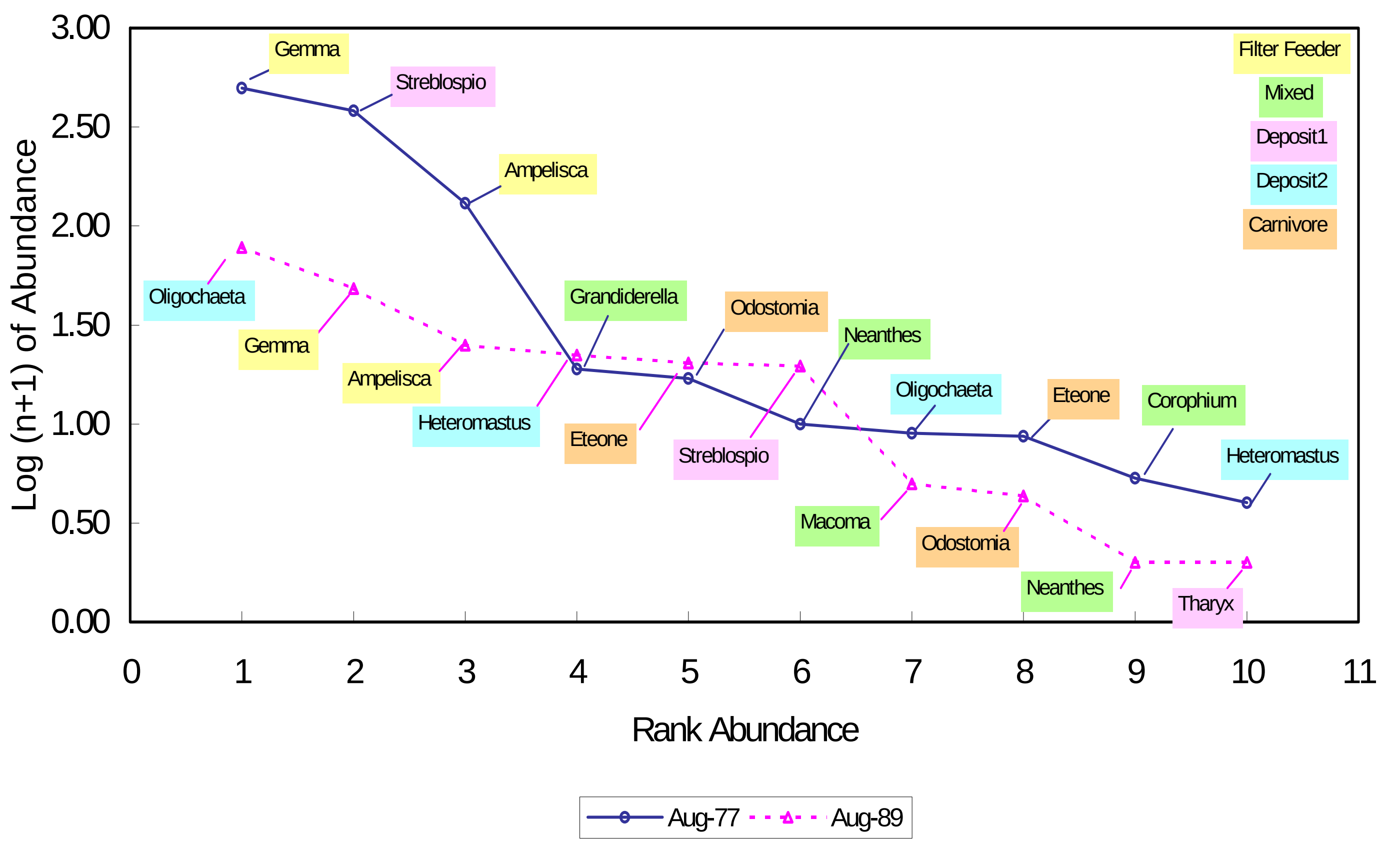
	Mean Clam Ag	Mean Sed Ag	Max Sed Ag	Mean Clam Cu	Max Clam Cu	Mean Sed Cu	Max Sed Cu
# of Taxa	-0.357*				-0.349*		
Carnivores			0.399*				
All Deposit Feeders						-0.390*	
Deposit Feeders2	-0.359*	-0.571****		-0.369*	-0.353*	-0.374*	-0.436**
Filter Feeders		0.429*				0.365*	0.426**
Surface Dwellers			0.420*				
Mixed Reproductive Type		-0.525***	-0.525***			-0.371*	-0.432**
Chitin Barrier		0.534****	0.414*			0.366*	
Tissue Barrier						-0.400*	

Figure 31. The increasing abundance of *H. filiformis* compared to the decreasing concentrations of silver from the tissues of *M. balthica*. Data for *H. filiformis* includes St. 46, to verify the increased abundance noted at St. 45.



