Environment Canada
Water Science and
Technology Directorate

Direction générale des sciences
et de la technologie, eau
Environnement Canada

Factors Influencing the Distribution of the Benthic Fauna of Lake Superior: Establishing Long Term Monitoring Sites

By:
Trefor B. Reynoldson

93-05

FACTORS INFLUENCING THE DISTRIBUTION OF THE BENTHIC FAUNA OF LAKE SUPERIOR: ESTABLISHING LONG TERM MONITORING SITES.

Trefor B. Reynoldson
National Water Research Institute
Lakes Research Branch
Environment Canada
867 Lakeshore Rd
BURLINGTON, Ontario

MANAGEMENT PERSPECTIVE

In the 1978 and 1987 Great Lakes Water Quality Agreements the governments of Canada and the United States agreed to adopt an Ecosystem Approach to the management of activities that may impact the Great Lakes ecosystem. An integral part of this approach is the development of ecosystem objectives and indicators that provide targets to define a healthy ecosystem and establish whether or not human activity within the basin is compatible with maintenance of ecosystem health. The first ecosystem objectives agreed to by the two national governments were for Lake Superior and included the lake trout and the amphipod *Pontoporeia hoyi*. However, until this study no investigations of the status of *P. hoyi* on a lakewide basis had been undertaken since 1973.

The results of this study demonstrate that the *Pontoporeia* ecosystem objective for L. Superior is being achieved. The data were also used to establish the number of sites required to provide an ongoing monitoring programme to ensure that the ecosystem objective is being met. From analysis of the data the lake was separated into an offshore zone and five nearshore zones. It is recommended that seven stations be sampled in the offshore zone and a total of 20 in the nearshore zone. This number of stations will be sufficient to detect a 50% change in amphipod abundance which is an acceptable resolution for an ecosystem objective monitoring programme.

INTRODUCTION

Lake Superior is the largest of the Laurentian Great Lakes and has a larger volume than the remaining Great Lakes combined. It is also the least impacted of the lakes due to both its large size and the fact that it has the smallest human population. Thus, it is likely to be the lake that best represents background, undisturbed conditions.

Investigation of the benthic fauna of Lake Superior began early with a survey in 1871 by the US Lake Survey (Smith and Verrill, 1871; Smith, 1874). In the intervening 121 years there have been only two other surveys of the benthic community of the whole lake in 1968 (Adams and Kregear, 1969) and in 1973 (Cook, 1975).

From these data the International Joint Commission (IJC) developed a biological objective for Lake Superior using the benthic community. The target for Lake Superior is that the lake "*should be maintained as a balanced and stable oligotrophic ecosystem with lake trout as the top aquatic predator of a cold-water community and Diporeia (Pontoporeia) hoyi as a key organism in the food chain*". To meet this target the Great Lakes Water Quality Agreement stipulates that "*The abundance of Diporeia (Pontoporeia) hoyi, should be maintained throughout the entire lake at present levels of 220-320 individuals/m2 (at water depths < 100m) and 30-160 individuals /m2 (at water depths >100m).*"

The purpose of this study was to investigate the current state of the benthic community and particularly *Pontoporeia hoyi*, to establish distribution patterns for the community in the lake, to attempt to relate the distribution of the fauna to environmental conditions, and to make recommendations on a reduced set of representative sampling stations for long term monitoring of the benthic community, and in particular *P. hoyi*, to determine whether the ecosystem objective is being met.

