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EFFECTS OF WOOD WASTE FOR OCEAN DISPOSAL ON THE RECRUITMENT OF MARINE MACROBENTHIC COMMUNITIES

by

E. R. McGreer[1], D. R. Munday[1], and M. Waldichuk[2]

[2]Department of Fisheries and Oceans
Fisheries Research Branch
West Vancouver Laboratory
4160 Marine Drive
West Vancouver, British Columbia V7V 1N6

[1]Coastline Environmental Services Ltd.
1866 West 11th Avenue
Vancouver, British Columbia V6J 2C5

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ABSTRACT

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The effect of different thicknesses (1, 5, and 15 cm) of a fine wood waste material on the recruitment of marine macrobenthic communities was experimentally assessed using in situ settlement trays. A clean marine sediment was used in the experiment as a reference substrate. Differences in species composition and abundance of macrobenthos settling on the reference and 1 cm wood waste substrate compared to the 5 and 15 cm wood substrates were found. Species richness showed a consistent decrease with increasing thicknesses of wood waste. Total mean abundance of macrofauna was highest in the substrate containing an intermediate thickness (5 cm) of wood. Species associated with the greater thicknesses of wood waste included common indicators of marine, organic pollution such as polychaete worms (Prionospio cirrifera, Armandia brevis, Capitella capitata) and amphipods (Ampelisca pugettica, Aoroides sp., Melita sp., Monoculodes zernori). However, only the number of amphipod taxa, and amphipod abundance were found to be significantly different ($p<0.05$) when the reference sediment and substrates covered by wood waste were compared statistically. Sample cluster analysis differentiated three groups: one containing all reference and 1 cm wood waste samples; and two groups containing samples from the 5 and 15 cm test substrates. Species cluster analysis differentiated four groups based on differences in recruitment density in the reference and wood substrates. The increased amount of wood waste was also reflected in a progressive increase in percent total organic carbon which ranged from 0.2% in the reference sediment to 35.9% in the 15 cm wood substrate. Sediment redox potential was shown to be a reliable, quantitative indicator of the thickness of wood waste present. Anoxia within the substrate was considered to be a major factor affecting the recruitment of macrobenthic species. Future research needs on effects of wood waste for ocean disposal are presented.

Key words: wood waste, macrobenthos, recruitment, recolonization, anoxic sediments

RÉSUMÉ

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L'effet de couches de déchets de bois fins d'épaisseurs diverses (1, 5 et 15 cm) sur le recrutement des communautés macrobenthiques marines ont été expérimentalement évalués *in situ* à l'aide de bacs de sédimentation. Des sédiments marins propres ont été utilisés comme substrat témoin. On a noté des différences touchant la composition en espèces et l'abondance du macrobenthos entre, d'une part, le substrat témoin et celui de la couche de 1 cm d'épaisseur et, d'autre part, les substrats de couches de déchets de 5 et 15 cm d'épaisseur. La diversité en espèces décroissait de façon constante avec l'augmentation de l'épaisseur des déchets. L'abondance moyene totale de la macrofaune était la plus élevée dans le substrat de la couche d'épaisseur intermédiaire (5 cm). Les espèces associées à la couche de déchets la plus épaisse comprenaient des organismes courants indicateurs de la pollution organique marine comme des vers polychètes (*Prinospio cirrifera*, *Armandia brevis*, *Capitella capitata*) et des ampiphodes (*Ampelisca pugettica*, *Aoroïdes* sp., *Melita* sp., *Monoculodes zernori*). Mais seuls le nombre de taxons d'amphipodes et l'abondance des amphipodes ont différé de façon significative (p 0.05) lors d'une comparaison statistique des sédiments témoins et des substrats recouverts par les déchets de bois. Une analyse d'échantillonnage par grappes a permis de différencier trois groupes: un groupe comprenant les échantillons des substrats de couches de 5 et 15 cm. L'analyse par grappes d'espèces a permis de différencier quatre groupes en fonction des différences de la densité du recrutement du substrat témoin et des substrats expérimentaux. La quantité accrue de déchets de bois se reflétait aussi par une augmentation progressive du pourcentage de carbone organique total qui passait de 0.2%, dans les sédiments témoins, à 35.9% dans le substrat de la couche de déchets de 15 cm. On a montré que le potentiel d'oxydo-réduction des sédiments constituait un indice quantitatif fiable de l'épaisseur des déchets de bois. L'anoxie du substrat est considérée comme l'un des principaux facteurs nuisant au recrutement des espèces macrobenthiques. On présente les recherches qu'il faudrait effectuer dans le domaine des effets des déchets de bois rejetés en mer.

Mots-clés: déchets de bois, macrobenthos, recrutement, recolonisation, sédiments anoxiques

INTRODUCTION

One of the most common types of dredge spoil dumped into Canadian coastal waters each year is material rich in wood wastes. The wood waste is generated by a variety of wood processing industries including sawmills, pulp and paper mills, and log sorting/storage activities. The material may consist of wood debris, bark, fibres, or chips of varying particle sizes from <63 um to more than 1 m. The size and specific gravity (usually 1.0-1.5) of the wood debris are important factors in determining the rate of microbial decay and sinking rate, respectively (Levings, 1982). In addition, natural sediments (e.g., fine sands, mud) are often mixed together with the wood wastes and sink at a different rate when dumped.

Dredging (and subsequent ocean disposal) of wood-rich spoils is frequently required as log sorting and mill loading operations are often located adjacent to shallow, navigable waters. Quantities involved can be significant. In one four-year period (1975-1978), over 55,000 m^3 of spoil containing wood waste was dredged from sites within the lower Fraser River, British Columbia (Levings, 1982).