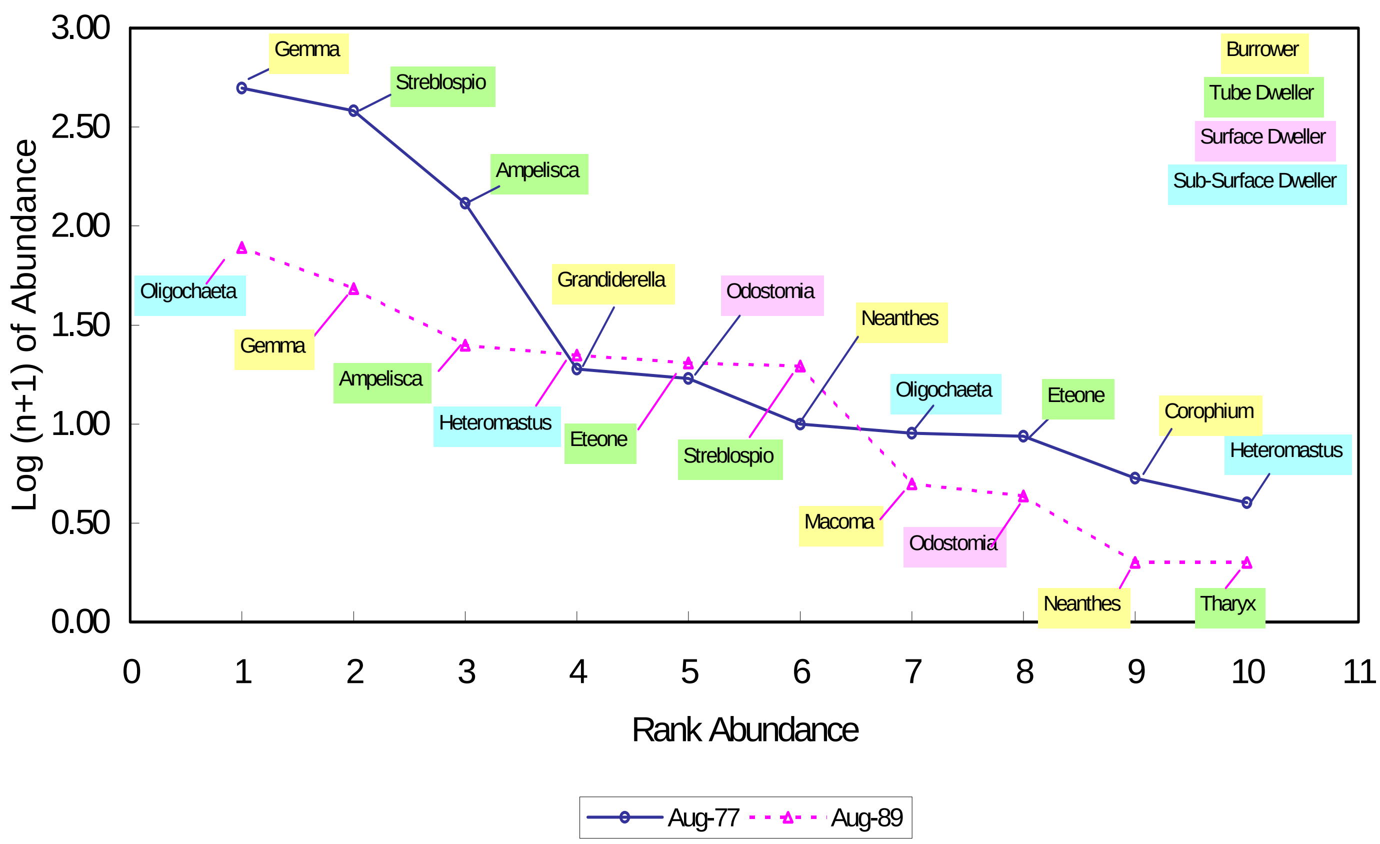
70
60
50
40
30
20
10
0
250
200
150
100
50
0
1974
1976
1978
1980
1982
1984
1986
1988
1990
Abundance of *Heteromastus filiformis*
(mean #/57 cm^2)
Ag Concentration (ug/g)
Date
St 45
St 46
Ag ug/g

Figure 32. Species rank abundance curves for the summers of 1977 and 1989, with species names and feeding type functional group information applied. The curves show the moving up in ranks of the subsurface deposit feeders (Deposit2 feeding types) Oligochaetes and *H. filiformis*.



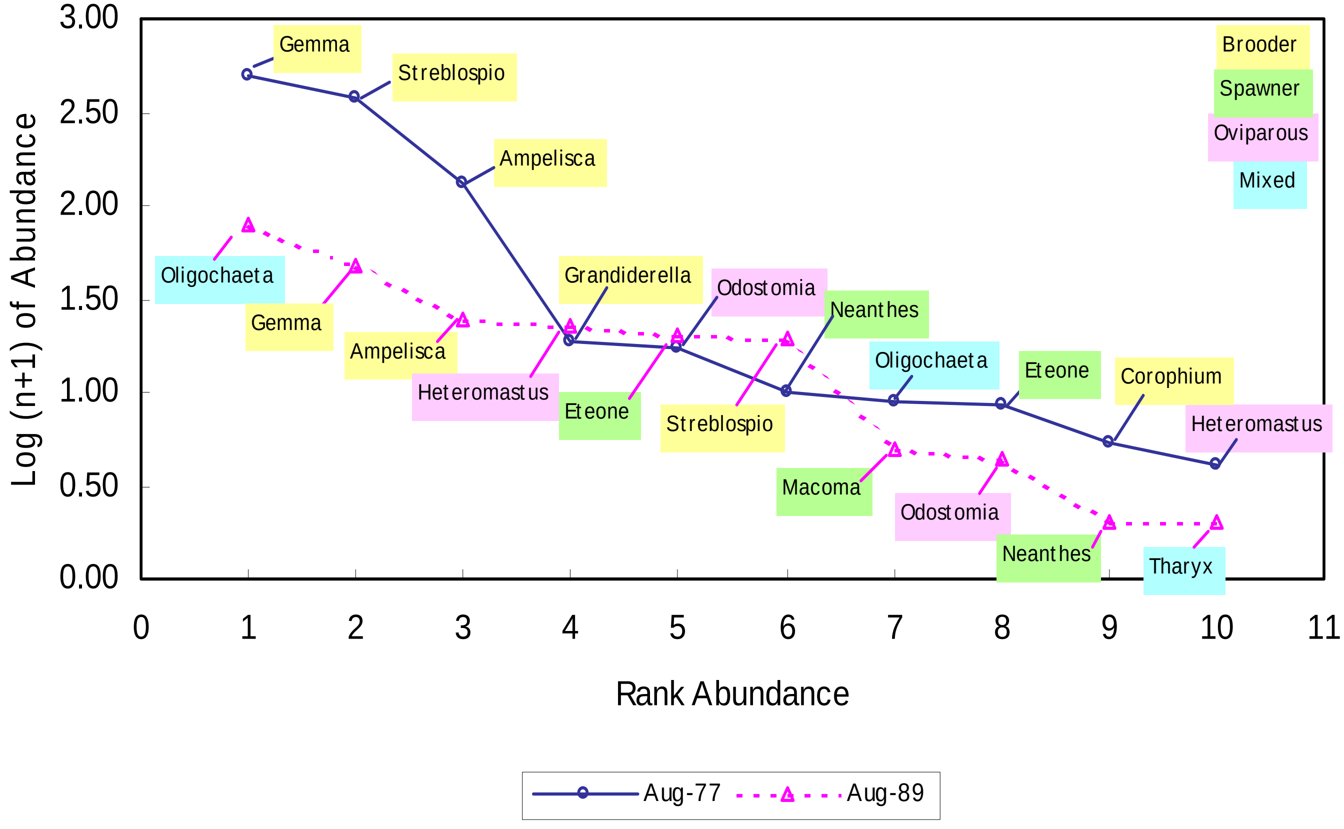
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Log (n+1) of Abundance
0
1
2
3
4
5
6
7
8
9
10
11
Rank Abundance
Gemma
Streblospio
Ampelisca
Grandiderella
Odostomia
Neanthes
Oligochaeta
Eteone
Corophium
Heteromastus
Oligochaeta
Gemma
Ampelisca
Heteromastus
Eteone
Streblospio
Macoma
Odostomia
Neanthes
Tharyx
Filter Feeder
Mixed
Deposit1
Deposit2
Carnivore
Aug-77
Aug-89

Figure 33. Species rank abundance curves for the summers of 1977 and 1989, with species names and habitat type functional group information applied. The curves show the moving up in ranks of the subsurface deposit dwellers) Oligochaetes and *H. filiformis*, replacing the surface burrower *G. gemma* and the surface tube dwellers *S. benedicti* and *A. abdita*.