METHODS

Since 1985 the Inland Waters Directorate of Environment Canada has conducted spring and summer water quality surveillance cruises on Lake Superior at 73 stations (Neilson, personal comm.). These stations, with minor modifications, were used for sampling the benthic community (Fig. 1). At each station a single box core was taken, the area sampled being 0.5 x 0.5 m (25,000 cm^2), to an average sediment depth of 40 cm. Each box core was treated as a portion of intact sediment from the lake bottom and it was sampled using small diameter core tubes. Five plexiglass core tubes with an inside diameter of 6.6 cm (34.2 cm^2) were inserted to a depth of 10 cm. These were removed placed in a plastic bag and stored at 4°C for sieving. Thus a sample of the benthic community was formed from five sampling units of 34.2 cm^2. Each sampling unit (replicate), was sieved through a 250μ mesh, stored in vials in buffered 4% formalin prior to sorting and counting. Sampling units were sorted under low power magnification, the Chironomidae and Oligochaeta were mounted in polyvinyl lactophenol for further identification. Prior to removing the small cores from the box core a sample of the top 5 cm of surficial material was removed for chemical analyses. Sediment was placed in a glass tray, homogenized with a plastic spoon and transferred to plastic vials. Samples were stored at 4°C in the field and freeze dried in the laboratory for chemical analysis. Concentrations of major elements (Si, Al, Fe, Mg, Ca, K, Na, Ti, P, Mn and P) and trace elements (Ag, As, Ba, Cd, Cu, Co, Cr, La, Mo, Ni, Pb, Sc, Y, V and Zn) in sediment samples were determined by x-ray fluorescence spectrometry (Mudroch, 1985). The precision of the analysis was determined by analyzing five pellets made from a homogenized sediment sample. Relative deviations for major elements in sediment samples can be expected at the following levels: SiO_2 2%, K_2O and Al_2O_3 4%, Fe_2O_3 and CaO 2%, MgO and Na_2O 10%. Absolute deviations of 0.01% to 0.02% were found for MnO, TiO_2, and P_2O_5. Generally, the coefficient of variation for trace elements was less than 10% and continuously declining with increased trace element concentrations in the samples. The accuracy of the analyses was verified by running Canadian reference standards Syenite SY-2 and soils SO-2 and SO-4 and comparing the analytical results with the stated reference values for major and trace elements. Particle size was estimated on wet samples using the sedigraph method (Duncan and LaHaie 1979) and data are expressed in terms of percentage sand, silt and clay. Total organic carbon (TOC) was estimated by converting a 0.1 g sample to CO_2 in a Leco carbon determinator. Loss on ignition (LOI) was estimated by ashing dry sediment at 450°C to constant weight (approx 3 h).

In order to discriminate patterns in the distribution of the benthic fauna and relationships between any such pattern and the surrounding environment a number of multivariate statistical techniques were used. Determination of structure in the benthic data and sediments was undertaken using classification and ordination techniques. The benthic data were not treated prior to analysis. The Bray Curtis metric was used as a measure of association. Classification was done using the UPGMA (unweighted pair group mean average) technique and is a hierarchical agglomerative method. The groups produced from the classification analysis were examined in ordination space to establish whether the classification groups are truly distinct rather than being dispersed along environmental gradients. Ordination was done using semi-strong hybrid multidimensional scaling (SSH). SSH is superior to other ordination techniques (e.g., PCA, CA, RA) as it equally weights the input distances, multidimensional scaling also permits greater flexibility in data handling than other ordination methods (Belbin, in press). Vector scores from SSH were correlated with environmental variables and discriminant analysis used with selected variables to establish the relationship between the community groups and sediment characteristics. The software packages PATN, SYSTAT and SAS were used for the data analysis.

RESULTS

Of 68 sites visited over a 5 day period from May 10 - 15 1991 (Fig. 1), samples were obtained from 64. Three sites were not sampled as the substratum was unsuitable, site 211 had a hard clay bottom and sites 198 and 52 were sand. Severe weather prevented sampling at site 80. At 9 of the 64 sites sampled a predominantly sand substrate prevented use of the large box core (Fig. 1), these sites were all near-shore and in shallow water (18-56 m). At these sites a Shipek sampler was used to obtain a qualitative estimate of the benthic fauna. At the time of preparation of this report the taxonomy of the benthic fauna has been completed to family level only, however, for the purposes of pattern analysis and the identification of major trends in the distribution of the benthic fauna present data are considered sufficient.