A number of studies have documented the impacts of sediments associated with wood wastes on marine benthic communities (e.g., Pearson, 1975; Rosenberg, 1973; McGreer et al., 1984; Fournier and Levings, 1982; Pomeroy, 1983; Sullivan, 1982; Conlan and Ellis, 1979). McDaniel (1973) documented impoverishment of benthic fauna associated with wood debris from several different sources including log storage, log dumping and pulp and paper mill operations in a British Columbia fjord. Generally, a reduction in overall species diversity has been noted in severely polluted areas compared with non-polluted sites. However, no comprehensive, quantitative investigations have been conducted on the specific characteristics of different types of wood waste which affect recruitment and maintenance of benthic communities.

The present study represents the second phase of an investigation of the effects of wood waste on the recruitment of marine benthic invertebrates. The first phase examined the effect of varying concentrations of fine wood waste mixed with natural sediment on the colonization potential of benthic invertebrates (Kathman et al., 1984).

This report presents results of the second phase on the effects of different thicknesses (1, 5 and 15 cm) of wood waste on the recruitment of marine benthos. Both studies have employed short-term (2-3 months) in situ exposures of wood waste to assess colonization. The scope and duration of these studies has been necessarily restricted to accommodate the funding available at the time the studies were initiated. As such, conclusions drawn are considered preliminary in nature, but represent an important first step in addressing the relative influence of concentration and thickness of wood waste as factors affecting marine benthic recruitment.

METHODS

EXPERIMENTAL APPARATUS

Polyethylene trays (30 x 30 x 15 cm) were filled to a depth of 0. 5 cm with clean, marine sediments and overlain with different thicknesses of wood waste (fine chips, shavings). Marine sediments were collected from a lower intertidal, sandy beach area within English Bay, Vancouver, B.C. The wood waste was collected from the lower intertidal zone adjacent to a chip loading dock in Howe Sound at Port Mellon, B.C. Seasoned, pulverized wood chips which had been exposed to seawater for some time were used to simulate dredge spoils similar to those dredged from other sites within British Columbia. Collection of the wood waste was made from the same location as that in the phase one portion of the investigation to facilitate comparison between the two studies. Wood waste was placed over the clean sediments in individual trays to depths of 1, 5, and 15 cm. A fourth tray containing only marine sediment served as a reference. Sediments and wood waste were frozen (-20 ° C) in the trays for several days to kill existing infaunal organisms before being placed in situ.

Each container was bolted to a separate, plexiglass sheet (60 x 60 cm) with plastic screws. A plastic lid was fitted to each tray and the trays lowered to the ocean bottom by SCUBA divers. Trays were put in place while still frozen to prevent disturbance of the contents. Each tray platform was anchored to the bottom with rock weights. After removal of the lid, a 1/4" Vexar mesh screen was placed over each tray to prevent disturbance by large mobile predators (e.g., starfish). Trays were placed in water off Bowyer Island, Howe Sound, B.C., at a depth of approximately 25 m. Test substrates were retrieved after a two-month exposure (June 26-August 28). Prior to retrieval, plastic lids were securely fastened to the containers to prevent washing out of the contents during ascent.

BENTHIC INVERTEBRATES

Subsampling of the experimental substrates was performed in the field. A divider-grid was inserted into each container and six subsamples from each substrate (6 x 6 cm square x 5 cm deep) removed for taxonomic analysis. No subsamples were taken within a 6 cm border around the inside walls of the container to avoid the "edge" effect noted by Berge (1980). Subsamples were placed in individual, labelled "Whirlpak" bags and preserved in 10% formalin. For taxonomic analysis, each sample was washed through a 0.5 mm mesh sieve. Contents retained on the sieve were examined under a Wild M5A stereomicroscope. All benthic invertebrates were sorted, enumerated and identified to the lowest taxonomic level practicable. Specimens identified were preserved in isopropyl alcohol and were sent for verification by independent taxonomic experts. Where sample volume was large, samples were divided by volume into two portions, one portion being analysed.

PHYSICAL/CHEMICAL VARIABLES

Core (surface to 5 cm depth) samples of the wood waste material from each tray and reference marine sediment taken prior to tray deployment were placed in Whirlpak bags and frozen for later physical/chemical analyses. Samples were later analysed for particle grain size, total organic carbon (TOC), and total Kjeldahl nitrogen (TKN). Samples for particle size analysis were wet-sieved through sieves with mesh sizes of 2.0 mm and 0.0625 mm. The silt/clay fraction (<0.0625 mm) was analysed by the pipette method described in Walton (1978). TOC was determined by the Walkey-Black wet oxidation method. TKN was determined colorimetrically on a sulfuric acid digest, using micro Kjeldahl procedures.

The oxidation-reduction potential (Eh) of the reference sediment, and test substrates was also determined on shipboard after field exposure as a measure of the depth of the anoxic layer within each substrate. Eh was measured with a Xertex Model 60 pH-mV meter equipped with a platinum electrode. The electrode was inserted directly into the substrate sample and recordings taken at 2 cm depth intervals from the surface to 10 cm. Prior to each measurement, the probe and meter were calibrated using Xertex R-508 ORP standard solution at 460 ±10 mV.

DATA ANALYSIS

Species composition and abundance for each of the 24 replicates were compared using the Shannon-Weaver (1963) diversity index,

$$H' = -\Sigma_{p_i} \log p_i$$

where, p_i = the abundance of species i; and Pielou's (1966) evenness index,

$$J = \frac{H'}{H'_{max}}$$

where, H'_{max} = log(s), and s = species richness. Evenness is a measure of the relative distribution of the number of individuals amongst species with a value of 1.0 indicating an even distribution. Mean values of H' and J for all taxa, and for the groups polychaeta and amphipoda were determined for each treatment.

One-way Analysis of Variance (ANOVA) was performed on all replicates within each treatment to determine the significant ($p<0.05$) differences between treatments. ANOVA was calculated for species richness, for total abundance of all taxa, and independently on abundance for the species groups polychaeta, mollusca, amphipoda and decapoda. Data were transformed to log + 1 prior to analysis.

The data were also subjected to hierarchical (cluster) analysis to identify similar groupings or clusters. Data were analysed in two ways:

i) Q-mode which explores the similarity among samples based on species composition and abundances, and,

ii) R-mode which explores the similarity among species based on differences in their abundance in different samples.