3.00
2.50
2.00
1.50
1.00
0.50
0.00
Log (n+1) of Abundance
0
1
2
3
4
5
6
7
8
9
10
11
Rank Abundance
Gemma
Streblospio
Ampelisca
Grandiderella
Odostomia
Neanthes
Oligochaeta
Eteone
Corophium
Heteromastus
Oligochaeta
Gemma
Ampelisca
Heteromastus
Eteone
Streblospio
Macoma
Odostomia
Neanthes
Tharyx
Burrower
Tube Dweller
Surface Dweller
Sub-Surface Dweller
Aug-77
Aug-89

Figure 34. Species rank abundance curves for the summers of 1977 and 1989, with species names and reproductive type functional group information applied. The curves show the moving up in ranks of the mixed reproductive species Oligochaetes and the oviparous species *H. filiformis*. Their increase in the ranks have shifted the brooding species down in the ranks.


Brooder
Spawner
Oviparous
Mixed
Gemma
Streblospio
Ampelisca
Oligochaeta
Gemma
Ampelisca
Heteromastus
Grandiderella
Eteone
Odostomia
Neanthes
Streblospio
Oligochaeta
Eteone
Corophium
Heteromastus
Macoma
Odostomia
Neanthes
Tharyx
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0 1 2 3 4 5 6 7 8 9 10 11
Log (n+1) of Abundance
Rank Abundance
Aug-77
Aug-89

Appendix 1. Cross-correlation of environmental parameters using Pearson pairwise correlation. Values are correlation coefficients.

Pearson pairwise correlation matrix

	SALINITYIN	H2OSALINITY	PRECIPIN	AIRTEMPOC	H2OTEMPOC
SALINITYIN	1.000				
H2OSALINITY	0.835	1.000			
PRECIPIN	-0.405	-0.435	1.000		
AIRTEMPOC	0.216	0.260	-0.581	1.000	
H2OTEMPOC	0.285	0.349	-0.572	0.947	1.000
CALCCHLORO	-0.341	-0.418	-0.001	-0.104	-0.146
TOC	-0.443	-0.485	0.358	-0.369	-0.501
BODKGDAY	0.037	-0.006	0.060	-0.030	-0.064
CUUGG	-0.311	-0.358	0.368	-0.308	-0.384
SEDIMENTCU	-0.294	-0.374	0.298	-0.177	-0.279
AGUGG	-0.169	-0.192	0.406	-0.351	-0.409
SEDIMENTAG	0.185	-0.041	-0.007	0.039	-0.095

	CALCCHLORO	TOC	BODKGDAY	CUUGG	SEDIMENTCU
CALCCHLORO	1.000				
TOC	0.214	1.000			
BODKGDAY	-0.096	-0.169	1.000		
CUUGG	-0.005	0.129	0.578	1.000	
SEDIMENTCU	0.016	0.487	0.258	0.451	1.000
AGUGG	-0.059	0.043	0.610	0.817	0.250
SEDIMENTAG	-0.064	0.259	0.414	0.426	0.663

	AGUGG	SEDIMENTAG
AGUGG	1.000	
SEDIMENTAG	0.413	1.000

Pairwise frequency table

	SALINITYIN	H2OSALINITY	PRECIPIN	AIRTEMPOC	H2OTEMPOC
SALINITYIN	110				
H2OSALINITY	93	148			
PRECIPIN	110	148	207		
AIRTEMPOC	108	144	202	202	
H2OTEMPOC	88	139	139	137	139
CALCCHLORO	91	131	131	127	122
TOC	101	92	111	109	87
BODKGDAY	109	140	169	164	131
CUUGG	107	102	120	118	97
SEDIMENTCU	100	96	111	109	92
AGUGG	107	102	120	118	97
SEDIMENTAG	69	67	80	80	62

	CALCCHLORO	TOC	BODKGDAY	CUUGG	SEDIMENTCU
CALCCHLORO	131				
TOC	90	111			
BODKGDAY	131	109	169		
CUUGG	100	108	118	120	
SEDIMENTCU	94	100	111	108	111
AGUGG	100	108	118	120	108
SEDIMENTAG	66	78	78	76	69

	AGUGG	SEDIMENTAG
AGUGG	120	
SEDIMENTAG	76	80

Appendix 2. Cross-correlation analysis of species abundances for St. 45. Values reflect Pearson correlation coefficients.

	AMPELISCA	ANTHOZOA	ODOSTOMIA	CIRRIPEDIA	COROPHIUM	CAPITELLA
AMPELISCA	1.000					
ANTHOZOA	-0.107	1.000				
ODOSTOMIA	0.093	-0.087	1.000			
CIRRIPEDIA	-0.109	-0.023	-0.068	1.000		
COROPHIUM	0.326	-0.070	0.243	-0.070	1.000	
CAPITELLA	-0.099	0.006	-0.072	-0.001	-0.040	1.000
ETEONE	-0.169	0.196	0.171	-0.056	0.228	-0.028
EUCHONE	-0.010	-0.033	0.019	-0.033	-0.083	-0.052
GEMMA	0.122	-0.089	0.303	0.196	0.040	-0.155
GLYCERA	-0.101	-0.026	-0.106	-0.026	-0.057	-0.014
GRANDIDERELL	0.188	-0.068	0.025	-0.071	0.540	-0.041
HETEROMASTUS	-0.182	-0.015	-0.163	0.059	-0.197	-0.169
ILYANASSA	-0.195	-0.045	0.181	-0.045	-0.118	0.785
MARPHYSA	0.130	-0.023	0.113	-0.023	-0.009	-0.037
MALDANIDAE	0.193	-0.023	-0.081	-0.023	0.035	-0.037
MACOMA	-0.117	0.050	-0.232	0.036	0.325	-0.076
MELITA	-0.112	-0.036	-0.102	-0.036	-0.089	-0.057
MUSCULISTA	0.113	-0.048	-0.133	-0.048	0.484	-0.021
MYA	-0.026	0.037	0.367	-0.002	0.581	-0.059
NEANTHES	0.023	-0.003	0.220	-0.019	0.111	-0.118
OLIGOCHAETES	-0.239	0.149	-0.084	0.226	-0.077	-0.167
POLYDORA	0.122	-0.061	0.095	-0.061	0.252	-0.019
POTAMOCORBUL	-0.068	-0.023	-0.081	-0.023	-0.053	-0.037
PSEUDOPOLYDO	0.205	-0.048	-0.062	-0.048	0.195	-0.005
SPHAEROMA	-0.098	-0.023	-0.037	-0.023	0.037	0.006
SPHAEROSYLLI	-0.086	-0.027	-0.093	-0.027	-0.066	0.146
STREBLOSPIO	0.096	-0.091	0.428	-0.073	0.109	-0.083
SYNIDOTEA	0.074	-0.023	-0.093	-0.023	0.048	-0.037
THARYX	0.025	-0.091	-0.064	-0.091	0.039	-0.083

