Study of the Recovery of Intertidal Benthos After Removal of Log Booms, Nanaimo River Estuary, British Columbia

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January 1984

Canadian Technical Report of Fisheries and Aquatic Sciences No. 1246

Fisheries and Oceans Pêches et Océans

Canada

Canadian Technical Report of Fisheries and Aquatic Sciences

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Canadian Technical Report of Fisheries
and Aquatic Sciences No. 1246

January 1984

STUDY OF THE RECOVERY OF INTERTIDAL BENTHOS AFTER REMOVAL OF LOG BOOMS, NANAIMO RIVER ESTUARY, BRITISH COLUMBIA

by

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Cat. No. Fs 97-6/1246 ISSN 0706-6457

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ABSTRACT

McGreer, E.R., D.M. Moore and J.R. Sibert. 1984. Study of the recovery of intertidal benthos after removal of log booms, Nanaimo River estuary, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 1246: vii + 63 p.

Intertidal benthic communities in the Nanaimo River estuary were monitored to assess their recovery from the impacts of log boom storage. Changes at a site from which log booms were removed were compared to those at an adjacent reference site which had not been used for log storage. Species composition of meiofauna (harpacticoid copepods) and macrofauna (amphipods, molluscs, annelid worms) at the log removal site remained substantially different from that at the reference site 13 months after log removal. Harpacticoids were frequently found in greater numbers at the log removal site while macrofauna species were reduced in number compared to the reference site. One species of amphipod, Corophium insidiosum, occurred in high numbers only at the log removal site and was suggested as a possible indicator species for future studies. Other species occurring at the log removal site were common indicators of organic enrichment in marine sediments.

Measurement of sediment physical/chemical characteristics showed no consistent differences between the two test sites for sediment particle size, total organic carbon and total Kjeldahl nitrogen. The most significant feature of the log removal site was the persistence of a shallow reducing layer which resulted in anoxia, and production of hydrogen sulfide. The anoxic sediments were considered to be a major factor affecting benthic communities at the log removal site. Implications of the findings with respect to estuarine fisheries are discussed.

Key words: Log storage: recovery, intertidal benthos, estuarine; Meiofauna: harpacticoids; Macrofauna: polychaetes, molluscs, amphipods; Sediments: redox potential, anoxia; Fisheries.

RÉSUMÉ

McGreer, E. R., D. M. Moore, and J. R. Sibert. 1984. Study of the recovery of intertidal benthos after removal of log booms, Nanaimo River estuary, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 1246: vii + 63 p.

Les communautés benthiques de la zone intercotidale de l'estuaire de la rivière Nanaimo ont fait l'objet d'une étude visant à évaluer leur reconstitution après l'enlèvement d'estacades servant à retenir des billots. Les modifications survenues à un emplacement d'où on avait enlevé les billots furent comparées à celles d'un site adjacent de référence où l'on n'avait pas retenu de billots. La composition des espèces constituant la mésofaune (copépodes harpactidés) et la macrofaune (amphipodes, mollusques et vers annélides) à l'emplacement de retenue des billots était toujours substantiellement différente, treize mois après, de celle des espèces du site de référence. Le nombre d'harpactides à l'emplacement de retenue des billots était souvent supérieur, cependant que celui des espèces constituant la macrofaune avait diminué comparativement au site de référence. Seul l'emplacement de retenue des billots recélait une espèce d'amphipodes en grande quantité, le Corophium insidiosum, espèce qui pourrait servir d'indicateur à l'occasion d'autres études. On y trouvait aussi d'autres espèces qui sont souvent des indices d'un enrichissement organique des sédiments marins.

L'établissement des caractéristiques physiques et chimiques des sédiments ne révéla aucune différence substantielle entre les deux sites, en ce qui concerne la taille des particules sédimentaires, le carbone organique total et l'azote total de Kjeldahl. L'emplacement de retenue des billots se caractérisait principalement par la persistance d'une couche réductrice peu profonde qui entraînait une anaéroliose et la production de sulfure d'hydrogène. Les sédiments anoxiques constituaient l'un des principaux facteurs influant sur les communautés benthiques qu'abritait l'emplacement de retenue des billots. Le document traite de la signification des résultats pour les pêches en estuaire.

Mots clés: Retenue des billots: reconstitution, benthos intercotidal, estuarien, mésofaune: harpactidés; macrofaune: polychètes, mollusques, amphipodes, sédiments: potentiel d'oxyde-réduction, anaérobie; pêches.

INTRODUCTION

BACKGROUND FOR MONITORING PROGRAM

The Nanaimo River estuary, located on the east coast of Vancouver Island, British Columbia, is a valuable resource to both logging and fisheries interests. For over 30 years, the estuary has been an area of intensive log storage and handling activity. More recently, the area has been shown to be important as a nursery for juvenile salmonids, which may be limited by available food and suitable habitat (Healey, 1979; Sibert, 1979). In 1977, plans for the development of a major industrial park and deepsea port facility at Duke Point were put forward by the British Columbia Development Corporation. The proposal was reviewed by a Department of Fisheries and Oceasn Task Force and generally accepted, except for the provision regarding additional log storage in the Nanaimo estuary. Concerns about further alienation of productive fish habitat by log storage activities were expressed in reports prepared by the Fish Habitat Sub-Committee of the Nanaimo Estuary Fish Habitat and Log Management Task Force (Anon., 1980 a,b). Recommendations of the Nanaimo Estuary Task Force, endorsed by the Federal Minister of Fisheries and Oceans, included a biological monitoring program to assess the degree to which intertidal benthic communities recovered after removal of logs from key areas of the Nanaimo estuary.

The present report summarizes the results of a 17-month monitoring study carried out from October, 1980 to February, 1982 to assess recovery of intertidal benthic communities after removal of boomed logs from a log storage site in the Nanaimo estuary. Results from the log removal site are compared with those from a nearby reference site which had not been subject to log storage. Biological components monitored included both meio- and macrobenthic invertebrate communities. Emphasis on meiofauna taxa was placed on harpacticoid copepods because of their importance as a food item in the diets of resident juvenile salmonids in the Nanaimo estuary (Sibert, 1979). Data

obtained on the macrobenthos represent the first data collected on this community from this area. Sediment physical/chemical variables monitored included particle size, depth of the anoxic layer, total organic carbon and total Kjeldahl nitrogen.

SITE DESCRIPTION AND STUDY CONSTRAINTS

Locations of the two sites used for comparison in this study are shown in Figure 1. The log removal (LR) site was situated approximately 50 m seaward of a dolphin (group of pilings) used for mooring boomed logs. This placed the site directly under a row of bundle booms which occupied the site prior to January 21, 1981, the date on which the bundled logs were permanently removed. The reference (REF) site was located approximately 100 m east of the LR site in an area which had not been used for log storage. The substrate at both sites was predominately medium to coarse sand. Both sites were at the same tidal elevation, approximately 3 m above MLLW. This estimate was made by recording the time at which the incoming tide reached the study sites on a number of occasions, and calculating the appropriate tidal height from tide tables. The tidal elevation of our test sites approximated that of "Site 5" on the west side of the estuary, a site sampled in previous benthic studies (Sibert and Harpham, 1979; Sibert, 1979).

A number of constraints were placed on the study in the process of selecting a suitable sampling site location. Prior to beginning field sampling, discussions were initiated with representatives of the Nanaimo User's Group (a collection of logging companies holding leases for log storage in the estuary) to select a possible study site. Our requirements were for a location which had been actively used for log storage for an extended period of time; which could have log booms removed from it at a time convenient for our monitoring; and, a site which could be left undisturbed for the duration of the study. The User's Group agreed to provide logistical support in removing log booms from the area, and in leaving it undisturbed. However, the User's Group could not designate a site immediately which met all of our requirements, and the final selection of a site was not completed until

October of 1980, three months prior to the date of boom removal in January, 1981. Without prior knowledge of the study site location, the six-month monitoring of the log removal site prior to removal of log booms originally envisioned was not possible. A second limitation was that the only site which met all the requirements for our study on log removal was in an area which had not been previously sampled in benthic studies in the Nanaimo estuary. This meant that seasonal variations in benthic community structure, and physical characteristics of the site were unknown. Thus, the study site was chosen primarily on the basis of its suitability with respect to history of log storage, and availability for prolonged monitoring without further disturbance. Biological monitoring of the site prior to log removal was limited to the 3-month period from October to December, 1980.

SUMMARY OF PREVIOUS RESEARCH ON EFFECTS OF LOG STORAGE

A number of published reports have reviewed the biological impacts of log handling activities on coastal marine environments (e.g. Anon., 1980a,b,c; Levy et al., 1983; Smith, 1977; Toews and Brownlee, 1981). It is not our intention to provide an exhaustive review of this literature here, but to summarize information relevant to the present study. In this regard, many of the impacts associated with log handling (e.g. smothering of benthos, lowered dissolved oxygen values, leachate toxicity) have been described from studies of subtidal log dumping sites, and are the result of the accumulation of bark deposits over bottom sediments. These conditions are generally not characteristic of intertidal log storage sites such as those monitored in the present study. Of the considerable number of studies on logging impacts in the literature, only a few have dealt with log storage areas *per se* (e.g. McDaniel, 1973; Pease, 1974). Pease (1974) reported "slightly reduced" epifauna species and "drastically reduced" infauna from one intertidal log storage site but the habitat was not comparable to the tidal marsh systems of typical Pacific Coast estuaries.

We found only two previously published studies dealing specifically with impacts on benthic communities at intertidal, estuarine log storage sites.

Smith (1977) reported greatly reduced numbers of species and abundance of macrobenthos under log rafts stored in intertidal sites in the Snohomish River estuary in Puget Sound. Infaunal species (e.g. Manayunkia aestuarina, Corophium salmonis) comprised the community affected. Smith (1977) also reported on short-term recolonization of an area from which log rafts had been removed. In the second study, Sibert and Harpham (1979) could not relate changes in the total abundance of major meiofaunal taxa or harpacticoid copepods directly to the presence of log booms. Areas under the booms were considered to be more suitable habitat for epibenthic than interstitial species.

METHODS

Sampling in the Nanaimo estuary was initiated in October, 1980, three months prior to the removal of the log booms. Over the period of the study sampling frequency was similar but not identical for the macro- and meiobenthic components of the study. A summary of the sampling schedule is given below:

	Macrobenthos		Meiobenthos	
1980	October		-	
	November		November	
	December		December	
1981	January	after log removal (LR)	January	
	February	LR + 2 wk	"	after log removal (LR)
	"	LR + 4 wk	"	LR + 24 h
	March		"	LR + 1 wk
	April		February	LR + 2 wk
	May		"	LR + 4 wk
	July		March	
	August		April	
	October		May	
	December		July	
			August	
			October	
			December	
1982	February		February	

BENTHIC INVERTEBRATES

Benthic invertebrates were sampled during low tide at the two sites shown in Figure 1. During the first three months of the study, when bundle booms occupied the log removal site, samples were taken in open spaces between grounded logs. The initial "recovery" sampling occurred on the first low tide following log removal. Log bundles were towed seaward from the site at high water on January 21, 1981.

Sampling for macrofauna (>500 μm in size) was carried out by scooping out the sediment within a 0.06 m^2 quadrat with a trowel to a depth of 2 cm. Samples were placed in polyethylene bags, and returned to the laboratory where they were washed through a 0.5 mm sieve. Organisms retained on the mesh were rinsed into plastic vials, and preserved with 10% buffered formalin. Subsamples (by weight) were later used for enumeration and taxonomic identification of species present. Three samples were analyzed from each site on each sampling occasion.

Sediment samples for meiofauna were collected by pushing an open-ended syringe (surface area 6 cm^2) into the sediment to a depth of 2 cm. Samples were placed in Whirlpak bags containing an excess of 4% formalin. On return to the laboratory, meiofauna were separated from the sediment by successive washing and decantation through a 44 μm sieve. Organisms retained were also sampled, and a portion examined in a petri dish under a dissecting microscope. Of the various groups segregated (e.g. nematodes, micro-annelids, ostracods), only the harpacticoid copepods were submitted for detailed taxonomic analysis. Triplicate samples were collected on each occasion.

SEDIMENT PHYSICAL/CHEMICAL ANALYSIS

Coincident with the biological sampling, sediment samples were collected for analysis of particle grain size, total organic carbon (TOC) and total kjeldahl nitrogen (TKN) analysis. Cores for physical/chemical analysis were

collected at each site with a plexiglass tube (5 cm diameter) pushed by hand into the mud to a depth of 2 cm. Duplicate cores were placed in a single Whirlpak bag, and immediately frozen in the field for return to the laboratory and later analysis. A well mixed subsample was wet sieved through a series of graded sieves, dried and the percent weight of each retained fraction determined. Sieves with mesh sizes of 2.0 mm and 0.0625 mm were used. The remaining subsample was submitted for analysis of TOC and TKN.