Data were transformed prior to analysis. The cluster analysis used was the University of British Columbia CGROUP program, employing the algorithm of Ward (1963). Owing to the high degree of variability associated with the treatment replicates, only the data set using those species occurring in greater than 25% of the samples was employed for interpretation and discussion.

RESULTS AND DISCUSSION

BENTHIC COMMUNITIES

Species Composition and Abundance

A summary of the total number of taxa and total mean abundance for the major taxonomic groups is given in Table 1. Species richness was highest in the reference substrate with 35 taxa recorded, of which 17 were polychaete worms. The fewest taxa (24) were found in the tray containing the deepest (15 cm) layer of wood waste. The total mean abundance of invertebrates was highest in the two trays with the thickest (5 and 15 cm) wood deposits. Polychaete worms represented the largest single group in all test substrates. The numbers of polychaete taxa were higher in the reference (17) and 1 cm wood waste (16) trays than in trays of 5 cm (14) and 15 cm (13) wood waste. The mean abundance of polychaete worms was considerably higher in trays with 5 and 15 cm wood waste (range 228 to 207, respectively) compared to the reference and 1 cm (range 133 to 154, respectively) wood substrates. Common polychaete taxa present (Table 2) included Pholoe minuta, Hesionidae sp., Prionospio cirrifera, Armandia brevis, and Capitella capitata. Both P. cirrifera and C. capitata were consistently present in greater numbers in the trays containing the deepest thicknesses of wood waste than in the reference and 1 cm wood substrates.

The second highest number of species recorded belonged to the amphipoda. The highest number of amphipod taxa (9) was found in the reference sediment, and the lowest number (4) in the tray containing 15 cm wood waste. Total mean amphipod abundance was greatest (9) in the 5 cm wood waste, and least (4) in the 1 and 15 cm wood waste substrates. Common amphipod species included Ampelisca pugettica, Monoculodes zernori, Tiron sp., Aoroides sp., Melita sp., and juvenile Phoxocephalidae. Of particular interest is the distribution of the amphipod species, M. zernori, which was found in the reference sediment only, and did not settle on any of the test substrates containing wood waste (Table 2).

Other taxonomic groups (e.g., mollusca, leptostraca, cumacea, decapoda) were represented by only a limited number of taxa and relatively few individuals (Table 2).

Results of the ANOVA analysis, applied to all taxa, and independently to the major groups (polychaeta, mollusca, amphipoda, and decapoda) are given in Table 3. The analysis showed that amphipods were the only group for which a statistically significant difference between test substrates could be demonstrated. Both the number of amphipod species ($p<0.01$) and the number of individuals ($p<0.05$) were found to be significantly different when the reference tray and the trays containing wood waste were compared.

Plots of diversity (H') and evenness (J) are given in Figure 1 for polychaete, amphipod, and combined taxa for each test substrate. Diversity was highest in the 5 cm substrate for all taxa combined and for polychaetes, and highest in the reference tray for amphipods. The lowest diversity values for all taxa and for polychaetes were found in the reference tray. In contrast, the lowest amphipod diversity occurred in the 15 cm wood substrate. Evenness (J) followed a similar pattern to the diversity values for the different groups. The results indicated a general trend of a greater number of individuals per species in the 5 cm thick wood waste than any of the other substrates.

Compared with the results of Phase I (Kathman et al., 1984), a number of distinct similarities and differences in the recruitment of macrobenthic species are apparent. Species common to both studies included the polychaetes P. cirrifera, A. brevis and C. capitata in substrates containing the largest amounts of wood waste.

Ampelisca sp. was an amphipod species common to both studies. Other crustacean groups (e.g. cumaceans, tanaids) were not found in Phase I. Species common to both studies have been shown to be reliable invertebrate indicators of organic pollution, and have been frequently reported from marine areas covered by wood debris and fibres (e.g., Conlan and Ellis, 1979; Fournier and Levings, 1982; Pearson and Rosenberg, 1978).

One species which was conspicuously absent in the present study was the wood-boring bivalve, Bankia setacea. Bankia was the most abundant species present in the Phase I study (Kathman et al., 1984). Its complete absence in 1984 can be explained by the different exposure periods for the two studies. The peak period for settlement and attack by Bankia in local waters is from August through September (D. Monteith, pers. comm.). The period of peak Bankia settlement coincides more closely with the later exposure period for the Phase I study (August-October) than the present investigation (July-August). With the exception of Bankia, however, the abundance of individuals recruited in the present study was considerably greater than that recorded in Phase I. Experimental recruitment studies using natural sediments have also demonstrated the importance of seasonal variation in macrobenthic colonization (Arntz and Rumohr, 1982).

Trends in diversity (H') and evenness (J) were similar in both the present and Phase I investigations. A peak in both indices was observed at an intermediate concentration of wood waste corresponding to 20% wood waste in Phase I and at a thickness of 5 cm in the present study. The numerical data indicate that diversity was primarily influenced by the greater number of individuals present in the samples. The greatest number of taxa did not occur in the samples with the highest diversity values.

Community Associations

Results of the clustering analysis are given in Figures 2, 3 and 4. Computer species codes used to identify individual taxa are given in Table 4.

Clustering of individual sample replicates produced three cluster Groupings (Fig. 2). Group 1 contained all 12 replicates of the reference and 1 cm wood waste substrates. One replicate from the 15 cm treatment was clustered with this group.

Groups 2 and 3 each contained replicates from the 5 and 15 cm test substrates. The primary difference between Groups 2 and 3 was the greater abundance of taxa making up the replicates in Group 3 (i.e., replicates 15, 16, 21, 22, 24). This can be seen in the raw data in Table 2 when the abundances for the two sets of replicates are compared. Similar species were found in both Groups 2 and 3. In contrast, replicates which comprised Group 1 showed a different species composition and lower numbers of individuals than either of Groups 2 or 3.