	ETEONE	EUCHONE	GEMMA	GLYCERA	GRANDIDERE	HETEROMAST
ETEONE	1.000					
EUCHONE	-0.085	1.000				
GEMMA	-0.113	-0.034	1.000			
GLYCERA	0.442	-0.036	-0.058	1.000		
GRANDIDERELL	-0.052	-0.090	0.264	-0.083	1.000	
HETEROMASTUS	-0.021	0.482	0.072	0.316	-0.120	1.000
ILYANASSA	0.005	-0.063	-0.130	-0.050	-0.095	-0.224
MARPHYSA	-0.005	-0.033	0.100	-0.026	-0.026	-0.068
MALDANIDAE	-0.072	-0.033	0.044	-0.026	-0.014	-0.035
MACOMA	0.130	-0.138	0.097	-0.010	0.184	-0.169
MELITA	-0.018	0.474	-0.161	-0.001	-0.108	0.545
MUSCULISTA	-0.060	-0.067	-0.064	-0.053	0.370	-0.126
MYA	0.481	-0.097	-0.048	-0.040	0.055	-0.270
NEANTHES	-0.069	0.049	0.485	0.036	0.397	0.159
OLIGOCHAETES	0.272	0.061	0.138	0.122	0.086	0.313
POLYDORA	-0.007	-0.086	-0.170	-0.065	-0.005	-0.341
POTAMOCORBUL	-0.063	0.537	-0.122	-0.026	-0.071	0.337
PSEUDOPOLYDO	-0.098	-0.068	-0.244	-0.054	-0.091	-0.266
SPHAEROMA	-0.074	-0.033	0.389	-0.026	0.115	0.183
SPHAEROSYLLI	-0.066	0.524	-0.152	-0.031	-0.078	0.304
STREBLOSPIO	0.117	-0.035	0.382	-0.022	0.149	-0.208
SYNIDOTEA	-0.050	-0.033	-0.047	-0.026	0.244	-0.038
THARYX	0.047	0.284	0.081	0.227	0.266	0.446

	ILYANASSA	MARPHYSA	MALDANIDAE	MACOMA	MELITA	MUSCULISTA
ILYANASSA	1.000					
MARPHYSA	-0.045	1.000				
MALDANIDAE	-0.045	-0.023	1.000			
MACOMA	-0.140	-0.071	0.095	1.000		
MELITA	-0.069	-0.036	-0.036	-0.166	1.000	
MUSCULISTA	-0.083	-0.048	-0.048	0.480	-0.073	1.000
MYA	-0.086	-0.069	0.066	0.255	-0.106	0.186
NEANTHES	-0.191	-0.099	-0.067	-0.138	0.048	0.144
OLIGOCHAETES	-0.197	0.102	-0.168	0.083	0.105	-0.116
POLYDORA	0.080	-0.061	-0.061	0.004	-0.086	-0.034
POTAMOCORBUL	-0.045	-0.023	-0.023	-0.115	0.906	-0.048
PSEUDOPOLYDO	0.052	-0.048	-0.048	-0.179	-0.074	-0.045
SPHAEROMA	-0.045	-0.023	-0.023	0.106	-0.036	-0.048
SPHAEROSYLLI	0.105	-0.027	-0.027	-0.131	0.887	-0.056
STREBLOSPIO	0.046	0.016	-0.097	-0.081	-0.090	-0.047
SYNIDOTEA	-0.045	-0.023	-0.023	0.101	-0.036	-0.048
THARYX	-0.176	-0.091	-0.091	-0.324	0.481	-0.157

	MYA	NEANTHES	OLIGOCHAET	POLYDORA	POTAMOCORB	PSEUDOPOLY
MYA	1.000					
NEANTHES	-0.090	1.000				
OLIGOCHAETES	-0.011	-0.060	1.000			
POLYDORA	-0.010	-0.233	0.113	1.000		
POTAMOCORBUL	-0.069	0.025	-0.019	-0.061	1.000	
PSEUDOPOLYDO	-0.085	-0.157	-0.040	0.668	-0.048	1.000
SPHAEROMA	-0.050	-0.099	0.119	-0.061	-0.023	-0.048
SPHAEROSYLLI	-0.078	0.007	-0.048	-0.067	0.983	-0.057
STREBLOSPIO	-0.050	0.466	0.128	0.495	-0.062	0.308
SYNIDOTEA	-0.040	-0.067	-0.058	-0.061	-0.023	-0.048
THARYX	-0.188	0.378	0.113	-0.165	0.416	0.021

	SPHAEROMA	SPHAEROSYL	STREBLOSPI	SYNIDOTEA	THARYX
SPHAEROMA	1.000				
SPHAEROSYLLI	-0.027	1.000			
STREBLOSPIO	-0.078	-0.076	1.000		
SYNIDOTEA	-0.023	-0.027	-0.100	1.000	
THARYX	-0.091	0.394	-0.007	-0.091	1.000

Number of observations: 44

Appendix 3. Cross-correlation analysis of functional group abundances for St. 45. Values reflect Pearson correlation coefficients.