TOC was determined by first treating a weighed (approx. 5 g) subsample with 4N hydrochloric acid to remove carbonates and bicarbonates, drying at 60^{o}C, and igniting 1 g portions in a LECO furnace. Organic carbon was calculated from the volume of carbon dioxide evolved. TKN was determined by digesting 0.5 g of sediment with 20% sulfuric acid/potassium sulfate mixture in a micro-kjeldahl apparatus for 2 h, diluting, filtering and analyzing for ammonia.

Cores of 5 cm diameter and up to 10 cm in depth were taken at each site for determination of the depth of the anoxic layer. Sediment was extruded from the core tube and the reduction potential determined in the field. Oxidation-reduction potential was measured with a platinum electrode and an Orion portable pH meter. The probe was inserted into the side of the core at 1 cm vertical intervals, and the redox potential measured. The anoxic layer was considered to be the depth at which redox readings changed from a positive to a negative value. Shallower cores often had to be taken at the LR site due to the presence of large pieces of bark within the sediment.

DATA ANALYSIS

Several different techniques were employed in analyzing the benthic data in an attempt to identify differences in the benthic communities between the two study sites. First, the mean abundance of numerically dominant species at both sites was plotted against time to show any easily identifiable patterns or trends in the populations. The next step was to test the statis-

tical significance of the differences in population abundance observed by 2-way Analysis of Variance (ANOVA). Species abundance data were transformed to Log(X + 1.0) for analysis. Differences between sampling sites and sample times were tested. In addition to testing data from all sampling occasions, ANOVA was also applied selectively to data from a portion of the study (i.e. October, 1980 to April, 1981) encompassing an equal time before and after log removal. This analysis was performed to minimize seasonal effects and to permit a better comparison with a previous study on recolonization after log removal (Smith, 1977).

As different species react differently to environmental perturbation, it was desirable to combine results from individual populations and examine changes in the whole community. To deal with the large number of species present, a multivariate, ordination technique, Analysis of Correspondence (ANACOR) was used to assess changes in community structure. ANACOR is a variant of a frequently used ordination technique known as Principal Component Analysis - PCA (see Cassie and Michael, 1968). Like PCA, ANACOR is used to reduce a large number of variables (in this study, species) to a much smaller number of "factors" which retain a significant fraction of their original variance. The values generated for these factors may be used as a measure of community structure.

However, ANACOR has a number of inherent advantages over PCA in the analysis of ecological data. Unlike PCA, ANACOR is not adversely affected when the original data are non-linear, and it can exploit the equivalence of both Q- and R-mode analyses (David et al., 1974). Q-mode explores the relationships among samples (in this study, sample site/times) based on their species composition; R-mode explores relationships among species based on differences in their abundance in different samples. Thus, ANACOR also has the particular virtue that both samples and species may be plotted to the same scale on the factor axes. Clusters of samples formed by ANACOR are more easily associated with the species which have determined the clusters than with other forms of multivariate cluster analyses. Another advantage of

ANACOR over most clustering techniques is that statistical significance of the "species-clusters" generated by the analysis can be tested.

Another advantage of ANACOR over PCA is that the structure of the clusters produced is less susceptible to external "influences" in the original data such as abundance of species, density of samples, and the double absences of species (Chardy et al., 1976). This means that the clusters formed are less susceptible to overriding influences of such factors as seasonal peaks in abundance.

For these reasons, ANACOR appeared to be the best choice as the multivariate analysis for the present study. However, ANACOR has not been used extensively in benthic studies and its merits need to be evaluated against results of PCA and other more common multivariate techniques. Chardy et al. (1976) have shown that the community structures obtained for any one data set will differ depending on the multivariate analysis used.

The ANACOR program used in this study was the same as that of David et al. (1974), and was adapted by one of the present authors (JS) to run on the VAX 11/780 at the Pacific Biological Station, Nanaimo. M. J.-M. Belisle of the École Poly-technique of Montreal supplied the original ANACOR program.

The ratio of nematode:harpacticoid abundance was also computed for each of the two test sites. This ratio has recently been applied to the study of marine pollution (Warwick, 1981).

The final step in the data analysis was to run a canonical correlation between the ANACOR factors (representative of species association) and the physical/chemical variables. This analysis relates changes in species groups to changes in environmental variables at each site.

RESULTS

A list of the computer code numbers used to identify the sample sites and times is given in Table 1. A total of 32 site/times were sampled for meiofauna and 28 site/times for macrofauna yielding 96 and 84 samples for taxonomic analysis, respectively. Due to the large data set, the raw species data for each sampling occasion will be published separately (Moore et al., 1983). Summary tables of the major benthic species, and corresponding abundance data are presented in this report.

MEIOFAUNA

Of the meiofauna identified, harpacticoid copepods and nematode worms were by far the most commonly occurring and numerically dominant groups. For purposes of this study, due to their importance as prey items for juvenile salmonids in the Nanaimo estuary, the harpacticoid group was selected for further detailed analysis. Approximately 35 species of harpacticoid copepods in nine families were identified from the LR and REF sites over the study period. A complete list of the harpacticoid species and their abundance is given in Moore et al. (1983). Twelve species were common throughout the sampling period, occurring in at least 10% of the samples. These species were selected for analysis (Table 2). Six of the twelve most common species (S. knabeni, H. jadensis, Mesochra sp., S. asetosa, N. palustris and R. propinqua) accounted for 92 and 93% of the total abundance of harpacticoids at the REF and LR site, respectively. Plots of the seasonal changes in the total number of harpacticoid species and the total mean abundance are given in Figure 2. A decrease in both the number of species and total abundance was evident between December 1980 and January 1981. The January 1981 sampling was carried out two days prior to the removal of the log booms from the LR site. The changes observed suggest that natural factors had disturbed both sites just prior to log removal. The number of harpacticoid species remained lower than in the November/December, 1980 period until April, 1981 at which time they slowly increased to pre-January levels. It is interesting to note

the nearly identical pattern shown for both the LR and REF sites. A similar pattern is evident for the total mean harpacticoid abundance (Fig. 2). The "recovery" from the reduced level of abundance noted in January, 1981 occurred after four months (May). A seasonal peak in abundance similar to that observed in November, 1980 was also evident in October, 1981. Again, the changes observed were very similar for both the LR and REF sites. The only major difference appears to be that harpacticoids were more abundant at the REF site during the period (November, 1980-January, 1981) when log booms were in place at the LR site.

Seasonal changes in the five most abundant harpacticoid species are shown in Figure 3. The seasonal patterns described for total mean abundance in Figure 2 are reflected in the changes in the individual harpacticoid species. One exception is that H. jadensis did not show a fall peak in abundance in 1982. The abundance of four taxa (S. knabeni, H. jadensis, Mesochra sp., and N. palustris) was greater at the REF than the LR site during the time when log booms were actually being stored at the latter location (Fig. 2). However, only S. knabeni, H. jadensis and N. palustris were found to be statistically ($p < 0.05$) different in terms of higher abundance (November, 1980-April, 1981) at the REF site prior to log removal (Table 3). The abundance of S. knabeni was not significantly different between the LR and REF sites when data from the entire study period (November, 1980-February, 1982) were included. This fact underlies how different "statistical" results can be derived from the same data set depending on how selective the investigator is in choosing data for analysis. The significance ($p < 0.05$) of seasonal (including pre- vs post-log boom removal) differences were also demonstrated (Table 3). Only the abundance of S. knabeni was not significantly different at the LR site before and after log boom removal (November, 1980 -April, 1981).

Results of the ANACOR analysis for harpacticoid copepods are presented in Tables 4 and 5, and in Figure 4.

The first five variables (or factors) generated by the Analysis of Correspondence (ANACOR) from the twelve most common harpacticoid species and the sixteen sampling occasions accounted for over 80% of the total species/sample variance (Table 4). Of the five factors identified, the first three factors proved the most useful in identifying the major patterns in species composition and abundance over the whole study period within the analysis. The first three factors accounted for 57.9% of the total variance.

As an aid in interpreting the most important factors, the highest value for each species among the five factors is underlined in Table 4. Similarly, the highest value for each station among the five factors in the lower half of Table 4 is also underlined. The values represent the contribution (or closeness in graphical terms) of each of the original axes for species and sample variables to each common factor axis. These values can be interpreted as measures of association between factors and original variables.

Inspection of Table 4 reveals clusters of large negative and positive scores. Scores of like signs indicate close association, opposite signs indicate dissimilarity, and the absolute score value, the strength of either. The first factor contained the largest proportion of the total species/sample variance (23.9%). Data in Table 4 also indicate that about half of the species produced the greatest similarities and differences between samples on factors 1 and 2, while the remainder were responsible for samples of unusual composition when compared to all other samples.

A plot of the first two factors (Fig. 4) identified four groups of species/samples which remained consistently clustered over the study period. The species and sample site-time code letters and numbers appearing on the figure are explained in Table 1. Only one species was associated with each cluster of samples (site-times), which suggests a succession of species dominating each site for a limited period of time. Also, species occupying opposing quadrants tended to be mutually exclusive. That is, an increase in abundance of one species at a particular site was accompanied by a decrease

in the former dominant. Major "outlier" groups (species which were irregular dominants) are circled.

In Group A (Fig. 4), Huntemannia jadensis (HJ) was the principal species in an equal number of LR and REF site samples. A second group (B) was ordinated along the same axis as A, and was closely related to A. However, a small, distinct separation in the scores was evident due to three REF site samples dominated by Nannopus palustris. In Group C, Stenhelia asetosa was singularly abundant in six LR samples; these species/samples being described chiefly by Factor 2. Due to the distinct lack of overlap between Factors 1 and 2, the major community patterns of the two sites were not auto-correlated.

A fourth group (D) was characterized as having no discernible pattern in common with other species/samples. Schizopera knabeni was the most common species in Group D, and was particularly dominant in one LR sample and three REF site samples.

The ANACOR analysis showed that neither Nannopus palustris (Group B) nor Huntemannia jadensis (Group A) co-dominated with Stenhelia asetosa (Group C). The factors which appeared to be involved in determining the community structure at the REF and LR sites had no discernible effect on the main population of Schizopera knabeni. Samples (site-times) which were clustered around the key species were dominated by those species either through sheer abundance or in the degree of changes in abundance, and usually both.

Plots of other factors on different axes (Factor 1 vs 3, 1 vs 4,, 2 vs 3, etc.) were generated by the ANACOR program to confirm the patterns identified in Figure 4. However, views of the dominant species groups in these three-dimensional spaces did not significantly alter the composition or spacing of the groups. Therefore, we chose to present one orientation (Fig. 4) to describe the clusters generated by ANACOR.

The changing patterns in community structure for the harpacticoid copepod populations at the two sites as interpreted from the ANACOR analysis is

summarized in Table 5. Generally, the communities inhabiting the LR and REF sites were different both before and after log boom removal. The results indicate that up to four months after log removal (LR + 24 h; LR + 4 wk, March, May, 1981), the LR harpacticoid community periodically resembled that of the REF site. The only species found in abundance at the LR site within the 4 month period following log removal was Huntemannia jadensis (Group A dominant). For reasons unknown, community type B, dominated Nannopus palustris, was not a successful colonizer at the LR site despite the co-occurrence of both the principal species in REF site samples.

The D-type community which was observed in late summer and fall (1981) at the REF site was characterized by relatively high numbers of Schizopera knabeni and Huntemannia jadensis, and to some extent Mesochra sp. Generally, more species were represented in this group than in other community types. Group D can be regarded as a relatively stable and diversified group. The sudden appearance of D-type community at the LR site within 24 h after log removal is noteworthy, suggesting an attempt by the REF site harpacticoid community to establish itself on the site just vacated by the log booms. All but one of the twelve species was present and in densities similar to that of the REF site at that time. At no other time in the study period was species diversity as marked at either site.

A second important feature of the LR site was the number of irregularly occurring dominant species or "outliers" (indicated by an asterisk * in Table 5) which occurred throughout the winter, before and after log removal. Apart from LR + 24 h, December 1980 marked the only occurrence of Enhydrosoma uniartriculatum and E. bucholtzi at the LR site. These species were never dominant at the control site. Samples from the log boom removal site taken at LR, LR + 1 wk and LR + 2 wk were outliers with no discernible relation to other samples (Fig. 4). Their relative distances from the origin of the factor axes suggest a decreasing order of anomaly: LR, LR + 2 wk then LR + 4 wk. It appears from Table 5 that the insurgence of community-type D within 24 h of log removal was preceded immediately by a highly unusual state

of affairs at time of LR, followed in the next one to two weeks by a return to an increasingly anomalous community compared to the REF site.