Comparison with Ecosystem Objectives

The two dominant groups in the benthic community are the Amphipoda and Oligochaeta, together these account numerically for almost 70% of the organisms found and their biomass would comprise an even greater proportion of the total benthic fauna.

Table 1. Summary of Benthic Fauna, L. Superior, 1991

Taxon	Proportion of Total Fauna (percent)	Abundance at water depth < 100m (no.m^{-2})	Abundance at water depth > 100m (no.m^{-2})
Amphipoda	42.4	1650	608
Oligochaeta	26.7	786	501
Pelecypoda	11.6	505	104
Chironomidae	5.6	255	52
Nematoda	2.9	49	97
Ostracoda	10.5	202	307
Hydra	0.3	1	12

The average densities at the two water depths distinguished in the Great Lakes Water

Quality Agreement (GLWQA) show that the amphipods, pelecypods and chironomids are more affected by water depth than the other families. Identification of the amphipods has been completed and over 60% have been found to be *Pontoporeia hoyi*, and thus the numbers found are considerably in excess of the ecosystem objective in the GLWQA.

Of the 30 sites sampled that were less than 100 m water depth 10 had amphipods at densities below the objective of 220 m^2 and of the 38 sites greater than 100 m depth of water 4 had densities of amphipods of less than 30 m^2 (Fig. 1).

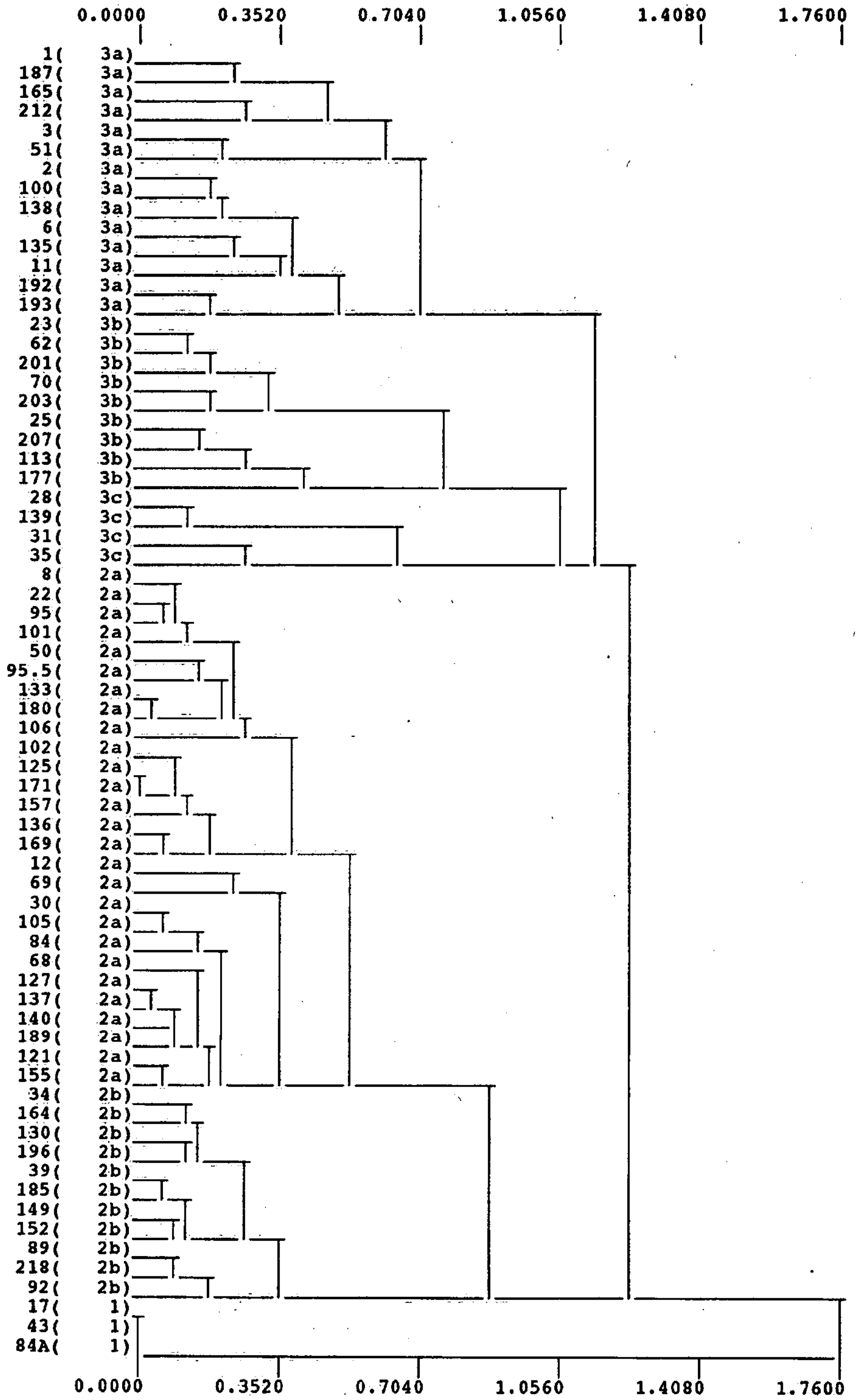
Classification of Community and Sediment