	TOT_CARN	TOT_DEP	TOT_DEP1	TOT_DEP2	TOT_FIFE
TOT_CARN	1.000				
TOT_DEP	0.284	1.000			
TOT_DEP1	0.255	0.962	1.000		
TOT_DEP2	0.152	0.303	0.032	1.000	
TOT_FIFE	-0.052	0.305	0.342	0.076	1.000
TOT_MFT	0.110	0.141	0.161	0.046	0.279
TOT_MFT1	0.108	0.117	0.135	-0.044	0.264
TOT_MFT2	0.051	0.455	0.492	0.051	0.328
TOT_BURR	0.067	0.427	0.375	0.254	0.792
TOT_SURF	0.997	0.283	0.258	0.137	-0.059
TOT_TUBE	0.069	0.600	0.683	-0.190	0.690
TOT_BROO	0.059	0.604	0.648	-0.052	0.929
TOT_MRT	0.204	0.382	0.130	0.945	-0.030
TOT_OVIP	0.211	0.127	0.018	0.404	0.013
TOT_SPAW	0.687	0.091	0.060	0.122	-0.068
TOT_SHEL	0.038	0.392	0.381	0.106	0.817
TOT_CHIT	-0.076	0.045	0.123	-0.268	0.673
TOT_TISS	0.387	0.993	0.951	0.316	0.275

	TOT_MFT	TOT_MFT1	TOT_MFT2	TOT_BURR	TOT_SURF
TOT_MFT	1.000				
TOT_MFT1	0.999	1.000			
TOT_MFT2	0.206	0.153	1.000		
TOT_BURR	0.403	0.382	0.450	1.000	
TOT_SURF	0.131	0.128	0.062	0.063	1.000
TOT_TUBE	0.253	0.241	0.272	0.304	0.068
TOT_BROO	0.385	0.364	0.461	0.788	0.058
TOT_MRT	0.042	0.049	-0.109	0.285	0.189
TOT_OVIP	-0.193	-0.212	0.307	0.156	0.213
TOT_SPAW	0.480	0.489	-0.077	0.164	0.694
TOT_SHEL	0.252	0.230	0.442	0.971	0.034
TOT_CHIT	0.429	0.431	0.041	0.193	-0.074
TOT_TISS	0.155	0.132	0.438	0.408	0.385

	TOT_TUBE	TOT_BROO	TOT_MRT	TOT_OVIP	TOT_SPAW
TOT_TUBE	1.000				
TOT_BROO	0.819	1.000			
TOT_MRT	-0.093	0.028	1.000		
TOT_OVIP	-0.117	0.002	0.143	1.000	
TOT_SPAW	-0.090	-0.001	0.202	-0.140	1.000
TOT_SHEL	0.311	0.791	0.137	0.132	0.096
TOT_CHIT	0.788	0.623	-0.207	-0.178	-0.077
TOT_TISS	0.580	0.578	0.398	0.128	0.180

	TOT_SHEL	TOT_CHIT	TOT_TISS
TOT_SHEL	1.000		
TOT_CHIT	0.156	1.000	
TOT_TISS	0.368	0.032	1.000

Number of observations: 44

Appendix 4. Cross-correlation of multi-dimensional functional groups for St. 45. Values reflect Pearson correlation coefficients.

	CARN_BURR	CARN_SURF	DEP1_BURR	DEP1_TUBE	DEP2_BURR
CARN_BURR	1.000				
CARN_SURF	0.344	1.000			
DEP1_BURR	-0.001	-0.023	1.000		
DEP1_TUBE	-0.020	0.259	-0.087	1.000	
DEP2_BURR	0.207	0.147	0.258	0.031	1.000
FIFE_BURR	-0.059	0.022	-0.163	0.381	0.114
FIFE_SURF	-0.059	-0.097	-0.080	-0.065	-0.110
FIFE_TUBE	-0.101	-0.115	-0.111	0.096	-0.284
MFT1_BURR	-0.073	0.112	-0.151	0.103	-0.043
MFT1_TUBE	-0.066	0.021	-0.086	0.493	-0.021
MFT2_BURR	0.034	0.026	0.045	0.472	-0.015
MFT2_SURF	-0.050	0.075	-0.069	0.044	-0.107
CARN_BRO	-0.034	-0.065	0.879	-0.085	0.073
CARN_OVIP	-0.106	0.518	-0.102	0.427	-0.139
CARN_SPA	0.474	0.927	-0.018	0.115	0.229
DEP1_BROO	-0.022	0.258	-0.086	1.000	0.031
DEP1_MRT	0.225	0.021	0.480	-0.010	0.213
DEP2_MRT	0.122	0.203	0.105	0.129	0.942
DEP2_OVIP	0.294	-0.089	0.489	-0.238	0.527
FIFE_BROO	-0.101	-0.059	-0.185	0.344	-0.074
FIFE_MRT	-0.026	-0.075	-0.036	-0.074	0.216
FIFE_SPAW	-0.049	0.510	-0.083	-0.061	-0.123
MFT1_BROO	-0.085	0.122	-0.119	0.187	-0.052
MFT1_MRT	-0.054	-0.110	-0.074	0.308	-0.122
MFT1_SPAW	-0.010	0.022	-0.166	-0.083	0.004
MFT2_OVIP	-0.050	0.075	-0.069	0.044	-0.107
MFT2_SPAW	0.034	0.026	0.045	0.472	-0.015
BURR_BRO	-0.071	0.033	-0.172	0.391	0.100
BURR_MRT	0.122	0.203	0.105	0.129	0.942
BURR_OVIP	0.294	-0.089	0.489	-0.238	0.527
BURR_SPA	0.024	0.184	-0.163	-0.015	-0.019
SURF_BROO	-0.034	-0.065	0.879	-0.085	0.073
SURF_MRT	-0.026	-0.075	-0.036	-0.074	0.216
SURF_OVIP	-0.109	0.512	-0.107	0.420	-0.148
SURF_SPAW	0.440	0.927	-0.022	0.115	0.219
TUBE_BROO	-0.088	0.073	-0.137	0.684	-0.190
TUBE_MRT	0.210	-0.000	0.456	0.048	0.186
BURR_SHEL	-0.059	0.023	-0.174	0.371	0.113
BURR_CHIT	-0.081	0.121	-0.100	0.150	-0.048
BURR_TISS	0.227	0.154	0.260	0.067	0.997
SURF_SHEL	-0.116	0.505	-0.117	0.418	-0.166
SURF_CHIT	-0.037	-0.107	-0.051	-0.125	0.105
SURF_TISS	0.441	0.930	0.018	0.114	0.229
TUBE_CHIT	-0.101	-0.115	-0.112	0.096	-0.285
TUBE_TISS	-0.022	0.256	-0.087	1.000	0.030