The LR site also appears to have been essentially barren at the time of log removal and up to two weeks after removal before community-type A had begun to develop. Clearly, community-type D which immediately moved into the LR site after log removal was extremely short-lived.

A community-type C, dominated by Stenhelia asetosa inhabited the log removal site from July 1981 to the end of the study period in February 1982. There is some suggestion from the plot of factor scores (Fig. 4) that the harpacticoid community of November 1980, prior to log boom removal was similar to community-type C. Community-type C did not develop fully at the LR site until four months after log boom removal.

In contrast to the LR site samples, "outlier" samples from the REF site were only present in summer and late fall (Table 5). Periods of successive colonization appeared to be superimposed on an essentially D-type community, beginning with Mesochra sp. in July, followed by Heterolaophonte sp. in October and Robertsonia propinqua in December 1981 - then returning to community D before February 1982. A seasonal recurrence of A- and B-type communities in early winter seemed a well established pattern (Table 5). The period of alternating A and B communities at the REF site coincided with the period of greatest change or anomaly in LR site samples.

In summary, the ANACOR analysis indicates that both before and after removal of log booms, the species which comprised the harpacticoid community at the LR site remained substantially different from those of the nearby REF site.

A summary of the ratio of the total numbers of harpacticoids and nematodes is given in Table 6. The highest numbers of nematodes occurred between October and December at the REF site. Nematode densities at the LR

site never reached more than about 10% of those of the REF. Numbers of harpacticoids were similar at both sites with peak values in October and November. The nematode/harpacticoid ratio ranged from less than 1 to 20.3 with values being generally higher at the REF site.

MACROFAUNA

Over 50 species of macrofauna in 13 taxonomic groups (predominantly polychaeta, pelecypoda, amphipoda and insecta) were identified from the LR and REF sites. A complete list of species and numbers per sample is given in Moore et al. (1983). Twenty-five species of macrofauna occurring in a minimum of 10% of the samples were selected for multivariate statistical analysis, and these are listed in Table 7. Three species of polychaete worms (M. aestuarina, P. elegans and C. capitata) accounted for 85% of the total species abundance at the REF site (Table 7). These three species plus the oligochaete T. gabrielli, the cumacean C. vulgaris, and Corophium sp. of amphipods made up 83% of the numbers of individuals at the LR site. Six species of amphipods were identified with Corophium and Eogammarus being the most abundant. Insect larvae (e.g. Chironomidae), two species of pelecypoda (Mya arenaria, Macoma balthica), and single representatives of the ostracoda, cumacea, tanaidacea and oligochaeta were also identified. Plots of the seasonal changes in the total number of macrofauna taxa and mean abundance data are given in Figure 5.

The total number of macrofauna taxa was relatively constant at each site throughout the study period. However, the numbers of taxa at the LR site were almost always greater than at the REF site. No obvious changes in conjunction with the removal of log booms from the LR site were evident in the numbers of taxa. The plot of the total mean abundance of macrofauna (Fig. 5) shows a greater abundance of macrofauna at the REF site than the LR site on most of the sampling occasions. More variability in the abundance data at the REF site appears after August 1982 than in the preceding months. Abundance at the LR site prior to log removal was lower than at the REF site. Macrofauna abundance increased starting two months (March) after log removal, and remain-

ed relatively stable at higher levels for the rest of the study. Total abundance at the REF site showed a decrease in the period November to January, preceding log removal.

Seasonal changes in some of the most common macrofauna species are shown in Figures 6 and 7. The relative pattern of abundance of M. aestuarina (Fig. 6) at both sites follows closely the patterns described previously for total macrofauna abundance. An increase in abundance is apparent at the LR site after log removal. P. elegans shows an increase in abundance at the REF site over previous month starting in February 1981 (Fig. 6). The cumacean C. vulgaris showed peaks in abundance at both sites on three occasions but did not occur regularly in high numbers (Fig. 7). A most interesting pattern was shown for the amphipod C. insidiosum (Fig. 7). It was present at the LR site in very low numbers from October to May, then showed an increase in density which was sustained to the end of the study period. Corophium sp. (which were most likely predominantly juveniles of C. insidiosum) showed a similar pattern. At no time was the Corophium well established at the REF site. A similar trend was followed by T. stanfordi at both LR and REF sites (Fig. 7). The trends in abundance of individual macrofauna populations were generally confirmed to be statistically significant by ANOVA (Table 8). One exception was the apparent increase in T. stanfordi from August 1981 to February 1982 which was not shown to be statistically significant compared to the other dates sampled (Table 8). All the most common macrofauna species (except T. stanfordi) showed a significant difference in abundance before and after log removal at the LR site.

Results of the ANACOR analysis for macrofauna are given in Tables 9 and 10, and in Figure 8. The first five factors generated by ANACOR from the twenty-five species and fourteen sampling times accounted for 74.4% of the total species/sample variance (Table 9). Despite having twice the number of species (i.e. sources of variability) in the analysis than for meiofauna, the five factors accounted for a similar proportion of variance. This result suggests that fewer variables controlled the macrofauna structure relative to

the meiofauna community. The early appearance of outlying species/samples in Factor 4 (Table 9) indicated that further extraction of factors was unwarranted. The relative contribution of the outliers to the total variance was less than 4%. Over half of the species produced the largest similarities and differences between samples on Factors 1 and 2 (Table 9).

A plot of the first two factors (Fig. 8) revealed smaller and less well defined groups of species/samples relative to the meiofauna (Fig. 4). Four consistent clusters were identified. Cluster A was centred at the LR site about one year following log removal. In contrast, cluster C was orientated near the REF site in both winter and summer. A third minor cluster, B, was marginally associated with Group A on Factor 1 and represented a dominance group at the LR site. A fourth minor cluster isolated by Factor 3 in the analysis was a dominance cluster of REF site samples from October to December, prior to the time of log removal. The remaining species/samples were minor to extreme outliers, unrelated to the principal groups. Generally, the difference between the LR and REF sites appeared to be the major source of variance in the analysis.

Table 10 shows the site and sampling times of each sample number and provides a comparison of the macrofauna community at the two sites over the entire sampling period. In Group A (Table 10), six species (Corophium insidiosum, Corophium sp., Eogammarus confervicolus, Mya arenaria, Amphicteis sp., and Macoma balthica) dominated the LR site prior to log removal, and in December and February 1982 returned to a pre-log removal community. Group B (Etone longa) was clustered in January and February at both the LR and REF sites. Pygospio elegans (Group C) was the second most abundant species in the study, and was the second most dominant species after Manayunkia aestuarina at the REF site, and at LR, LR + 4 wk, July and August 1981 following log removal. Surprisingly, Manayunkia aestuarina, the most abundant species in the study, did not contribute to any community pattern. Capitella capitata (Group D) was the community dominant at the REF site in October, November and December prior to log removal.

In summary, the macrofauna community at the LR site remained substantially different from that of the REF site throughout the study. Unlike the harpacticoid community which included a number of mobile, opportunistic, hyperbenthic species, the major macrofauna groups were not generally found at both sites. A larger number of "outlier" species appeared at the LR site than the REF site, which suggests that, as with the meiofauna, no well defined community recolonized the LR site following log removal.

PHYSICAL/CHEMICAL VARIABLES

A summary of surface sediment characteristics at the REF and LR sites is given in Table 11. Both sites were composed primarily of sand with the REF site being slightly coarser than the LR site as indicated by the larger percentage of gravel. Values for total organic carbon (TOC) and total kjeldahl nitrogen (TKN) were similar at both sites, with a mean ratio of TOC:TKN of approximately 27.

Results of canonical correlation analysis between the five meiofauna factors and sediment physical/chemical data (% gravel/sand/mud, TOC, and TKN) are given in Table 12. The analysis revealed no significant correlations between meiofauna community patterns at either site and changing physical/chemical conditions. Bartlett's test indicated that no canonical variable expressed dependency between factors and physical/chemical data at the 0.05 level of significance. Significant correlations between percentage gravel and sand, and between TKN and mud were found, but these are of little practical value for identifying the processes associated with community patterns.

Similar results were obtained from canonical correlation of the first five macrofauna community pattern factors and the physical/chemical data (Table 13). No physical/chemical variables were significantly correlated with biological community factors. Bartlett's test indicated that one canonical variable (percentage sand versus percentage gravel) was significant at $p = 0.05$.

Results of the sediment oxidation-reduction potential (Eh) measurements are given in Tables 14 and 15, and depth of the anoxic layer at each site summarized in Table 16. A reducing (anoxic) layer was generally not present at the REF site during the study period except in November, 1980 and in April, 1981. The change in redox profiles between November and December, 1980 (Table 14) coincided with the deposition of a large quantity of clean river sand over the area (see Figure 1). The cause of the redox discontinuity apparent in April 1981 at the REF site (Table 15) is unknown. The redox profiles at the LR site showed an anoxic layer close to the surface frequently throughout the study. The frequent changes in depth of this layer may have been due to continual deposition of clean sand from the adjacent river channel (Fig. 1). However, the major difference between the two study sites was that the shallow reducing layer was a consistent feature of the LR site only. The difference in the depth of the anoxic layer at the two sites is more clearly illustrated in the summary of the data in Table 16.

DISCUSSION

BENTHIC COMMUNITIES

Species Composition

Our multivariate analysis showed that the species composition of benthic communities was different at the REF and LR sites both before and after removal of log booms. The ANACOR analysis indicated that the dominant harpacticoid and macrofauna species at each site changed over time but that different species generally dominated each site on any one occasion. The harpacticoids Schizopera knabeni and Stenhelia asetosa dominated the REF and LR sites respectively. The total number of harpacticoid species was remarkably similar at both sites throughout the study. Some harpacticoid species were common to both sites throughout the study, indicating a degree of similarity in community structure.

A macrofauna community comprised of Corophium insidiosum, Eogammarus confervicolus, Mya arenaria, Macoma balthica and Amphicties sp. was the most consistent community occupying the LR site over the study period. The plychaetes P. elegans and C. capitata were the dominant community species at the REF site. The polychaete M. aestuarina was present on each sampling occasion at both REF and LR sites but because it did not respond to changes in the other species was not identified as contributing to a "community" by the ANACOR analysis. The larger number of "outlier" (i.e. irregular dominant) species occupying the LR site for both macrofauna and harpacticoids suggested a frequently changing pattern in community structure and hence a low degree of stability with respect to any single community group.

A major assumption in our original study design was that "recovery" of benthic communities at the LR site after log removal would result in a convergence of the LR community-type with that at the REF site after log removal. On this basis, it appears that benthic communities at the LR site did not "recover" after removal of the log booms. However, the concepts of community structure and stability in marine benthic ecosystems are the subject of much debate (e.g. Gray, 1977; Mills, 1969; Hargrave and Thiel, 1983). Mills (1969) recognized that various types of species associations can exist, from closely associated groups to loosely integrated aggregations due to co-occurrence. Inevitably, knowledge of the natural, undisturbed community and its variability over time is required in making any comparison. However, our present knowledge of the natural, long-term temporal changes in community structure in benthic ecosystems is incomplete or completely lacking (Hargrave and Thiel, 1983; Coull and Bell, 1980). To resolve the questions about undisturbed communities, it would be desirable to have data on long-term changes in community structure at more than one reference location with which to compare data from a log removal site. It has been suggested that a study of at least five years in length is required to adequately document changes due to log booming (Waldichuk, 1979). Unfortunately, long-term (i.e. annual) studies of community structure are highly labour-intensive and expensive. Data generation is also slow and time-consuming. One approach for overcoming these problems is to concentrate efforts

on one or more "target species" (Hargrave and Thiel, 1983). Time for sample processing and data interpretation would be reduced substantially. In addition, this approach would facilitate research on life history and natural succession for individual species, aspects which are required if biologists are to quantitatively model benthic ecosystems (Gray, 1977). One such "target species" evident from our study on log storage is the amphipod Corophium insidiosum. This species occurred in very low numbers at the LR site before log removal, but showed a significant "recovery" starting in May (Fig. 7). In contrast, C. insidiosum occurred infrequently at the REF site throughout the study. Confirmation of the role of C. insidiosum as a potential "target species" for monitoring the impacts of log storage is a high priority for future studies in the Nanaimo and other estuaries.

One feature of the REF site used in the present study was that it was subject to a major disturbance one month prior to removal of the log booms from the LR site. In December 1980, heavy rains caused the Nanaimo River to flood its banks and forge a new channel across the estuary (Fig. 1). Clean river sand to about 5 cm depth was deposited over the study area. Proximity to the new channel may also have lowered the salinity of the overlying water at both the REF site and LR site. Changes in community structure from those recorded in preceding months at the REF site were evident (Tables 5 and 10) in the January samples. The timing of this disturbance makes it difficult to compare communities which developed after log removal with those which existed prior to log removal for any one site. Similar difficulties may be reduced in future studies by the use of more than one reference site.