One of the objectives of this study was the establishment of sites representative of large and defined areas of the lake for monitoring the benthic community and specifically the *Pontoporeia* objective of the GLWQA. To establish patterns in the distribution of the benthic community pattern analysis was used with the taxa identified in Table 1 as the grouping variables. Classification of the groups was performed using an agglomerative clustering technique and ordination on raw data scores. The Bray Curtis association measure of similarity was used.

The result of the classification analysis (Fig. 2), shows clearly identifiable groups. The first division separates three sites (Gp 1) located in the eastern portion of the lake (Fig. 3) with very few organisms but with the highest abundance of *Hydra spp.* It was noted in the field that the sediment at these sites appeared to be highly scoured with a high proportion of clay and little recent material and apparently exposed to fast underwater currents. The next separation of sites are those comprising Gp 3 (3a, 3b, 3c), these sites are generally in shallower water and are all located in the nearshore zone which has been divided into five zones (Fig. 3). The most notable feature of the sites comprising Gp 3 is that the sediment contains more sand (44%) and have the greatest number of chironomids. The Gp 2 sites (2a, 2b) comprise the entire offshore area (Fig. 3) and 32 of 38 (84%) of the sites in this group are geographically contiguous and separate from the Gp 3 sites and form what is defined as the offshore zone.

The next division separates the Gp 3 sites into three groups 3a, 3b and 3c. These groups do not appear to be based on geographical differences but rather on "local" sediment characteristics. Gp 3a sites are in shallower water with sandy sediment with the lowest total organic carbon (TOC) but the richest benthic fauna. This fauna appears characteristic of Whitefish Bay (Fig. 3 - Zone F) and the southern part of Zone A (Duluth Basin and Apostle Islands). Gp's 3b and 3c represent a less diverse nearshore community representing silty sediment habitats such as Michipicoten Bay (Gp 3c) where oligochaete worms are the dominant component or deeper (mean water depth 176 m) nearshore habitats (Gp 3b). Gp 3b although spatially nearshore represents some of the deepest water areas of the lake such as along the northshore of the Duluth Basin and deep water trenches in Michipicoten Bay.