These results indicate that the faunal assemblage in the test substrate with 1 cm wood waste was similar to that of the reference sediment. The 5 and 15 cm wood waste substrates were shown to be similar to each other, but together were markedly different from the reference/1 cm sample group. From the point of view of marine disposal of wood waste, it appears that relatively small amounts of wood waste (i.e., up to 1 cm thick) do not adversely affect the recruitment of macrobenthos compared to natural sediments. This conclusion is supported by the results of at least one field study which also found little effect of wood waste deposits of 1 cm or less (Conlan and Ellis, 1979).

A second result of the clustering analysis was the classification of samples containing increasing amounts of wood waste on the basis of differences in faunal abundance. Differences in the clustering technique were based largely upon changes in abundance of the polychaete P. cirrifera (Table 2) in the edited data set used, and as such, indicated increased abundance of species settling on the thicker amounts of wood waste. Clustering of replicates from different tests (e.g., 5 and 15 cm) in any one group indicates the high degree of variability in settlement between replicates within each experimental substrate. When the entire community was considered (Table 1), peak abundance was apparent at an intermediate thickness of wood waste (5 cm), followed by a decline in the 15 cm thick deposits. This pattern was also followed for diversity (Fig. 1). The enhancement of abundance at intermediate concentrations of wood waste was also a characteristic of the Phase I portion of the present experimental study at a mixture of 20% wood waste in natural sediment (Kathman et al., 1984). Results of field studies on the effects of wood waste deposits have supported the hypothesis of increased impact with increased concentration of wood waste (Conlan and Ellis, 1979; McGreer et al., 1984; Pearson, 1975).

Results of cluster analysis by species (R-mode) differentiated four major groups, two of which were comprised of only one species (Fig. 3). The relative abundance of each species association with respect to the different treatments is shown in Figure 4. Group A consisted of 3 polychaetes (P. minuta, S. brandhorsti, P. granulata), 2 amphipods (Melita sp., juvenile amphipods) and 1 echinoderm (Ophiuroidea). Taxa in Group A occurred in relatively low numbers in all test substrates. This group did not show a notable response to increased concentrations of wood waste, and as such, settlement of these taxa did not appear to be affected. Group B consisted of 1 polychaete, A. brevis. This species occurred in greater abundance in all test substrates compared to members of Group A, reaching a peak density in the 5 cm test substrate (Fig. 4). Members of Group C included 1 leptostraca (N. pugettensis), and 2 polychaetes (Hesionidae, C. capitata). This group showed an increase in abundance at higher wood waste concentrations of 5 and 15 cm compared to the 1 cm or reference sediments (Fig. 4). Peak abundance occurred in the 5 cm wood substrate. Group D was comprised of the dominant polychaete species in the study, P. cirrifera. The abundance of P. cirrifera in all test sediments far exceeded that of any other group. This species also showed a distinct increase in density in the higher wood waste concentrations, reaching a peak in the intermediate, 5 cm tray.

Although similarities existed between the two studies, a number of differences in the species associations identified in the present study were apparent compared to those of Phase I. Group A in the present study was similar to a Phase I group which had the lowest overall abundance, and which did not respond overtly to higher concentrations of wood waste. The polychaete S. brandhorsti was present in these groups in both studies. Similar groups were identified in both studies with common polychaete species such as P. cirrifera, C. capitata and A. brevis, which showed a marked increase in settlement in substrates containing higher concentrations of wood waste. A major difference between the two studies was the absence in the present investigation of a sensitive group of species showing a strong decrease in density in response to increasing concentrations of wood. In the previous study (Kathman et al., 1984), a sensitive group comprised primarily of bivalve molluscs was identified through cluster analysis. However, none of the species associated with this group was found in the present study.

One explanation for the lack of a sensitive bivalve species may be associated with the earlier seasonal exposure time for the experimental substrates in the present study than used in 1983. Ambrose (1984) has recently reviewed the influence of "resident" fauna on the settlement and development of marine macrobenthic communities. He found that assemblages of initial colonizers persisted for the duration of experiments (up to 8 weeks) using a variety of disturbed sediments. Bivalve molluscan larvae have been shown to be consumed upon settling by a host of polychaete (Breese and Phibbs, 1972; Ambrose, 1984) and amphipod species (Segerstråle, 1962; Oliver et al., 1982). As the density of polychaete and amphipod species was far greater in the present study than in Phase I, it appears that peak settlement of these groups occurred during the 1984 study, and these earlier settling species may have consumed any bivalve mollusc larvae which settled. This phenomenon of larval predation by amphipods has been used to explain failures of recruitment success in an entire year class of the bivalve Macoma balthica in parts of the Baltic Sea (Segerstråle, 1962).

RELATIONSHIP TO PHYSICAL/CHEMICAL VARIABLES

The physical/chemical characteristics of the test substrates are given in Table 5. Reference and 1 cm wood substrates were primarily sand (63-66%) and silt (32%) with smaller amounts of clay-sized particles (2-4%). The 5 and 15 cm substrates were composed predominantly of silt-sized particles (43-54%) with smaller fractions of sand (26-32%) and clay (19-24%). The smaller sized particles in the 5 and 15 cm substrates were largely small wood shavings. Values for total organic carbon showed a direct increase related to the amount of wood waste with a high of 35.9% in the 15 cm wood substrate. Values for total nitrogen were generally higher in the substrates with the most wood, but the increase was not directly proportional to thickness of the deposits.

Measurements for substrate oxidation-reduction potential (Eh) are presented in Table 6. The vertical profiles indicated a progressively reducing environment in the substrates with greater thicknesses of wood waste. This can be seen most easily by comparing the readings at a specific depth (e.g., 4 cm) for each test substrate. Values decreased from +58 mV in the reference substrate to -371 mV in 15 cm wood waste. The anoxic nature of the 5 and 15 cm wood substrates was also apparent from the strong smell of hydrogen sulfide emanating from these trays when the sediments were disturbed. In contrast to substrates covered with wood waste, the reference sediment appeared to be well oxygenated (as indicated by positive Eh values) from the surface to 8 cm depth.