In a previous study on the recovery of intertidal benthos after removal of log booms, Smith (1977) found little recruitment of additional species, but found significant increases in the relative abundance of resident species after log removal.

Species Abundance

The "recovery" of benthic species can also be assessed by comparing changes in numerical density before and after log removal. Prior to log removal the total mean abundance of harpacticoid taxa (Fig. 2) and macrofauna (Fig. 5) was greater at the REF than LR site. After log removal, the total mean abundance of macrofauna at the REF site remained generally above that at the LR site. An increase in total mean abundance at the LR site over densities occurring prior to log removal was apparent after April (Fig. 5). This increase in density or "recovery" at the LR site was primarily influenced by only two key species, namely M. aestuarina and C. insidiosum (Fig. 6,7).

Total harpacticoid densities were lower at the LR site after log removal until March, when they appeared to respond to seasonal cycles (Fig. 2). From March until October harpacticoid abundance was frequently greater at the LR site. This observation was also made by Sibert and Harpham (1979) who concluded that the habitat at a log boom site was more favourable for interstitial harpacticoid copepods than habitats between booms.

Recolonization studies of macrofauna species in the Snohomish River estuary indicated that abundances in previously rafted areas reached reference site levels usually in less than one month (Smith, 1977). Seasonal differences in the rate of recovery for some species were also suggested. However, conclusions regarding recovery in this study (Smith, 1977) were based on comparison of a limited number of sampling occasions after log removal. Although no statistical differences in abundance between previously rafted and reference areas were found for six macrofauna species, differences in abundance at times longer than two months were not assessed. Even shorter time frames have been used to assess "recovery" for meiofauna. Studies on the rates of recolonization of meiofauna after physical disturbance of the sediment have shown partial to complete recovery (in terms of species abundance) compared to controls after one or two tidal cycles (Sherman and Coull, 1980; Thistle, 1980). The question thus becomes one of defining an appropriate length of time for monitoring "recovery" of a system.

The current view is that conclusions drawn from such limited time frames may not be valid when applied to benthic communities over longer (e.g. seasonal, yearly) periods of time. The need to analyse data from long-term studies is essential if consistent differences due to anthropogenic impacts are to be separated from those due to natural variation on the ecosystem level. Based on the growing knowledge of natural variability for benthic ecosystems, the length of time to carry out such monitoring must be several years to adequately characterize changes in population dynamics, habitat and sediment type (Coull and Bell, 1980; Hargrave and Thiel, 1983).

Indicator Species

One of the most widely used methods of assessing the response of macrobenthic communities to environmental disturbance relies on the identification of indicator species or groups. Species common to the LR site (e.g. M. balthica, M. arenaria, Corophium insidiosum) are species known to be tolerant of organically enriched areas and associated physical conditions such as low dissolved oxygen, presence of hydrogen sulfide and reducing sediments (Pearson and Rosenberg, 1978; Anger, 1975). Although the presence of these indicator organisms is well documented, it has proved more difficult to relate species distributions to the specific causal factors which have produced the biological changes observed (Pearson and Rosenberg, 1978). The indicator species noted above were on the average far more abundant at the LR than the REF site (Table 7). The polychaetes P. elegans and C. capitata were more common at the REF site. These species have been used as indicators of "organic enrichment"; they are also euryhaline species tolerant of low salinity and are often present on upper estuarine sandflats (Pearson and Rosenberg, 1978; Levings and Coustalin, 1975). This observation is consistent with the tidal flows in our study area which tended to push freshwater up the tidal channel towards the REF site on a flooding tide.

Meiofauna pollution work has focused less on the use of single indicator species, and more on relative proportions of larger groups. Raffaelli and Mason (1981) suggested the use of the ratio of numbers of nematodes:copepods

as a pollution index. This idea was based on the assumption that copepods were more sensitive to environmental stress. When applied in the present study, the nematode:copepod ratio was consistently higher at the REF site. Generally, the values at the REF site were below 10, a number suggested as indicating polluted sandy sediments (Warwick, 1981). The fact that the nematode:copepod ratio was not a useful indicator in the present study is not surprising given the fact that harpacticoids were frequently more abundant at the LR site. Sibert and Harpham (1979), in their earlier study of the impacts of logging in the Nanaimo estuary, also concluded the ratio to be of little value. Critics of this index have stressed that non-pollution factors may also significantly influence the nematode:copepod ratio, and these factors should be thoroughly investigated before the index can gain widespread use (Coull et al., 1981).

Relationship to Physical/Chemical Variables

No significant correlations between the "factors" associated with the various species groups and sediment physical/chemical variables were demonstrated in the present study. Both sites were similar with respect to particle size characteristics, and values for TOC and TKN. The major physical difference between the two sites was the depth of the anoxic layer as determined by redox measurements. Depth of the anoxic layer at the LR site was consistently shallower than the REF site. Persistence of a strong anoxic sediment at the LR site was further supported by the black, reducing appearance of sediments at this site, and the smell of hydrogen sulfide which was always present. These features were never present at the REF site. The presence of the anoxic sediment at the LR site is the most likely cause of the differences observed in biological communities at the two sites. It is interesting to note that the shallow anoxic layer quickly returned to the LR site even after clean river sand had been deposited over the area in December, 1980.

Compaction of sediments under grounded logs, reduced pore water space, decreased interstitial water circulation, and development of reducing sediments have been well documented in other studies on the impacts of log storage

(Pease, 1974; Sibert and Harpham, 1979). As in the study by Sibert and Harpham (1979), we found it difficult to sink cores more than 15-20 cm into the sediment due to its compact nature. In addition to compaction, development of the anoxic layer may be due in part to the settlement of fine material as a result of the decreased carrying capacity of tidal currents under log booms. The continued existence of a shallow reducing layer after log removal was also recorded by Smith (1977) in the Snohomish estuary. Further work into the persistence of anoxia after log removal, and its relationship to estuarine benthic community structure is a research priority.

Bark deposits have not been found to be a significant feature of log storage sites (Pease, 1974; Smith, 1977). However, we noted a number of large pieces of bark mixed with the sediment to a depth of 10-15 cm. The presence of wood was also suggested by the ratio of sediment TOC:TKN (26.7) recorded. Ratios for TOC:TKN greater than 25 have been shown to generally indicate the presence of wood in marine sediments (Borhhold, 1978). However, this same ratio was observed at the REF site where no wood was present. Additional work on development of a reliable indicator of wood waste in estuarine areas is required. Conlan and Ellis (1979) reported the impact of wood waste on benthos at a shallow (4-11 m) marine log handling site. The authors noted only slight recolonization at a site which had not been used for over 17 years. However, the possible effects of the presence of wood waste per se were not distinguished from any effects due to anoxia in the sediments. Additional research is required to identify the factors associated with wood waste which affect benthic infauna.

IMPLICATIONS FOR ESTUARINE FISHERIES RESOURCES

The present study demonstrated that the benthic communities at a former log storage site and a nearby reference site remained different 13 months after log boom removal. The persistence of anoxic, hydrogen sulfide producing sediments at the log storage site was considered to be a significant factor affecting the recruitment of benthic species to this site. These results raise important questions about possible, long-term impacts of log storage on

estuarine fisheries resources, particularly with respect to the abundance of fish food items. Juvenile chum salmon in the Nanaimo estuary have been shown to feed selectively on one species of harpacticoid copepod, H. uniremus (Sibert, 1979). However, this copepod was not found in any of the samples taken in the present study. This may have been due to the fact that our sampling stations were located at a higher intertidal elevation compared to previous studies (e.g. Sibert, 1979). It is not known whether juvenile salmonids would "switch" to feeding on harpacticoids which were found in our samples such as S. knabeni. Other potential fish prey items such as the amphipod C. insidiosum, and the cumacean C. vulgaris were most abundant at the former log storage site studied. The extent to which juvenile salmonids would feed on these species if present over a previous log storage site is unknown. Difficulties in interpreting traditional benthic data in terms of available fish food are due in part to our lack of knowledge about the behaviour of benthic species, and predator-prey interaction. Recent studies in the Nanaimo estuary indicate that hyperbenthic populations may be an important source of food items for juvenile salmonids (Sibert, 1981). To more directly address the possible effects of log storage areas on estuarine fisheries, sampling techniques appropriate for estimating hyperbenthic populations (Sibert, 1981) may be required. In addition, manipulative field experiments using caged fish also appear to be a valuable tool in testing specific hypotheses in estuarine research (McGreer et al., 1983).

ACKNOWLEDGEMENTS

We would like to thank Ms. R. Woods of EVS Consultants and Dr. E. Anderson of Edward Anderson Marine Sciences for identification of harpacticoid copepods, and Mr. J.-B. Coustalin for macrofauna taxonomy. Ms. Bev Kask of the Pacific Biological Station, Nanaimo, verified harpacticoid species. The cooperation of the members of the Nanaimo User's Group in setting aside a study site is gratefully acknowledged. We also wish to express our appreciation to T.J. Brown Dr. C.D. McAllister and Dr. C.D. Levings of the Department of Fisheries and Oceans, and Dr. G.A. Vigers of EVS Consultants for their critical review the manuscript.

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Table 1. Sample code numbers used in computer analysis of benthic data.

Sampling Date		Code Numbers			
		Harpacticoids		Macrofauna	
		Reference Site	Log Removal Site	Reference Site	Log Removal Site
1980	October	--	--	01	02
	November	01	02	03	04
	December	03	04	05	06
1981	January LR* -24h	05	06	--	--
	" LR	07	08	07	08
	" LR +24h	09	10	--	--
	" LR +1wk	11	12	--	--
	February LR +2wk	13	14	09	10
	" LR +1mo	15	16	11	12
	March	17	18	13	14
	April	19	20	15	16
	May	21	22	17	18
	July	23	24	19	20
	August	25	26	21	22
	October	27	28	23	24
	December	29	30	25	26
1982	February	31	32	27	28

*LR = Date of Log Removal from study site, January 21, 1981.

Table 2. Most common harpacticoid copepod species from all samples and computer codings used in Analysis of Correspondence.

Species Identification	Code	Average Abundance/ $10cm^2$ Reference Site	% of Total Abundance	Average Abundance/ $10cm^2$ Log Removal Site	% of Total Abundance
Schizopera knabeni	SK	49	28	26	22
Huntemannia jadensis	HJ	37	21	20	17
Mesochra sp.	M	35	20	19	16
Stenhelia asetosa	SA	9	5	25	21
Nannopus palustris	NP	22	12	20	18
Robertsonia propinqua	RP	11	6	1	< 1
Heterolaophonte discophora	HD	1	< 1	2	< 1
Heterolaophonte sp.	H	3	< 1	< 1	< 1
Nitocra sp.	N	7	< 1	< 1	< 1
Leimia vaga	LV	< 1	< 1	2	< 1
Enhydrosoma unarticulatum	EU	< 1	< 1	2	< 1
E. buchholtzi	EZ	< 1	< 1	< 1	< 1

Table 3. Results of two-way ANOVA by date and site for abundance of dominant harpacticoid species.

Taxa	Period	Nov. 1980 - Apr. 1981		Nov. 1980 - Feb. 1982	
		Date	Site	Date	Site
Schizopera knabeni		NS	$p<0.05$	$p<0.01$	NS
Huntemannia jadensis		$p<0.05$	$p<0.01$	NS	$p<0.05$
Mesochra sp.		$p<0.01$	NS	$p<0.01$	NS
Stenhelia asetosa		$p<0.01$	NS	$p<0.01$	$p<0.01$
Nannopus palustris		$p<0.05$	$p<0.01$	$p<0.05$	$p<0.01$

NS = not significant

Table 4. Factor scores resulting from Analysis of Correspondence for harpacticoid species and sample site - times. Maximum factor scores for each species and site - time analysis is underlined. Species and sample code numbers are explained in Tables 1 and 2.