Figure 2. L. Superior benthos 91 untransformed 6 taxa



The final meaningful division is the separation of Gp 2 sites. A large group of 27 sites (Gp 2a) represents the most widespread offshore community (mean water depth 148.7 m) dominated by amphipods and characterised by a high proportion of clay in the sediments (57%). The other group of sites (Gp 2b) may be considered as a transition zone, the sites are in shallower water (mean depth 95 m) and the sediment has a higher sand content. The Gp 2b sites are all on the periphery of the offshore zone (Fig. 3).

No further interpretable division of sites was possible as the data structure resulted in a large number of small groups being formed (Fig. 2).

Table 2. Distribution of benthic fauna in 6 cluster groups.

Taxon	Gp 3	Gp 3a n=14	Gp 3b n=9	Gp 3c n=4	Gp 2	Gp 2a n=27	Gp 2b n=11	Gp 1 n=3
Amphipoda	4.6	6.9±9.7	0.5±0.2	0.0	3.7	3.1±4.0	8.1±3.9	0.0
Oligochaeta	2.6	2.4±2.5	1.7±1.2	2.8±2.2	2.2	2.6±3.0	2.7±3.2	0.0
Chironomidae	0.2	2.1±1.3	0.1±0.1	0.5±0.3	1.2	0.1±0.2	0.5±0.6	0.0
Pelecypoda	1.3	2.0±2.0	0.2±0.7	2.0±1.9	1.4	0.5±1.0	3.2±5.3	0.0
Ostracoda	1.2	1.2±1.7	1.0±1.1	1.0±0.2	1.1	1.1±0.9	1.3±1.6	0.4±0.7
Hydra	0.0	0.1±0.4	0.0	0.0	0.1	0.0	0.0	0.3±0.5
Depth (m)	133	60	176	85	102	149	95	159
Sand (%)	20	64	28	22	45	15	32	7
Silt (%)	26	16	29	43	25	28	21	46
Clay (%)	53	19	43	35	30	57	43	47
TOC	1.9	0.8	1.1	2.6	1.2	2.0	1.5	1.2

The distribution of the benthic fauna among the site groupings shows the amphipods are most abundant in Gp's 3a and 2b which tend to be in shallower water and have a higher proportion of sand in the sediment. The Oligochaeta are broadly dispersed across the groups, except Gp 1. The Chironomidae characterise the shallow water, sandy sediments with low organic carbon in Gp 3a. The pelecypods appear strongly influenced by water depth being found in the three shallow water groups (Gp's 2b, 3a and 3c).

To determine whether the site groupings from classification analyses were discrete assemblages rather than arbitrarily separated along a gradient ordination was used to discriminate between the groups from cluster analysis in ordination space (Fig. 4). Vector 1 separates the three sites forming Gp 1. Groups 2 and 3 are separated on the third vector, largely by differences in numbers of oligochaetes and *Hydra* (Fig 4b). The second vector is more important in discriminating differences within Gp's 2 and 3 where amphipods and ostracods differentiate between the site clusters (Fig. 4a). The correlation between each taxa and the ordination vectors is shown in Table 3.

Table 3. Ordination vector scores for benthic taxa.

Taxon	Vector 1	Vector 2	Vector 3	Corr. Coeff.
Oligochaeta	-0.249 (6)	0.627 (3)	-0.738 (2)	0.829
Ostracoda	-0.614 (4)	0.738 (1)	0.278 (4)	0.820
Pelecypoda	-0.680 (3)	-0.353 (6)	-0.642 (3)	0.506
Hydra	-0.321 (5)	0.485 (4)	0.813 (1)	0.449
Amphipoda	-0.766 (2)	0.639 (2)	-0.066 (6)	0.278
Chironomidae	-0.867 (1)	0.476 (5)	-0.147 (5)	0.136

Relationship with environmental variables

Two approaches were used to determine the relationships between the benthic community and environmental characteristics. Correlation coefficients between the site vector scores and environmental characteristics were determined and discriminant analysis was used to attempt to predict biological site groupings from environmental characteristics.