	FIFE_BURR	FIFE_SURF	FIFE_TUBE	MFT1_BURR	MFT1_TUBE
FIFE_BURR	1.000				
FIFE_SURF	-0.048	1.000			
FIFE_TUBE	0.121	0.091	1.000		
MFT1_BURR	0.201	0.555	0.206	1.000	
MFT1_TUBE	-0.176	-0.048	0.127	0.103	1.000
MFT2_BURR	0.495	0.138	0.035	0.217	-0.240
MFT2_SURF	-0.132	-0.092	-0.195	-0.148	0.080
CARN_BRO	-0.159	-0.068	-0.075	-0.089	-0.075
CARN_OVIP	0.311	-0.150	0.094	0.045	0.089
CARN_SPA	-0.103	-0.047	-0.170	0.108	-0.014
DEP1_BROO	0.380	-0.064	0.095	0.102	0.494
DEP1_MRT	0.082	-0.182	0.045	0.061	-0.166
DEP2_MRT	0.138	-0.077	-0.239	0.040	0.108
DEP2_OVIP	-0.016	-0.126	-0.222	-0.228	-0.335
FIFE_BROO	0.824	0.012	0.661	0.262	-0.060
FIFE_MRT	0.196	0.054	-0.109	-0.058	-0.062
FIFE_SPAW	-0.039	0.349	-0.010	0.440	-0.022
MFT1_BROO	0.179	0.452	0.289	0.947	0.197
MFT1_MRT	-0.246	-0.055	0.205	-0.022	0.694
MFT1_SPAW	0.103	0.488	-0.117	0.565	-0.005
MFT2_OVIP	-0.132	-0.092	-0.195	-0.148	0.080
MFT2_SPAW	0.495	0.138	0.035	0.217	-0.240
BURR_BRO	0.982	0.042	0.171	0.370	-0.142
BURR_MRT	0.138	-0.077	-0.239	0.040	0.108
BURR_OVIP	-0.016	-0.126	-0.222	-0.228	-0.335
BURR_SPA	0.163	0.515	-0.113	0.643	-0.050
SURF_BROO	-0.159	-0.068	-0.075	-0.089	-0.075
SURF_MRT	0.196	0.054	-0.109	-0.058	-0.062
SURF_OVIP	0.285	-0.156	0.067	0.025	0.096
SURF_SPAW	-0.106	0.004	-0.164	0.141	-0.014
TUBE_BROO	0.316	0.027	0.792	0.214	0.408
TUBE_MRT	0.034	-0.189	0.082	0.056	-0.033
BURR_SHEL	0.997	-0.009	0.110	0.243	-0.175
BURR_CHIT	0.194	0.461	0.282	0.950	0.121
BURR_TISS	0.151	-0.100	-0.282	-0.027	-0.041
SURF_SHEL	0.281	-0.046	0.080	0.089	0.093
SURF_CHIT	0.106	0.001	-0.025	0.092	-0.088
SURF_TISS	-0.109	-0.047	-0.173	0.108	-0.015
TUBE_CHIT	0.121	0.091	1.000	0.206	0.127
TUBE_TISS	0.371	-0.066	0.098	0.104	0.513

	MFT2_BURR	MFT2_SURF	CARN_BROO	CARN_OVIP	CARN_SPAW
MFT2_BURR	1.000				
MFT2_SURF	-0.196	1.000			
CARN_BRO	-0.005	0.099	1.000		
CARN_OVIP	0.231	0.181	-0.104	1.000	
CARN_SPA	-0.067	0.003	-0.072	0.164	1.000
DEP1_BROO	0.470	0.045	-0.084	0.427	0.114
DEP1_MRT	0.366	-0.182	0.379	-0.073	0.048
DEP2_MRT	-0.051	-0.197	-0.055	-0.084	0.272
DEP2_OVIP	0.084	0.187	0.354	-0.192	-0.022
FIFE_BROO	0.395	-0.209	-0.162	0.282	-0.183
FIFE_MRT	-0.021	-0.045	-0.030	-0.068	-0.056
FIFE_SPAW	-0.068	-0.098	-0.056	0.323	0.440
MFT1_BROO	0.284	-0.112	-0.065	0.145	0.076
MFT1_MRT	-0.163	0.052	-0.062	-0.062	-0.098
MFT1_SPAW	-0.145	-0.140	-0.117	-0.232	0.127
MFT2_OVIP	-0.196	1.000	0.099	0.181	0.003
MFT2_SPAW	1.000	-0.196	-0.005	0.231	-0.067
BURR_BRO	0.530	-0.147	-0.158	0.313	-0.092
BURR_MRT	-0.051	-0.197	-0.055	-0.084	0.272
BURR_OVIP	0.084	0.187	0.354	-0.192	-0.022
BURR_SPA	0.003	-0.185	-0.122	-0.082	0.248
SURF_BROO	-0.005	0.099	1.000	-0.104	-0.072
SURF_MRT	-0.021	-0.045	-0.030	-0.068	-0.056
SURF_OVIP	0.200	0.300	-0.089	0.993	0.159
SURF_SPAW	-0.063	0.001	-0.075	0.164	0.998
TUBE_BROO	0.306	-0.114	-0.109	0.329	-0.056
TUBE_MRT	0.328	-0.168	0.359	-0.083	0.029
BURR_SHEL	0.478	-0.142	-0.166	0.290	-0.091
BURR_CHIT	0.307	-0.121	-0.048	0.138	0.077
BURR_TISS	0.063	-0.122	0.072	-0.122	0.232
SURF_SHEL	0.218	0.294	-0.097	0.987	0.154
SURF_CHIT	-0.065	-0.064	0.049	-0.115	-0.076
SURF_TISS	-0.070	0.009	-0.031	0.167	0.998
TUBE_CHIT	0.035	-0.195	-0.076	0.093	-0.170
TUBE_TISS	0.459	0.046	-0.085	0.424	0.113