Species Code	Factors 1	2	3	4	5
SK	0.160	-0.003	0.111	0.178	0.102
HJ	-0.891	0.084	-0.154	0.152	0.046
M	0.482	-0.166	-0.006	-0.358	0.161
SA	0.239	-0.875	0.264	0.406	0.078
NP	-0.373	0.513	-0.004	-0.217	0.048
RP	1.098	1.539	-0.045	0.854	-0.446
HD	-0.234	0.309	0.018	-0.750	-0.316
N	0.301	0.350	0.070	-0.956	-0.122
H	0.606	0.317	-0.090	-0.992	0.022
LV	-0.492	-1.013	1.298	-0.260	-3.245
EU	0.950	-1.335	-4.219	0.179	-1.127
EZ	0.064	-0.710	-3.069	0.173	-0.781
Sample site - time code					
01	-0.141	0.138	0.002	-0.463	0.104
02	0.149	-0.376	0.121	-0.214	0.156
03	-0.133	-0.042	-0.007	-0.172	0.217
04	0.710	-0.884	-2.391	0.001	-0.595
05	-0.448	0.133	0.055	0.218	0.188
06	-1.449	0.201	-0.308	0.341	0.130
07	-1.031	0.288	-0.171	0.117	0.111
08	-0.265	-1.362	1.467	-0.233	-3.526
09	-1.211	0.284	-0.268	0.267	0.058
10	0.007	-0.053	-0.016	0.479	0.038
11	-0.517	0.477	-0.020	0.047	0.075
12	-0.796	-0.194	-0.014	-0.024	-0.096
13	-0.368	-0.111	-0.074	0.316	0.138
14	0.406	-0.412	-0.686	0.392	-0.108
15	-0.471	0.222	-0.009	0.375	0.145
16	-1.386	0.119	-0.282	0.352	0.112

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Table 4 (continued)

Sample site - time code	Factors 1	2	3	4	5
17	-1.346	0.128	-0.268	0.293	0.087
18	-0.944	0.040	-0.110	0.349	0.056
19	-0.964	0.270	-0.344	-0.035	-0.008
20	-0.617	-0.550	0.699	-0.034	-1.829
21	-0.545	0.661	-0.051	-0.804	-0.218
22	-0.986	0.041	-0.317	0.159	0.085
23	0.437	-0.207	0.062	-0.541	0.210
24	0.290	-0.583	0.209	0.097	0.206
25	0.086	0.074	-0.079	-0.203	0.101
26	0.242	-0.542	0.243	0.259	0.211
27	0.675	0.288	0.055	-0.498	0.072
28	0.302	-0.776	0.299	0.408	0.263
29	0.820	1.121	0.029	0.584	-0.272
30	0.359	-0.586	0.253	0.244	0.267
31	0.200	0.069	0.240	-0.735	-0.364
32	0.187	-0.869	0.524	0.127	-0.629
% variance for each factor	23.9	19.9	14.1	11.9	10.9
Cumulative %	23.9	43.8	57.9	69.8	80.7

Table 5. Harpacticoid copepod community-species associations identified by Analysis of Correspondence for Log Removal and Reference sites on each sampling occasion. An asterisk (*) indicates samples of unusual composition when compared to all other samples. Brackets indicate a loose association of the grouped species.

Sampling Period		Log Removal Site	Reference Site
		sample #	sample #
1980	November	(C)	D
	December	*(EU,EZ)	D
1981	January LR -24h	A	B
	" LR	*	A
	" LR +24h	D	A
	" LR +1wk	*	B
	February LR +2wk	*	(B)
	" LR +4wk	A	B
	March	A	A
	April	*LV	A
	May	A	B
	July	C	*M
	August	C	D
	October	C	*H
	December	C	*RP
1982	February	C	D

Major species groups:
A. Huntemannia jadensis
B. Nannopus palustris
C. Stenhelia asetosa
D. Schizopera knabeni

Outliers *(irregular dominants):
EU, Enhydrosoma unarticulatum
EZ, Enhydrosoma buchholtzi
H, Heterolaophonte sp.
LV, Leimia vaga
M, Mesochra sp.
RP, Robertsonia propinqua

Table 6. Summary of densities and ratio of harpacticoid copepods and nematode worms over a one-year period. Number of individuals expressed per 6 cm^2 ± 1 standard error.

	Month								
	1980		1981						1982
	Nov.	Dec.	Apr.	May	Jul.	Aug.	Oct.	Dec.	Feb.
Reference Site									
Nematodes	3459±337	592±298	334±76	1749±544	439±65	650±260	3053±986	1527±348	388±100
Harpacticoids	755±80	195±99	89±16	86±29	244±47	300±192	599±95	247±77	145±86
Nematode/harpaticoid ratio	4.6	3.0	3.8	20.3	1.8	2.2	5.1	6.2	2.7
Log Removal Site									
Nematodes	297±80	301±40	392±134	308±43	199±40	221±10	326±15	289±37	135±10
Harpacticoids	174±47	151±30-	283±78	91±27	292±40	219±46	534±58	231±25	97±26
Nematode/harpacticoid ratio	1.7	2.0	1.4	3.4	0.7	1.0	0.6	1.3	1.4

Table 7. Most common macrofauna species from all samples and computer coding used in Analysis of Correspondence.

Species Identification	Code	Average Abundance m^2 Reference Site	% of Total Abundance	Average Abundance m^2 Log Removal Site	% of Total Abundance
Manayunkia aestuarina	MA	23,346	42	11,355	38
Pygospio elegans	PY	15,559	28	2,312	8
Capitella capitata	CP	8,405	15	3,309	11
Cumella vulgaris	CU	1,562	3	3,090	10
Tubificoides gabrieli	TU	2,115	4	2,208	7
Corophium sp.	CO	74	0.1	2,592	9
Tanais stanfordi	TA	1,467	3	1,107	4
Corophium insidiosum	CI	118	> 0.2	1,617	5
Nemertean sp.	NM	870	2	22	< 1
Eogammarus confervicolus	EO	660	1	11	< 1
Corophium spinicorne	CS	11	< 1	522	2
Eteone longa	ET	247	< 1	232	< 1
Chironomidae sp.	CM	379	< 1	46	< 1
Mya arenaria	MY	94	< 1	324	1
Amphicteis sp.	AM	6	< 1	386	1
Pseudopolydora kempi japonica	PK	55	< 1	240	< 1
Ostracoda sp.	OS	254	< 1	2	< 1
Macoma balthica	MB	18	< 1	203	< 1
Tipulidae sp.	TI	210	< 1	13	< 1
Amphithoe sp.	AS	38	< 1	153	< 1
Dipteran pupae	DI	99	< 1	10	< 1
Amphithoe valida	AV	48	< 1	43	< 1
Paranemertes peregrina	PA	77	< 1	< 1	< 1
Nereis sp.	NR	0	-	60	< 1
Armandia brevis	AR	0	-	62	< 1

Table 8. Results of two-way ANOVA by data and site on abundance of dominant macrofauna species.

Taxa	Period	Oct. 1980 - Apr. 1983		Oct. 1980 - Feb. 1982	
		Date	Site	Date	Site
Manayankia aestuarina		p<0.05	p<0.01	p<0.01	p<0.05
Pygospio elegans		p<0.05	p<0.01	p<0.01	p<0.01
Capitella capitata		p<0.01	p<0.01	p<0.01	NS
Tubificoides gabrielli		p<0.05	NS	p<0.05	NS
Cumella vulgaris		p<0.01	p<0.01	p<0.01	p<0.01
Corophium insidiosum		p<0.05	p<0.05	p<0.05	p<0.05
Corophium sp.		p<0.05	p<0.05	p<0.05	p<0.01
Tanais stanfordi		NS	p<0.05	NS	p<0.01

NS = not significant

Table 9. Factor scores resulting from Analysis of Correspondence for macrofauna species and sample site - times. Maximum factor scores for each species and site - time analysis is underlined. Species and sample code numbers are explained in Tables 1 and 5.

Species Code	Factors 1	2	3	4	5
MA	0.087	0.055	0.018	-0.069	-0.085
PY	0.582	0.139	0.222	0.084	0.015
CP	0.156	-0.080	-0.546	-0.399	0.058
CU	-1.279	0.604	0.856	-0.420	0.196
TU	-0.064	-1.579	0.582	0.592	0.255
CO	-1.044	-0.612	-0.842	0.125	-0.595
TA	-0.664	0.789	-0.553	1.496	0.281
CI	-1.169	-0.152	-0.517	0.040	-0.588
NM	0.252	0.722	-0.281	0.297	0.251
EO	-1.155	-0.325	1.606	-0.263	0.677
CS	-1.821	0.269	0.131	-0.244	-0.594
ET	-0.489	0.102	0.232	-0.224	0.150
CH	0.209	0.445	0.153	1.006	0.404
MY	-0.917	-0.219	-0.116	-0.480	0.565
AM	-0.990	-0.564	-0.339	-0.038	-0.511
PK	-0.582	-0.921	-0.857	-0.062	0.443
OS	0.526	0.517	-0.394	-0.074	-0.022
MB	-1.032	-0.303	-0.086	-0.353	0.366
TI	0.064	0.910	-0.538	1.262	0.552
AS	-0.643	-1.259	-0.792	0.591	0.258
DI	-0.904	2.177	-1.211	4.905	1.988
AV	-0.297	-0.016	-0.646	0.974	0.294
PA	1.121	0.231	0.458	0.163	-0.019
NR	-0.669	-1.918	-0.773	0.529	-0.446
AR	-1.394	-1.261	-4.284	-3.582	10.421
Sample site - time code					
01	0.237	0.022	-0.506	-0.446	-0.020
02	-0.856	-0.554	-1.152	-0.585	0.366
03	0.297	0.057	-0.614	-0.418	0.056
04	-0.752	-0.591	-2.025	-1.692	4.429
05	0.245	0.078	-0.646	-0.442	0.033
06	-0.186	-0.222	-0.799	-0.466	-0.149
07	0.376	0.211	0.055	-0.058	0.040

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Table 9 (continued)

Sample site - time code	Factors 1	2	3	4	5
08	-0.607	0.111	0.433	-0.268	0.123
09	-0.447	0.536	0.617	-0.298	0.187
10	-1.477	0.631	0.867	-0.469	0.158
11	0.426	0.274	0.217	-0.005	-0.001
12	-0.435	0.238	0.296	-0.247	0.000
13	0.134	0.217	0.097	-0.186	-0.004
14	-0.892	0.095	1.046	-0.371	0.377
15	0.765	0.168	0.259	0.077	0.028
16	-0.098	-0.777	0.649	0.239	0.244
17	0.485	-0.347	0.228	0.157	0.105
18	-0.162	-1.407	0.451	0.529	0.160
19	0.481	0.146	-0.110	-0.150	-0.028
20	-0.372	-0.982	-0.370	0.277	-0.147
21	0.442	0.228	0.111	0.021	-0.117
22	-0.265	-0.158	-0.358	-0.090	-0.457
23	0.354	0.251	-0.017	-0.000	-0.061
24	-0.390	-0.093	-0.436	0.223	-0.215
25	-0.909	1.636	-0.922	3.158	1.073
26	-0.966	-0.041	-0.540	0.177	-0.496
27	0.210	0.369	0.125	0.230	0.019
28	-1.074	0.268	0.049	-0.242	-0.248
% variance for each factor	22.1	15.8	14.2	13.0	9.4
Cumulative %	22.1	37.9	52.1	65.1	74.5

Table 10. Macrofauna community-species associations identified by Analysis of Correspondence for Log Removal and Reference sites on each sampling occasion. An asterisk (*) indicates samples of unusual composition when compared to all other samples. Brackets indicate a loose association of the grouped species.

Sampling Period			Log Removal Site	Reference Site
			sample #	sample #
1980	October		(A)	D
	November		*	D
	December		*	D
1981	January	LR	B	C
	February	LR +2wk	*CU	B
	"	LR +4wk	B	C
	March		*	*MA
	April		*	*
	May		*TU	*
	July		*PK	C
	August		*	C
	October		*	*
	December		A	*
1982	February		(A)	*

Major species groups:
A. Mya arenaria, Corophium insidiosum, Macoma balthica, Amphicteis sp., Corophium sp., Eogammarus confervicolus
B. Eteone longa
C. Pygospio elegans
D. Capitella capitata

Outliers *(irregular dominants):
CU, Cumella vulgaris
TU, Tubificoides gabrielli
PK, Pseudopolydora kempi japonica
MA, Manayunkia aestuarina
DI, Dipteran pupae

Table 11. Summary of surface sediment characteristics at Reference and Log Removal sites over study period. Percentages are by weight: gravel >2.0 mm; sand 2.0-0.625 mm; mud <0.0625 mm. Mean and standard deviation (SD) are for the range of values shown.

Station	Percent Gravel	Percent Sand	Percent Mud	Total Organic Carbon %	Total Kjeldahl Nitrogen %
Reference site	1.7-28.3	48.4-91.1	7.2-27.6	0.3-3.2	0.02-0.10
Mean	14.1	71.6	14.3	1.6	0.06
SD	11.8	10.8	5.8	1.2	0.03
Log Removal site	0.0-39.9	55.0-88.0	5.1-34.9	0.3-3.0	0.03-0.10
Mean	8.0	77.6	14.2	1.6	0.06
SD	12.6	11.0	7.7	0.9	0.03

Table 12. Canonical correlation coefficients for harpacticoid copepod community factors and physical/ chemical variables at Log Removal and Reference sites.