Redox potential appeared to be a key physical factor associated with the depth of wood deposits which could be used to explain the differences in recruitment observed in the present study. The type of species which settled in large numbers on the thickest (and most reducing) substrate (e.g., A. brevis, P. cirrifera) are known indicators of organic pollution (Pearson and Rosenberg, 1978), which can tolerate the typically anoxic conditions associated with this type of environment. Redox was also found to decrease with increasing proportions of wood waste mixed with clean sediment in the Phase I portion of the investigation (unpublished data).

The importance of redox potential in marine sediments as an indicator of impaired recruitment has been demonstrated in other studies on the effects of wood waste. In a series of papers (Pearson et al., 1982; Pearson and Stanley, 1979; Vance et al., 1982) changes in macrobenthic fauna in Loch Eil, Scotland, associated with the input of pulp and paper mill effluent, have been described. A time lag of approximately 4-6 weeks was observed between an increase in carbon input to the sediment and a detectable change in benthic community structure. The additional input of carbon by the effluent (and associated wood fibres) was linked to changes in benthos through a series of changes in sediment chemistry and microbiology, most notably by increases in cellulose-digesting and aerobic heterotrophic bacteria. The consumption of oxygen by the bacteria eventually leads to anoxic sediment in the areas of highest wood fibre concentrations. Pearson and Stanley (1979) used the measurement of redox potential (Eh) as a rapid means of assessing the potential impact of additional organic input to marine benthos. Changes in redox were related to changes in species richness, abundance and biomass. Bacterial respiration and the oxidation of sulfide have been shown experimentally to be important factors in the development and maintenance of anoxic conditions in estuarine ecosystems influenced by cellulose fibre (Poole et al., 1977).

In a long-term study of the recovery of intertidal benthos from the impacts of log boom storage in the Nanaimo River estuary, British Columbia, McGreer et al. (1984)

found that sediment anoxia as indicated by negative Eh measurements was the most significant feature related to the distribution and abundance of benthic infauna. Measurement of common physical/chemical variables (e.g., particle grain size, total Kjeldahl nitrogen, and total organic carbon) showed no statistically significant differences between the impacted test site and a reference location over a 13-month period. Canonical correlation analysis applied to particle size, TKN and TOC also did not show a significant correlation with changes in benthic communities.

In conclusion, sediment redox potential appears to be a reliable, quantitative physical measurement which can be related to changes in benthic communities. Measurement of sediment Eh should be included in monitoring programs associated with wood and cellulose fibre pollution. Results of the present experimental study suggest that the onset of anoxia is brought about by thicknesses of fine wood deposits between 1 and 5 cm. These results should be confirmed by field monitoring of wood wastes which have been on the sea floor for various periods of time.

FUTURE RESEARCH NEEDS

Several research needs are identified as a result of the findings of the present study, and these include requirements for:

1. Assessment of the influence of timing (seasonal) of initial exposure (i.e., timing of spoil disposal) on the development and stability of macrobenthic communities for different thicknesses of wood waste.

2. Evaluation of the experimental results obtained from sediment trays with those from a natural community in a habitat which has received wood waste.

3. Assessment of the effect of different types of wood waste (e.g., green vs aged wood, different wood species, different particle composition, hog fuel, etc.) on development and stability of macrobenthic communities.

4. Investigation of different disposal techniques as a means of mitigating the impacts of wood waste on sensitive marine habitats.

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TABLE 1

TOTAL NUMBER OF SPECIES AND TOTAL MEAN ABUNDANCE FOR MAJOR TAXONOMIC GROUPS IN EACH TEST SUBSTRATE

	Test Substrate							
	Reference		1 cm		5 cm		15 cm	
	Taxa	Abund.	Taxa	Abund.	Taxa	Abund.	Taxa	Abund.
Polychaeta	17	133	16	154	14	228	13	207
Gastropoda	1	<1	0	0	1	<1	1	1
Bivalvia	1	<1	1	<1	1	<1	1	<1
Leptostraca	1	<1	1	5	1	10	1	8
Cumacea	2	<1	1	<1	1	<1	1	<1
Tanaidacea	0	0	0	0	0	0	1	<1
Isopoda	0	0	0	0	1	<1	0	0
Amphipoda	9	5	6	4	6	9	4	4
Decapoda	3	<1	3	1	2	3	1	<1
Ophiuroidea	1	<1	0	0	1	1	1	1
Total No. Taxa	35		28		28		24	
Total Mean Abundance		144		166		255		225

TABLE 2

NUMBERS OF BENTHIC INVERTEBRATE TAXA IN REPLICATE TEST SAMPLES

Taxa	Reference						1 cm						5 cm						15 cm					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
ANNELIDA																								
Polynoidae																								
Polynoidae sp. (juv.)		1			1													2						
Sigalionidae																								
Pholoe minuta	3		2	3		3	1	1	3		1				4	4	2		2	2	4	4	2	
Phyllodocidae																								
Eteone sp. (juv.)		1													2	2						2		
Hesionidae																								
Gyptis brevipalpa		1																						
Micropodarke dubia																2				2	4			
Ophiodromus pugettensis					1				1		1													
Hesionidae sp. (juv.)	6	4	1	3	2	2	15	4	10	11	4	7	12	10	22	12	10	14	6		22	14	4	28
Syllidae																								
Sphaerosyllis brandhorsti		1				1			1				2			2						8		2
Glyceridae																								
Glycera sp. (juv.)			1		3	1															2			
Goniadidae																								
Glycinde picta							1																	
Glycinde sp. (juv.)	1	3				1					1				4							2		
Lumbrineridae																								
Lumbrineris sp. (juv.)	2										1					2							2	
Dorvilleidae																								
Ophryotrocha sp. (damaged)														4			2	2				2		

TABLE 2 (continued)