	DEP1_BROO	DEP1_MRT	DEP2_MRT	DEP2_OVIP	FIFE_BROO
DEP1_BROO	1.000				
DEP1_MRT	-0.015	1.000			
DEP2_MRT	0.129	0.096	1.000		
DEP2_OVIP	-0.238	0.378	0.213	1.000	
FIFE_BROO	0.342	0.091	-0.032	-0.134	1.000
FIFE_MRT	-0.073	-0.094	0.226	0.055	0.086
FIFE_SPAW	-0.060	-0.189	-0.028	-0.286	-0.053
MFT1_BROO	0.185	0.174	0.024	-0.213	0.294
MFT1_MRT	0.307	0.016	-0.040	-0.256	-0.068
MFT1_SPAW	-0.081	-0.315	0.083	-0.199	0.007
MFT2_OVIP	0.045	-0.182	-0.197	0.187	-0.209
MFT2_SPAW	0.470	0.366	-0.051	0.084	0.395
BURR_BRO	0.389	0.120	0.133	-0.046	0.839
BURR_MRT	0.129	0.096	1.000	0.213	-0.032
BURR_OVIP	-0.238	0.378	0.213	1.000	-0.134
BURR_SPA	-0.014	-0.265	0.069	-0.230	0.050
SURF_BROO	-0.084	0.379	-0.055	0.354	-0.162
SURF_MRT	-0.073	-0.094	0.226	0.055	0.086
SURF_OVIP	0.420	-0.093	-0.106	-0.163	0.247
SURF_SPAW	0.115	0.031	0.268	-0.041	-0.182
TUBE_BROO	0.683	0.020	-0.096	-0.314	0.691
TUBE_MRT	0.043	0.982	0.087	0.322	0.076
BURR_SHEL	0.370	0.056	0.143	-0.032	0.816
BURR_CHIT	0.148	0.196	0.018	-0.184	0.301
BURR_TISS	0.067	0.244	0.935	0.536	-0.045
SURF_SHEL	0.419	-0.113	-0.120	-0.179	0.252
SURF_CHIT	-0.124	-0.135	0.121	-0.000	0.066
SURF_TISS	0.114	0.055	0.271	-0.019	-0.189
TUBE_CHIT	0.095	0.045	-0.239	-0.223	0.661
TUBE_TISS	1.000	-0.014	0.130	-0.242	0.337

	FIFE_MRT	FIFE_SPAW	MFT1_BROO	MFT1_MRT	MFT1_SPAW
FIFE_MRT	1.000				
FIFE_SPAW	-0.011	1.000			
MFT1_BROO	-0.084	0.385	1.000		
MFT1_MRT	-0.048	-0.092	0.092	1.000	
MFT1_SPAW	0.036	0.322	0.278	-0.179	1.000
MFT2_OVIP	-0.045	-0.098	-0.112	0.052	-0.140
MFT2_SPAW	-0.021	-0.068	0.284	-0.163	-0.145
BURR_BRO	0.168	0.019	0.360	-0.222	0.147
BURR_MRT	0.226	-0.028	0.024	-0.040	0.083
BURR_OVIP	0.055	-0.286	-0.213	-0.256	-0.199
BURR_SPA	0.027	0.544	0.381	-0.214	0.955
SURF_BROO	-0.030	-0.056	-0.065	-0.062	-0.117
SURF_MRT	1.000	-0.011	-0.084	-0.048	0.036
SURF_OVIP	-0.071	0.301	0.126	-0.053	-0.242
SURF_SPAW	-0.058	0.468	0.104	-0.100	0.154
TUBE_BROO	-0.125	-0.044	0.327	0.347	-0.135
TUBE_MRT	-0.101	-0.202	0.188	0.203	-0.342
BURR_SHEL	0.196	-0.014	0.199	-0.258	0.180
BURR_CHIT	-0.081	0.390	0.997	0.040	0.279
BURR_TISS	0.212	-0.128	-0.031	-0.135	-0.008
SURF_SHEL	-0.077	0.343	0.181	-0.059	-0.190
SURF_CHIT	0.699	-0.042	0.063	-0.069	0.097
SURF_TISS	-0.057	0.449	0.077	-0.100	0.125
TUBE_CHIT	-0.109	-0.010	0.289	0.205	-0.117
TUBE_TISS	-0.074	-0.061	0.189	0.322	-0.082

	MFT2_OVIP	MFT2_SPAW	BURR_BRO	BURR_MRT	BURR_OVIP
MFT2_OVIP	1.000				
MFT2_SPAW	-0.196	1.000			
BURR_BRO	-0.147	0.530	1.000		
BURR_MRT	-0.197	-0.051	0.133	1.000	
BURR_OVIP	0.187	0.084	-0.046	0.213	1.000
BURR_SPA	-0.185	0.003	0.220	0.069	-0.230
SURF_BROO	0.099	-0.005	-0.158	-0.055	0.354
SURF_MRT	-0.045	-0.021	0.168	0.226	0.055
SURF_OVIP	0.300	0.200	0.285	-0.106	-0.163
SURF_SPAW	0.001	-0.063	-0.089	0.268	-0.041
TUBE_BROO	-0.114	0.306	0.359	-0.096	-0.314
TUBE_MRT	-0.168	0.328	0.076	0.087	0.322
BURR_SHEL	-0.142	0.478	0.983	0.143	-0.032
BURR_CHIT	-0.121	0.307	0.374	0.018	-0.184
BURR_TISS	-0.122	0.063	0.139	0.935	0.536
SURF_SHEL	0.294	0.218	0.292	-0.120	-0.179
SURF_CHIT	-0.064	-0.065	0.114	0.121	-0.000
SURF_TISS	0.009	-0.070	-0.097	0.271	-0.019
TUBE_CHIT	-0.195	0.035	0.171	-0.239	-0.223
TUBE_TISS	0.046	0.459	0.381	0.130	-0.242

	BURR_SPA	SURF_BROO	SURF_MRT	SURF_OVIP	SURF_SPAW
BURR_SPA	1.000				
SURF_BROO	-0.122	1.000			
SURF_MRT	0.027	-0.030	1.000		
SURF_OVIP	-0.102	-0.089	-0.071	1.000	
SURF_SPAW	0.278	-0.075	-0.058	0.159	1.000
TUBE_BROO	-0.092	-0.109	-0.125	0.305	-0.051
TUBE_MRT	-0.300	0.359	-0.101	-0.101	0.012
BURR_SHEL	0.236	-0.166	0.196	0.263	-0.092
BURR_CHIT	0.387	-0.048	-0.081	0.119	0.106
BURR_TISS	-0.018	0.072	0.212	-0.134	0.221
SURF_SHEL	-0.046	-0.097	-0.077	0.994	0.159
SURF_CHIT	0.069	0.049	0.699	-0.119	-0.079
SURF_TISS	0.247	-0.031	-0.057	0.163	0.998
TUBE_CHIT	-0.113	-0.076	-0.109	0.066	-0.164
TUBE_TISS	-0.017	-0.085	-0.074	0.417	0.113