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	% Gravel	% Sand	% Mud	TOC	TKN
Principal group or species associated with each factor	HJ, NP, M	SA, RP	EU, EZ	H	LV					
Factor 1	1.000									
Factor 2	0.316	1.000								
Factor 3	0.259	-0.140	1.000							
Factor 4	0.297	0.197	0.185	1.000						
Factor 5	-0.154	0.162	-0.013	0.167	1.000					
% Gravel	-0.121	-0.427	0.352	-0.220	0.001	1.000				
% Sand	0.023	0.441	-0.264	0.123	0.110	-0.843**	1.000			
% Mud	0.181	0.054	-0.204	0.200	-0.187	-0.442	-0.110	1.000		
TOC (0-2 cm)	0.359	-0.247	0.182	0.211	-0.111	0.127	-0.135	-0.018	1.000	
TKN (0-2 cm)	0.334	-0.103	0.266	0.231	-0.127	-0.166	-0.192	0.630	0.274	1.000

TOC = total organic carbon, TKN = total kjeldahl nitrogen
** Indicates signifcance at p 0.05

Table 13. Canonical correlation coefficients for macrofauna community factors and physical/chemical variables at Log Removal and Reference sites.

	% Gravel	% Sand	% Mud	TOC	TKN	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
Principal group or species associated with each factor						A, ET, PY, CU	NM, TU, PK	CP, EO	DI	AR	no dominants	
% Gravel	1.000											
% Sand	-0.843**	1.000										
% Mud	-0.221	-0.267	1.000									
TOC	0.127	-0.135	-0.118	1.000								
TKN	-0.166	-0.192	0.490	0.274	1.000							
Factor 1	0.316	-0.188	-0.364	0.047	-0.076	1.000						
Factor 2	0.148	-0.265	0.172	-0.031	0.013	-0.092	1.000					
Factor 3	0.098	-0.124	0.201	-0.155	-0.317	0.073	0.102	1.000				
Factor 4	0.027	0.036	-0.154	0.393	-0.263	-0.025	0.412	0.091	1.000			
Factor 5	-0.141	0.001	0.264	0.180	0.604	-0.236	-0.086	-0.524	-0.238	1.000		
Factor 6	-0.138	0.044	0.069	0.339	0.353	-0.103	-0.290	-0.349	-0.431	0.558	1.000	
Factor 7	0.071	0.075	-0.029	0.130	-0.192	-0.074	-0.168	0.007	-0.165	0.234	0.225	1.000

TOC = total organic carbon, TKN = total kjeldahl nitrogen
** Indicates significance at p 0.05

Table 14. Sediment oxidation-reduction potential measurements (mV) at Reference and Log Removal sites November 1980 to March 1981.

Depth (cm)	Nov 1980	Dec 1980	Jan 1981	+LR	LR + 24 h	LR + 1 wk	LR + 2 wk	Feb	Mar
				Sampling Occasion					
				Reference Site					
Surface	+60	+175	+80	+160	+100	+75	+120	+180	+40
1	0	+175	+100	+150	+100	+120	+140	+150	+100
2	-30	+175	+120	+150	+120	+120	+150	+150	+150
3	-50	+175	+175	+250	+120	+120	+100	+150	+90
4	-135	+175	+200	+200	+120	+200	+400	+150	+110
5	-90	+175	+180	+200	+120	+170	+300	+150	+120
6		+175	+180	+160	+140	+180	+280	+150	+55
7		+175	+200	+180	+140	+180	+210	+175	+80
8		+175	+180	+180	+130	+180	+200	+150	+80
9		+175	+140	+200	+130	+180	+220	+150	+80
10		+175	+90	+180	+150	+180	+200	+190	+45
				Log Removal Site					
Surface	+110	+50	+300	+180	+170	+120	+200	+100	+110
1	-60	+50	+100	+150	+170	+80	+140	+100	-50
2	-120	+20	+100	-50	+100	+20	+100	+100	-75
3	-80	-50	+360	0	+60	0	-80	+80	+90
4	-40	-250	+150	0	+40	-10	-250	+100	+50
5	-75	-250	+80	-10	-10	-175	-50	+80	0
6		-300	0	-30	0	-80	-220	+80	-220
7		-300	-30	-80	+30	-20	-200	-50	-100
8		-300	0	-120	-50	-50	-160	0	-80
9		-190	0		-80	-200	-260	0	-100
10			-150		-100				-100

*LR = Date of Log Removal January 21, 1981.

Table 15. Sediment oxidation-reduction potential measurements (mV) at Reference and Log Removal sites April 1981 to February 1982.

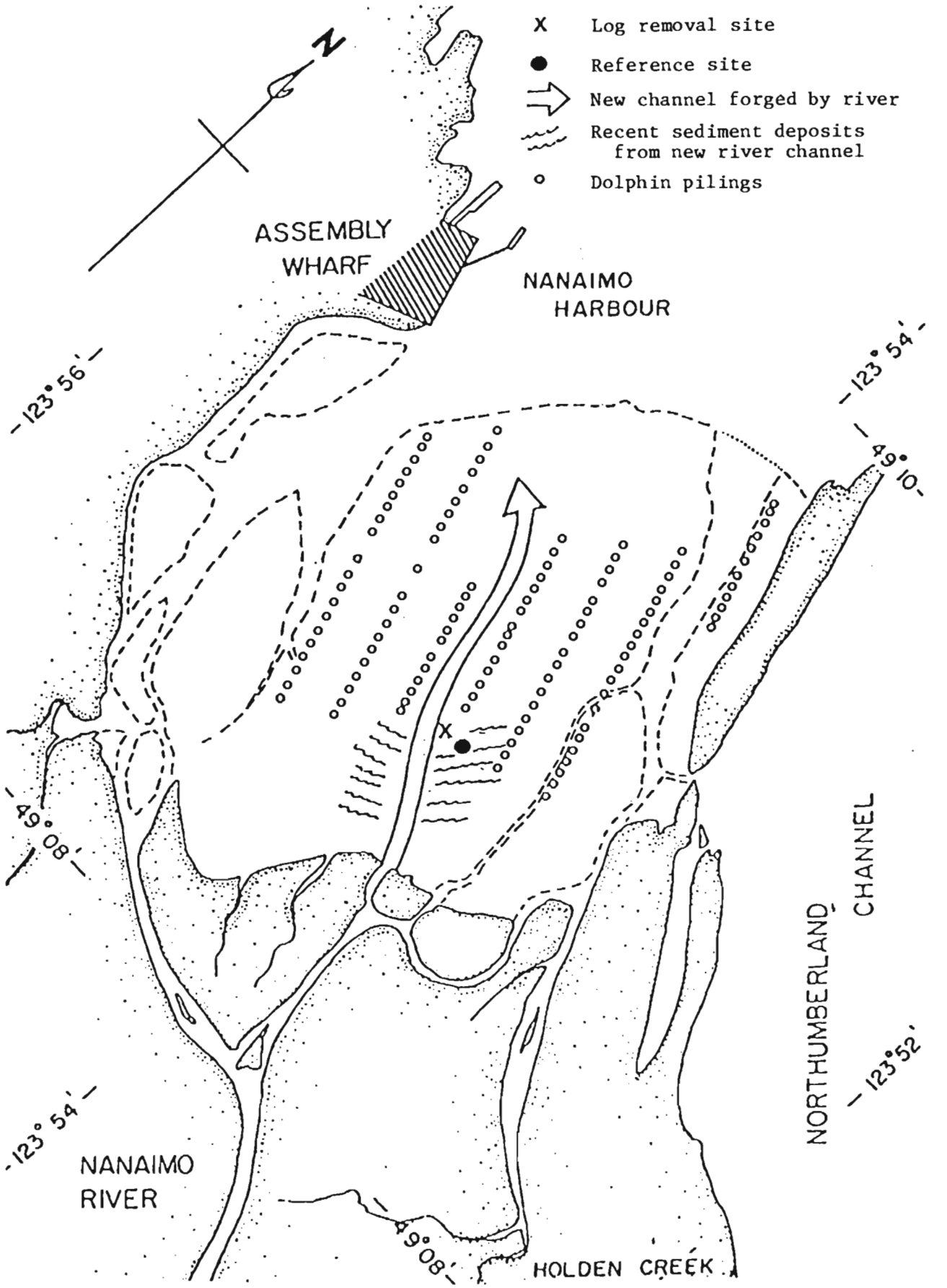
Depth (cm)	Apr 1981	May	Jul	Aug	Dec	Feb 1982
			Sampling Occasion			
			Reference Site			
Surface	0	+200	-50	+200	+150	+190
1	+50	+120	-100	+200	+100	+180
2	+80	+200	+100	+180	+300	+140
3	+120	+150	+120	+180	+200	+140
4	+120	+150	+120	+180	+180	+140
5	-80	+200	+150	+180	+180	+140
6	-100	+180	+180	+180	+200	+140
7	-40	+180	+180	+180	+80	+160
8	-80	+180	+150	+180	+150	+160
9		+180	+140	+180	+150	+140
10		+100	+100	+180	+150	+140
			Log Removal Site			
Surface	-80	+90	-60	+200	+150	+175
1	-150	+90	-50	+200	+120	+150
2	-220	+80	-50	+180	+40	+150
3	-250	+60	-50	+100	-20	+100
4	-250	+20	-40	-40	-20	+80
5	-250	-90	-200	-180	-100	+20
6	-220	0	-150	-180	-150	0
7	-220	-200	-200	-100	-50	0
8	-220	-100	-200	-160	-100	-20
9		-100	-40	-160	-150	-20
10		-50	-20	-140	-150	-40

Note: Oct. 1981 not sampled due to instrument malfunction.

Table 16. Depth (cm) at which anoxic layer commenced as determined by oxidation - reduction potential measurements at Reference and Log Removal sites.

	Sampling Occasion														
	Nov. 1980	Dec.	Jan. 1981	+LR	LR +24h	LR +1wk	LR +2wk	Feb.	Mar.	Apr.	May	July	Aug.	Dec.	Feb. 1982
LR	1	3	6	2	5	3	3	7	1	0	5	0	4	3	6
REF	1	>10	>10	>10	>10	>10	>10	>10	>10	5	>10	0	>10	>10	>10

Fig. 1. Study site locations in the Nanaimo River estuary.



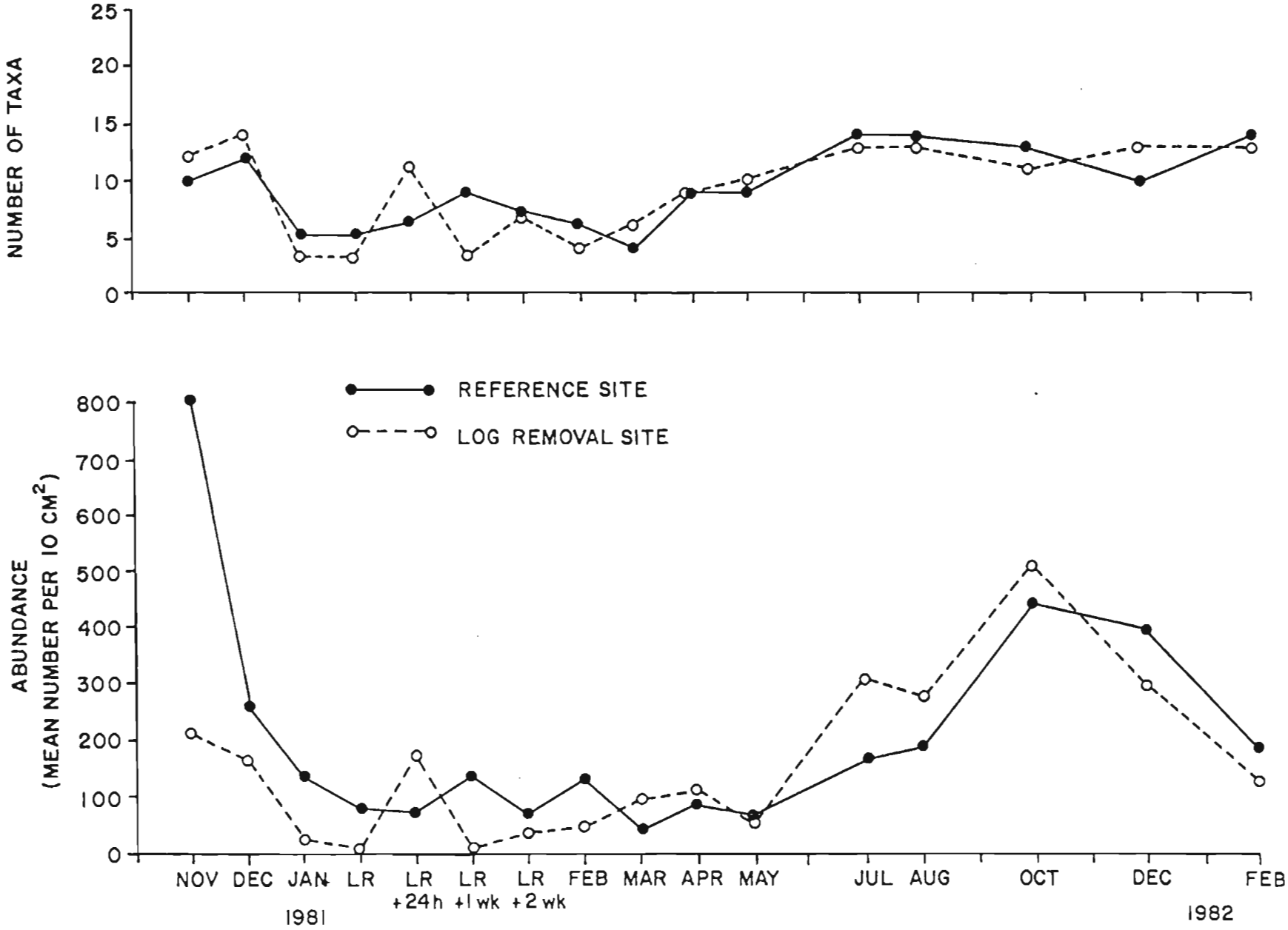


Fig. 2. Time series plots of the total number of harpacticoid taxa and total mean harpacticoid abundance at the Reference and Log Removal sites.