Taxa	Reference						1 cm						5 cm						15 cm					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Spionidae																								
Prionospio cirrifera	109	117	77	130	81	106	147	144	143	144	75	66	194	126	268	388	20	12	68	14	172	272	96	326
Prionospio steenstrupi								1				1												
Spio cirrifera				1					1	1			2			2								
Spionidae sp. (damaged)						1				1														
Cirratulidae																								
Caulleriella alata						1																		
Opheliidae																								
Armandia brevis	16	16	13	29	25	12	24	20	18	16	16	10	18	24	46	46	6	2	14		36	22	12	30
Capitellidae																								
Capitella capitata		2					1	5	1	9	8	1	20	12	12	10	16	24	10		8	26	4	16
Mediomastus sp.											2													
Amphictenidae																								
Pectinaria granulata	6	1	1	1	2	1		2			3	2			2									4
Terebellidae																								
Polycirrus sp.											1													
MOLLUSCA																								
Gastropoda																								
Littorina sitkana																2			4					2
Alvania sp.																								
Gastropoda sp. (damaged)						1																		
Tellinidae sp. (juv.)	1				1		1			2	1						2							
Cardiidae sp. (juv.)																					2			
ARTHROPODA																								
Nebalia pugettensis				1	1		8	4	2	6	6	4	12	4	8	20	10	8	6		8	26	2	6

TABLE 2 (continued)

Taxa	Reference						1 cm						5 cm						15 cm					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Cumacea																								
Diastylidae sp.	1																							
Cumella sp. (damaged)				2					1	6					2									2
Tanaidacea																								
Leptochelia dubia																					8			
ISOPODA																								
Limnoridae																								
Limnoria lignorum																		2						
AMPHIPODA																								
Ampeliscidae																								
Ampelisca pugettica	1	2					3				1				2									
Aoridae																								
Aoroides sp. I								1		2					2	2		4						4
Corophiidae																								
Corophium acherusicum		1					1																	
Corophium sp. (juv.)						1																		
Gammaridae																								
Melita sp. (juv.)					1		1					1		1	2	2					2	2		
Lysianassidae sp. (juv.)												1			2	2		2						
Oedicerotidae																								
Monoculodes zernovi	1	6	1	3	3	1																		
Phoxocephalidae																								
Paraphoxus sp. (damaged)					1																			
Phoxocephalidae sp. (juv.)					1								2	2			2							2

TABLE 2 (continued)

Taxa	Reference						1 cm						5 cm						15 cm					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Tironidae																								
Tiron sp.	2	1	1																					
Amphipoda sp. (juv., dam.)	1		2	1	1	1		1	1		2	1	2	8		8	4	6	2			2	8	
DECAPODA																								
Natantia sp. (juv., dam.)											2	2												
Hippolytidae sp. (juv.)		1	1						3					2		2		6						
Eualus sp. (damaged)						1																		
Reptantia																								
Brachyura sp. (damaged)			1							2					4			2				2		
ECHINODERMATA																								
Ophiuroidea sp. (juv.)	1			1	1	1												6			2		2	2

TABLE 3

PROBABILITY OF DETECTING A SIGNIFICANT DIFFERENCE BETWEEN TEST SUBSTRATES FROM ANOVA FOR DIFFERENT TAXONOMIC GROUPINGS

	All Taxa	Polychaeta	Mollusca	Amphipoda	Decapoda
Number of Species	0.113	0.445	0.933	0.001*	0.335
Number of Individuals	0.372	0.465	0.564	0.004*	0.122

*Result significant at $p < 0.05$

TABLE 4

FREQUENCY OF OCCURRENCE FOR COMMON SPECIES IN EACH TEST SUBSTRATE AND COMPUTER CODE USED IN CLUSTER ANALYSIS

		Frequency of Occurrence			
	Code	Ref	1 cm	5 cm	15 cm
ANNELIDA					
Polychaeta					
Sigalionidae					
Pholoe minuta (Fabricius)	1	5	4	3	5
Phyllodocidae					
Eteone sp. (juveniles)		1	0	2	1
Hesionidae					
Hesionidae sp. (juveniles)	2	6	6	6	5
Syllidae					
Sphaerosyllis brandhorsti Hartmann-Schröder	3	2	1	2	2
Glyceridae					
Glycera sp. (juvenile)		3	0	0	1
Goniadidae					
Glycinde sp. (juveniles)		3	1	1	1
Lumbrineridae					
Lumbrineris sp. (juveniles)		1	1	1	1
Dorvilleidae					
Ophryotrocha sp. (damaged)		0	0	3	1
Spionidae					
Prionospio cirrifera Wiren	4	6	6	6	6
Spio cirrifera (Banse & Hobson)		1	2	2	0
Opheliidae					
Armandia brevis (Moore)	5	6	6	6	5
Capitellidae					
Capitella capitata (Fabricius)	6	1	6	6	5
Amphictenidae					
Pectinaria granulata (Linnaeus)	7	6	3	1	1

TABLE 4 (continued)

		Frequency of Occurrence			
	Code	Ref	1 cm	5 cm	15 cm
MOLLUSCA					
Pelecypoda					
Tellinidae sp. (juveniles)	7	2	3	1	0
ARTHROPODA					
Leptostraca					
Nebalia pugettensis (Clark)	8	2	6	6	5
Cumacea					
Cumella sp. (damaged)		1	2	1	1
AMPHIPODA					
Ampeliscidae					
Ampelisca pugettica Stimpson		2	2	2	0
Aoridae					
Aoroides sp. I		0	2	3	1
Corophiidae					
Gammaridae					
Melita sp. (juveniles)	9	1	2	3	2
Lysianassidae sp. (juveniles)		0	1	3	0
Oedicerotidae					
Monoculodes zernovi Gurjanova		6	0	0	0
Phoxocephalidae					
Phoxocephalidae sp. (juveniles)		1	0	3	1
Amphipoda sp. (juveniles)	10	5	4	5	3
DECAPODA					
Natantia					
Hippolytidae sp. (juveniles)		2	1	3	0
Reptantia					
Brachyura sp. (damaged)		1	1	2	1
ECHINODERMATA					
Ophiuroidea sp. (juveniles)	11	4	0	1	3