	TUBE_BROO	TUBE_MRT	BURR_SHEL	BURR_CHIT	BURR_TISS
TUBE_BROO	1.000				
TUBE_MRT	0.084	1.000			
BURR_SHEL	0.302	0.007	1.000		
BURR_CHIT	0.298	0.199	0.213	1.000	
BURR_TISS	-0.167	0.214	0.148	-0.025	1.000
SURF_SHEL	0.314	-0.121	0.263	0.174	-0.150
SURF_CHIT	-0.095	-0.145	0.112	0.070	0.098
SURF_TISS	-0.058	0.036	-0.098	0.079	0.231
TUBE_CHIT	0.792	0.082	0.111	0.282	-0.282
TUBE_TISS	0.685	0.047	0.361	0.151	0.066

	SURF_SHEL	SURF_CHIT	SURF_TISS	TUBE_CHIT	TUBE_TISS
SURF_SHEL	1.000				
SURF_CHIT	-0.128	1.000			
SURF_TISS	0.157	-0.078	1.000		
TUBE_CHIT	0.080	-0.025	-0.173	1.000	
TUBE_TISS	0.415	-0.126	0.112	0.09	1.000

Number of observations: 44

Appendix 5. Significant correlations between the multi-dimensional functional groups for St. 45 and the environmental variables using Pearson pairwise correlation. Significance values are identified as:
* p<=0.05, ** p<0.02, *** p<0.01, **** p<0.005, ***** p<0.002, and ****** p<0.001

Salinity	Min Clam Sal	Max Clam Sal	Max H20 Sal
Deposit Feeders1/Burrowers			0.316*
Deposit Feeders1/Mixed Reproductive Type			0.316*
Filter Feeders/Tube Dwellers	0.473***	0.487****	0.358*
Filter Feeders/Brooders	0.416**	0.386*	0.322*
Mixed Feeding Type1/Tube Dwellers	-0.443**	-0.507****	
Tube Dwellers/Chitin Barrier	0.473***	0.487****	0.358*

Temperature	Mean Air Temp	Min Air Temp	Max Air Temp	Mean H20 Temp	Min H20 Temp	Max H20 Temp
Filter Feeders/Tube Dwellers	0.479**	0.418****	0.481******	0.502*****	0.415***	0.542******
Mixed Feeding Type1/Burrowers	0.387***	0.379**	0.352**	0.427***	0.432***	0.400**
Mixed Feeding Type2/Surface Dwellers				-0.354*		-0.408***
Filter Feeders/Brooders			0.312*	0.391**		0.451****
Mixed Feeding Type1/Brooders	0.359**	0.362**	0.322*	0.407**	0.429***	0.355*
Mixed Feeding Type2/Oviparous				-0.354*		-0.408***
Surface Dwellers/Brooders			-0.312*			
Tube Dwellers/Brooders	0.356**	0.344*	0.314*	0.343*		0.353*
Burrower/Chitin Barrier		0.368**	0.332*	0.417***	0.432***	0.372**
Tube Dwellers/Chitin Barrier	0.476*****	0.419****	0.482******	0.502*****	0.416***	0.542******

Chlorophyll	Min Chloro	Max Chloro
Mixed Feeding Type1/Tube Dweller		0.491***
Carnivores/Spawners	0.394*	
Mixed Feeding Type1/Spawners		0.471***
Burrowers/Spawners		0.428*
Surface Dwellers/Spawners	0.403*	
Surface Dwellers/Tissue Barrier	0.405*	

Total Organic Carbon in the Sediment	Mean TOC	Min TOC	Max TOC
Deposit Feeders1/Tube Dwellers		-0.459**	
Filter Feeders/Tube Dwellers	-0.501***		-0.552****
Mixed Feeding Type1/Burrowers	-0.389*		
Mixed Feeding Type2/Surface Dwellers			0.408*
Deposit Feeders1/Brooders		-0.458***	
Filter Feeders/Brooders	-0.484***	-0.441**	-0.426*
Mixed Feeding Type1/Brooders	-0.411*	-0.380*	
Mixed Feeding Type2/Oviparous			0.408*
Burrowers/Brooders		-0.389*	
Tube Dwellers/Brooders	-0.599******	-0.532****	-0.533****
Burrowers/Chitin Barrier	-0.412*	-0.379*	
Tube Dwellers/Chitin Barrier	-0.501***		-0.552****
Tube Dwellers/Tissue Barrier		-0.459**	

Biological Oxygen Demand	Mean BOD	Max BOD
Filter Feeders/Tube Dwellers	0.412**	0.491****
Mixed Feeding Type1/Burrowers		0.419**
Deposit Feeders2/Oviparous	-0.424***	-0.480****
Filter Feeders/Brooders	0.426***	0.492****
Filter Feeders/Spawners		0.334*
Mixed Feeting Type1/Brooders	0.341*	0.465****
Burrowers/Brooders		0.335*
Burrowers/Oviparous	-0.424***	-0.480****
Tube Dwellers/Brooders	0.423**	0.516*****
Burrowers/Chitin Barrier	0.333*	0.456***
Tube Dwellers/Chitin Barrier	0.413**	0.492****

Metals	Mean Clam Ag	Max Clam Ag	Mean Sed Ag	Max Sed Ag	Mean Clam Cu	Max Clam Cu	Mean Sed Cu	Max Sed Cu
Deposit Feeders1/Burrowers	-0.352*				-0.387*	-0.368*		
Deposit Feeders2/Burrowers			-0.511***	-0.511***				-0.402*
Filter Feeders/Tube Dwellers			0.527***	0.396*			0.397*	0.375*
Mixed Feeding Type1/Tube Dwellers	0.380*		0.524***	0.623******				0.407*
Mixed Feeding Type2/Surface Dwellers	0.405*			0.531***	0.433**	0.378*		0.390*
Carnivores/Oviparous				0.464**				
Carnivores/Spawners					-0.357*			
Deposit Feeders1/Mixed Reproductive Type	-0.357*	-0.423**			-0.382*			
Deposit Feeders2/Mixed Reproductive Type			-0.409*	-0.419*				
Deposit Feeders2/Oviparous	-0.610******	-0.557******	-0.668******	-0.625******	-0.569*****	-0.499*****		-0.399*
Filter Feeders/Brooders				0.413*				0.410*
Mixed Feeding Type2/Oviparous	0.405*			0.531***	0.433**	0.378*		0.390*
Burrowers/Mixed Reproductive Type			-0.409*	-0.419*				
Burrowers/Oviparous	-0.610******	-0.557******	-0.668******	-0.625******	-0.569******	-0.499*****		-0.399*
Surface Dwellers/Oviparous				0.483**				
Tube Dwellers/Brooders			0.452*	0.449*				