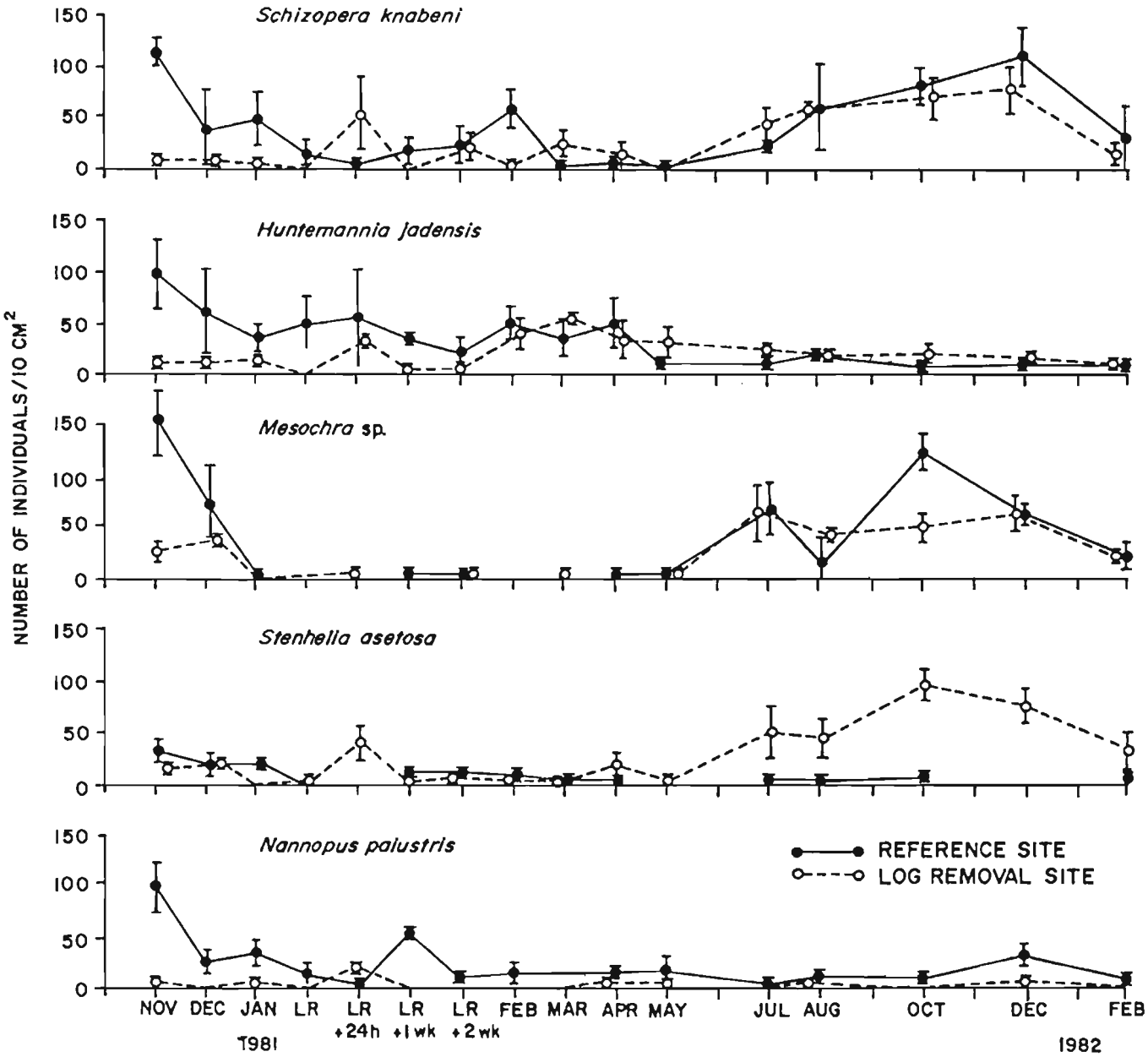


Fig. 3. Time series plots of the mean abundance (±1 S.E.) of five dominant harpacticoid species at the Reference and Log Removal sites.

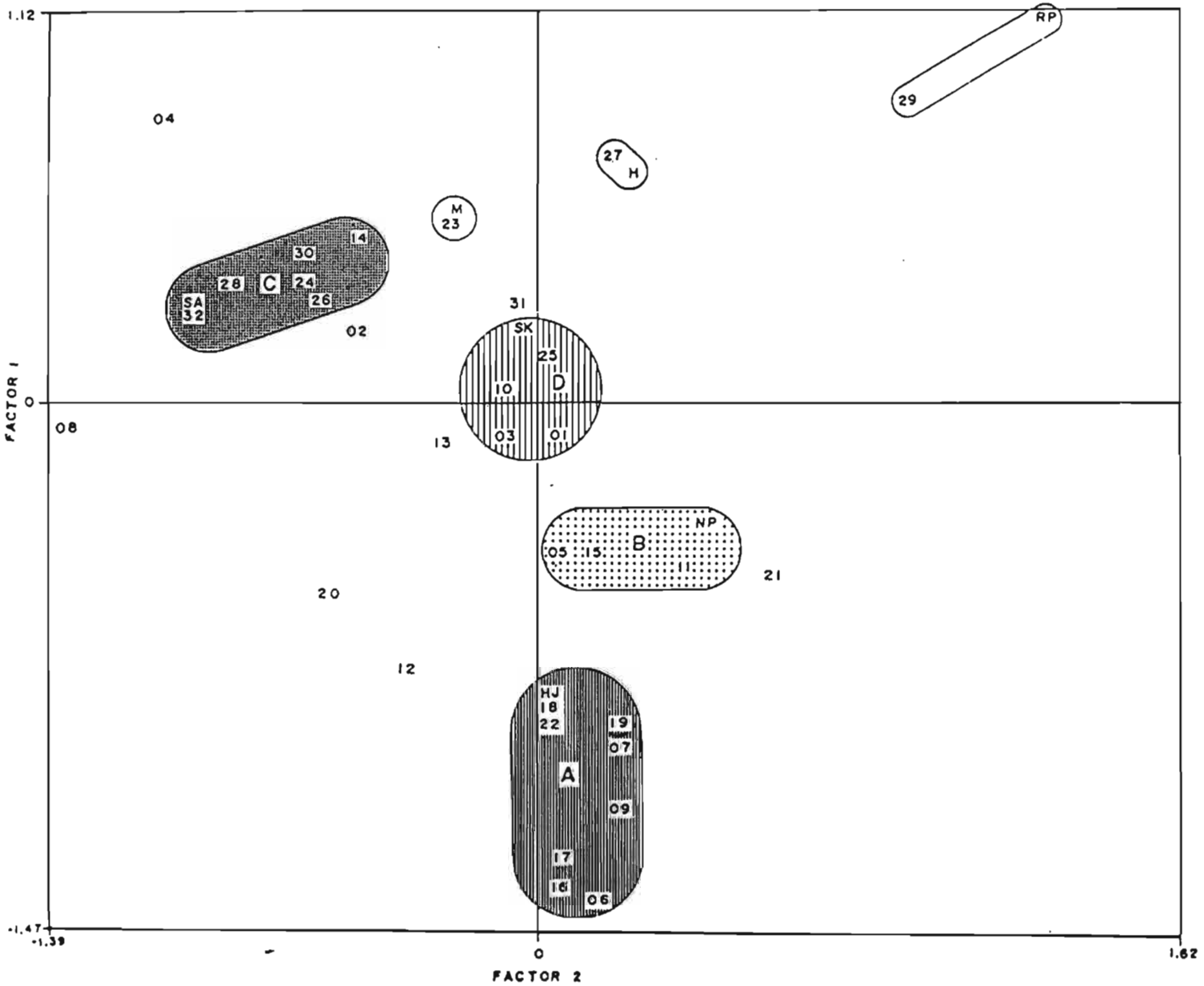


Fig. 4. Scatter diagram of Analysis of Correspondence component factors 1 and 2, based on correlation of meiofauna species abundance with sampling site/times. Species and sample code numbers are explained in Tables 1 and 2.

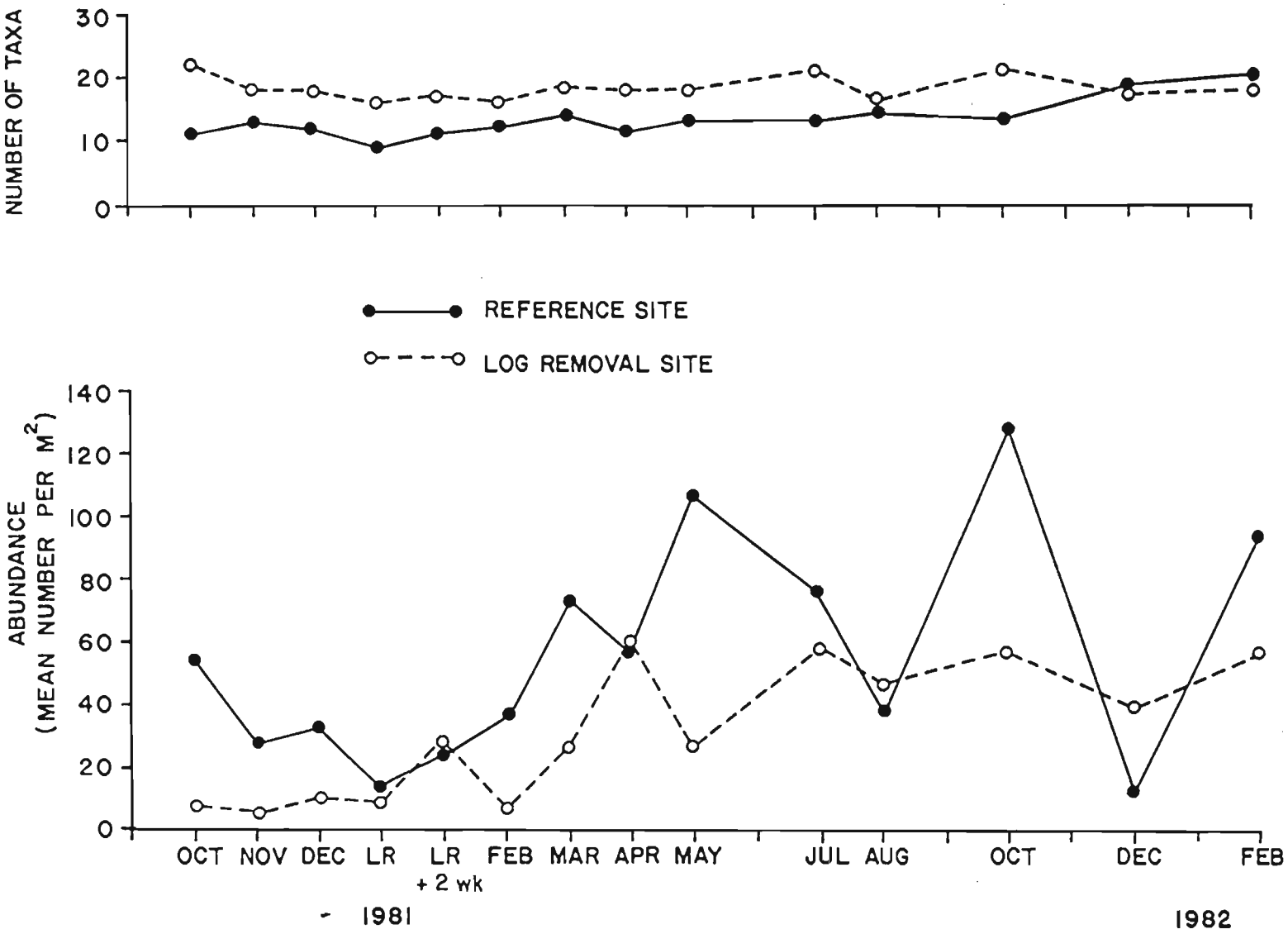


Fig. 5. Time series plots of the total number of macrofauna taxa and total mean macrofauna abundance at the Reference and Log Removal sites.