TABLE 5

PHYSICAL/CHEMICAL CHARACTERIZATION OF REFERENCE SEDIMENT AND TEST SUBSTRATES CONTAINING WOOD WASTE

		Substrate		
Parameter	Reference	1 cm	5 cm	15 cm
Particle Size			%	
Sand (0.063-2 mm)	65.7	63.4	32.3	26.6
Silt (0.002-0.063 mm)	32.3	32.7	43.3	54.0
Clay (<0.002 mm)	2.0	3.9	24.4	19.4
Total Organic Carbon	0.2	2.9	26.4	35.9
Total Nitrogen	0.018	0.052	0.239	0.135

TABLE 6

SUBSTRATE OXIDATION-REDUCTION POTENTIAL MEASUREMENTS (mV) AT TEST TERMINATION

Depth (cm)	Reference	Test Substrate 1 cm	5 cm	15 cm
sfc	+ 50	- 60	- 93	- 31
2	+ 60	-160	-212	-283
4	+ 58	-294	-342	-371
6	+ 60	-322	-387	-404
8	+ 20	-	-390	-428
10	-164	-	-392	-444

- not measured

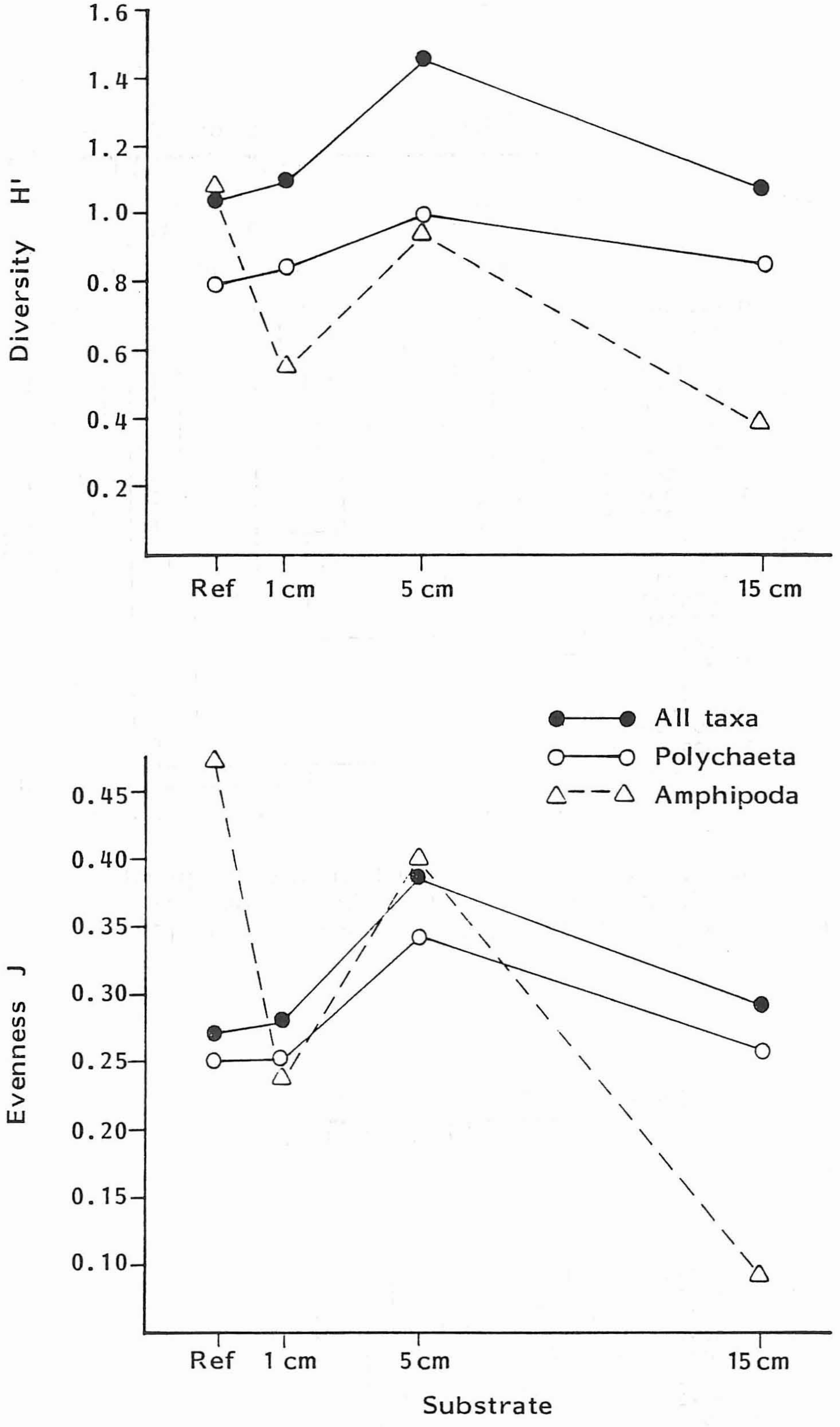

Fig. 1. Relative changes in means of diversity (H') and evenness (J) for different test substrates and taxonomic groups.

```
         ITEMS GROUPED
STEP       I      J       ERROR

  1        8     11    0.7522202
  2        3      6    0.8321400
  3       17     19    1.3249397
  4        5     12    1.5284443
  5        4      9    1.6597891
  6        2     10    1.7773705
  7        3      4    1.9668150
  8        2      8    3.0618629
  9       15     21    3.0775280
 10        2      5    3.9242020
 11        3     20    3.9346333
 12       14     23    4.4472160
 13        2      7    4.6136389
 14       13     17    5.5937815
 15       13     14    9.2879782
 16        2      3   10.871360
 17        1      2   11.590469
 18       15     16   13.996828
 19       15     24   19.801788
 20       13     18   20.086716
 21       15     22   26.306854
 22        1     13   31.528885
 23        1     15   82.032578
```

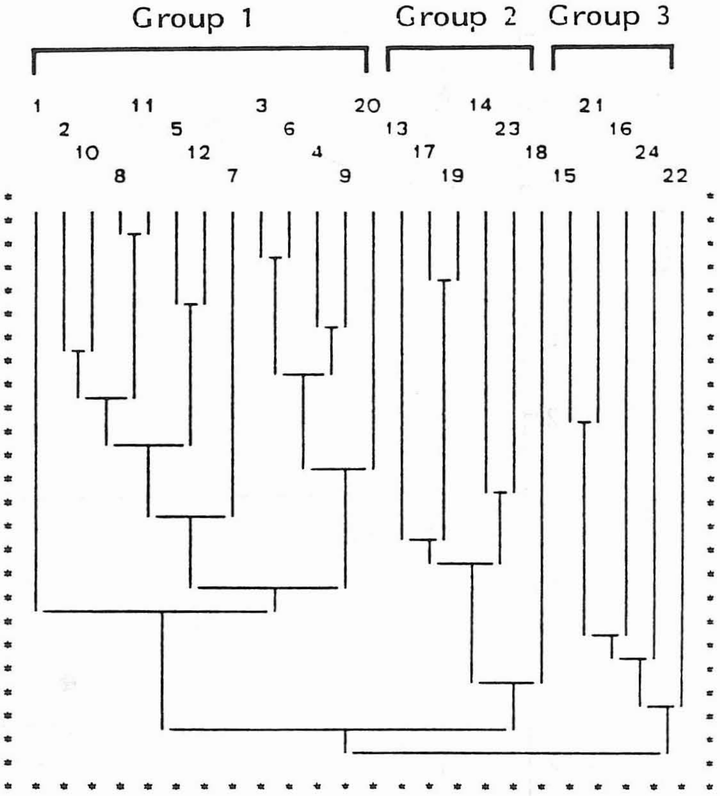

Fig. 2. Cluster analysis of individual treatment replicates. Numbered replicates refer to the following treatments: 1-6 (Reference), 7-12 (1 cm), 13-18 (5 cm), 19-24 (15 cm).

```
         ITEMS GROUPED
STEP       I      J       ERROR

  1        3      9    0.0096367
  2        3      7    0.0548897
  3       10     11    0.2509196
  4        1      3    0.2928478
  5        2      8    0.5507941
  6        1     10    1.0510654
  7        2      6    2.8517218
  8        1      5    6.0536871
  9        1      2   12.700068
 10        1      4  240.18338
```

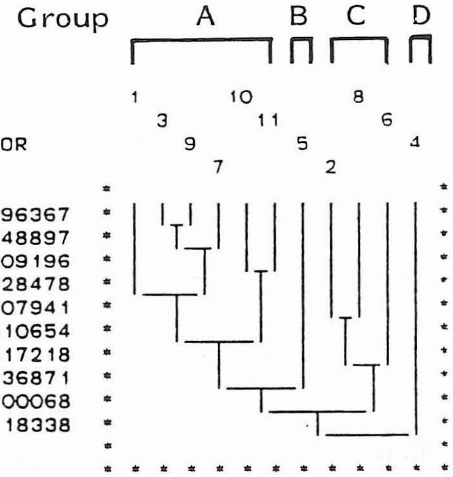

Fig. 3. Cluster analysis by species. Species code numbers given in Table 3.

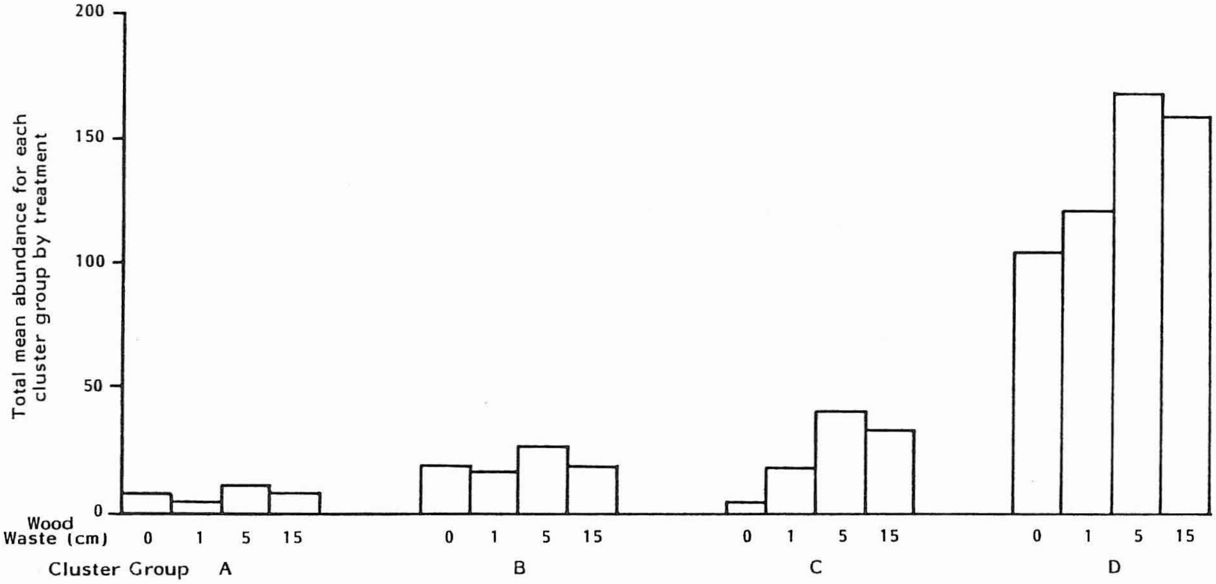

Fig. 4. Total mean number of individuals for each cluster analysis species group. Original cluster analysis shown in Figure 3.