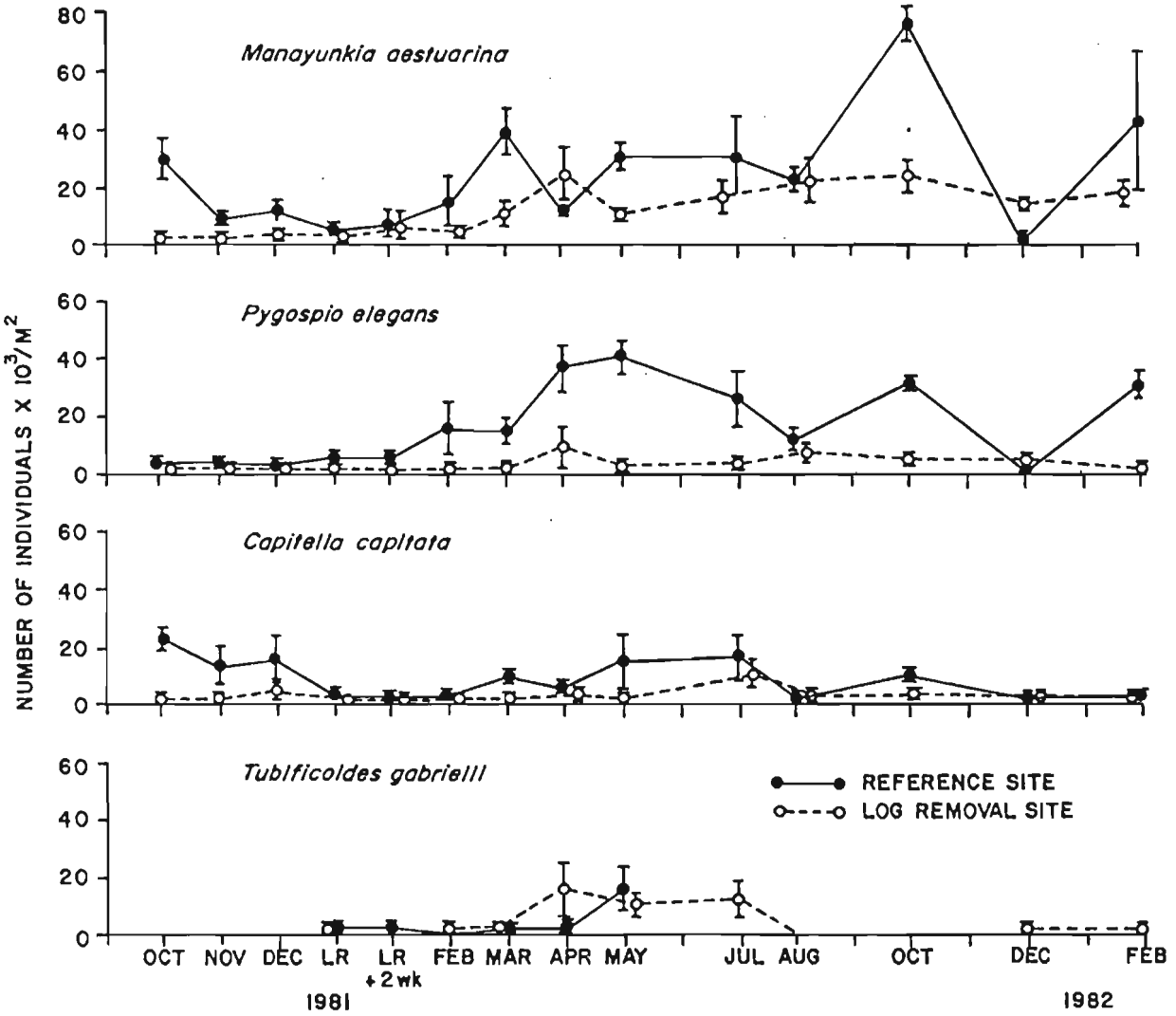


Fig. 6. Time series plots of the mean abundance (±1 S.E.) of four dominant annelid worms at the Reference and Log Removal sites.

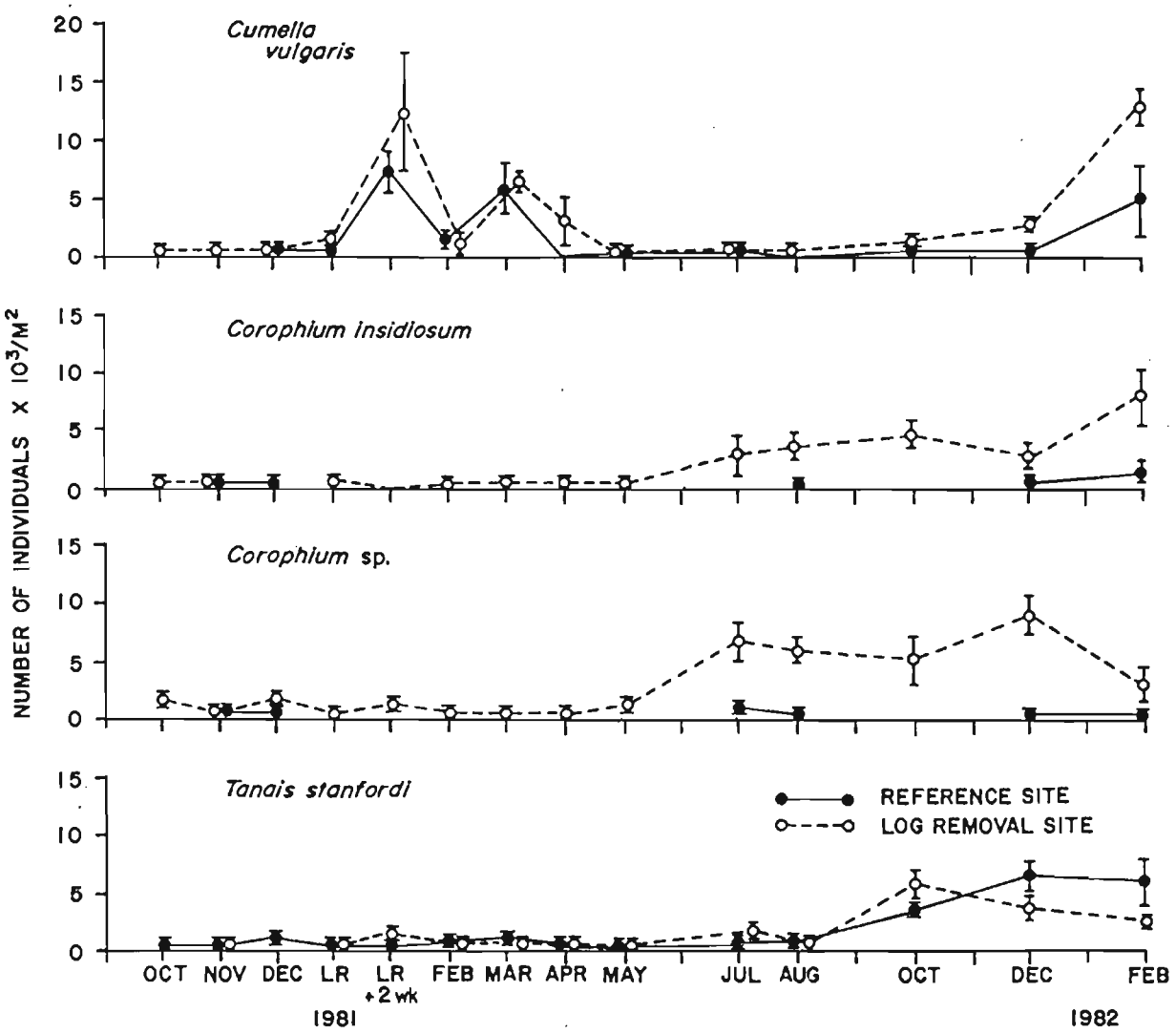


Fig. 7. Time series plots of the mean abundance (±1 S.E.) of four dominant crustaceans at the Reference and Log Removal sites.

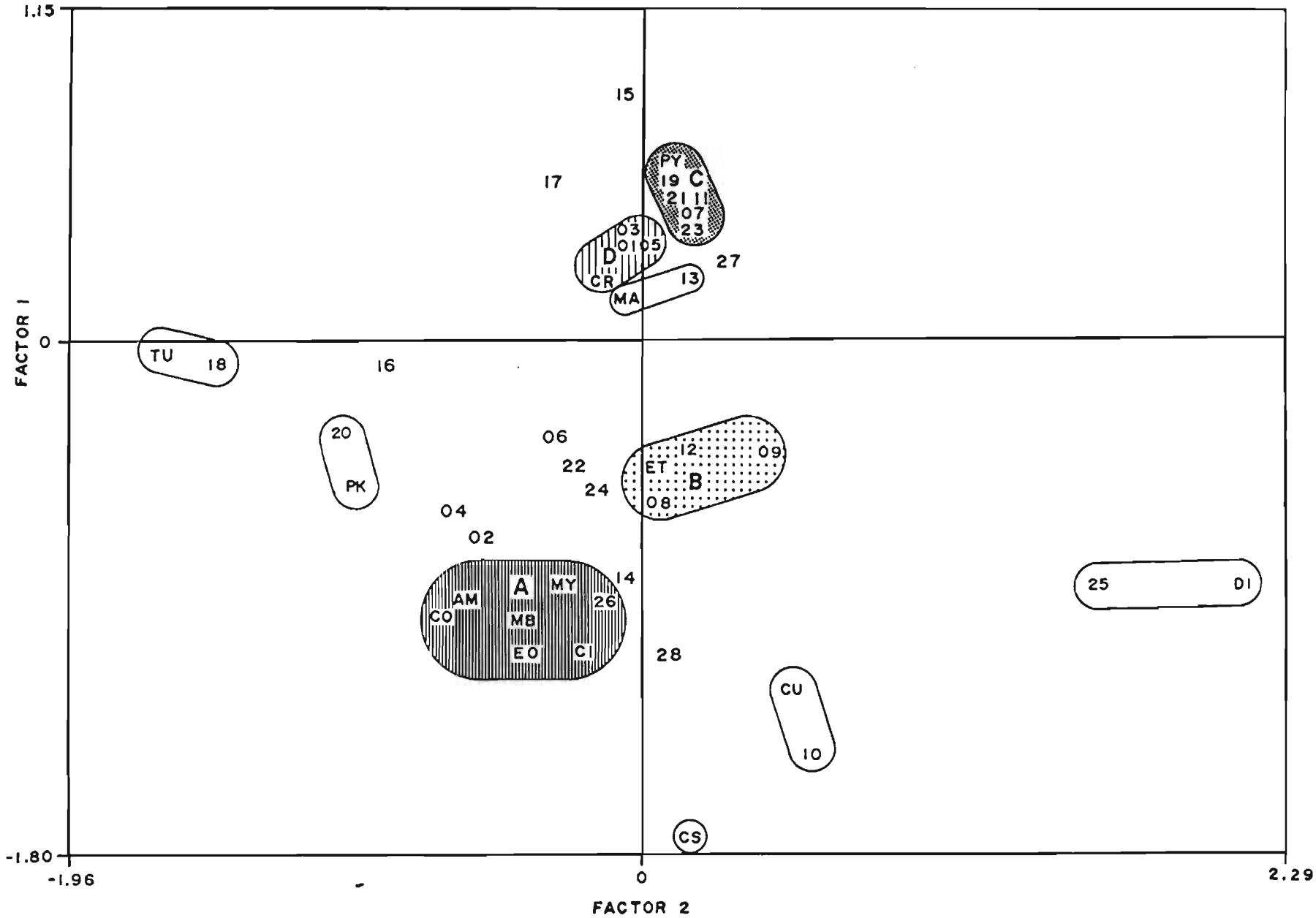


Fig. 8. Scatter diagram of Analysis of Correspondence component factors 1 and 2 based on correlation of macrofauna species abundance with sampling site/times. Species codes and sample numbers are explained in Tables 1 and 6.