Table 4. Pearson Correlation Coefficients for 12 Variables significantly (P<0.005) related with community ordination scores.

Variable	Vector 1	Vector 2	Vector 3
Calcium	0.397		
Depth		-0.407	
Iron		-0.392	
Scandium			-0.484
Aluminium			-0.400
Lanthium			-0.400
Potassium			-0.397
Cobalt			-0.381
Nickel			-0.371
Barium			-0.370
Chromium			-0.367
Vanadium			-0.366

Correlation Relationships

The only variable that was significantly ($P<0.005$) related with community ordination scores on Vector 1 was the concentration of calcium (CaO) and only two variables were significantly related with ordination scores on the second vector, water depth and the concentration of total iron (Fe_2O_3). There is a calcium concentration gradient (Table 5) from Gp 3a to Gp 1, with Gp 1 sites having the highest sediment calcium concentration

Table 5. Values of selected variables in groups formed by benthic invertebrates.

Variable	Gp3a	Gp3b	Gp3c	Gp2a	Gp2b	Gp1
Ca	1.6	1.7	2.4	2.6	3.0	3.4
Depth	60.1	175.7	84.8	148.7	95.3	158.7
Fe	4.1	9.5	6.8	6.8	5.8	5.0
Sc	4.2	4.4	4.3	6.9	5.7	4.7
Al	8.8	8.9	12.4	12.3	11.8	10.8
La	21.9	27.5	29.3	35.6	32.2	30.3
K	2.3	2.2	2.2	2.7	2.8	2.4
Co	10.0	13.4	18.3	19.3	15.5	14.7
Ni	27.4	31.8	44.0	47.6	38.4	40.0
Ba	92.0	117.6	145.7	160.7	139.4	143.3
Cr	35.2	36.0	58.7	60.1	49.0	55.0
V	54.5	52.0	71.3	75.4	66.6	58.0

Gp's 3a and 2b which are positively associated with vector 2 are shallow water groups of sites with greater numbers of amphipods and lower iron concentrations. Group 3b is negatively associated with the second vector and has the greatest average water depth and low numbers of organisms. The majority of variables, including several metal concentrations, are correlated with the third vector scores which discriminate within the larger groups 2 and 3 (Fig. 4b). The sites in Gp 3 have generally lower sediment concentrations of metals, *e.g.* Cr, V, Ba, Ni (Table 5) than those in Gp 2, which tend to be in deeper water, further offshore and with finer grained sediments.

Discriminant Analysis

In order to discriminate the relationship between the biological assemblages produced from pattern analysis with the environmental variables multiple discriminant analysis (MDA) was used. The six groups formed from classification analysis on were discriminated using two strategies. First, stepwise discriminant analysis was used to identify which of 35 environmental variables best predicted the biological site groupings (STEP1); second, the 12 variables identified from correlation analysis (Table 4) were used in discriminant analysis (COREL).

The canonical scores from discriminant analysis using the two sets of variables indicates the strength of the relationship between the discriminating variables and the site groupings (Table 6). By plotting the canonical scores for each site the ability of the selected variables to discriminate between the site groups can be determined and the canonical plots are shown for the two variable sets STEP2 and CORREL.

Table 6. Correlations with canonical variables.

STEP var	CAN 1	CAN 2	CAN 3	COREL var	CAN 1	CAN 2	CAN 3
As	0.520	0.251	0.667	Fe_2O_3	-0.323	0.381	0.227
Slt	-0.445	-0.262	0.318	Depth	-0.322	0.612	0.393
NaO	0.256	0.491	0.173	Al_2O_3	0.318	0.552	-0.226
Depth	-0.208	-0.622	0.444	Cr	0.294	0.530	0.004
Fe_2O_3	-0.178	-0.306	0.697	V	0.233	0.458	-0.192
Y	-0.162	-0.065	0.541	Ni	0.204	0.561	-0.010
Cr	0.140	-0.052	0.316	Co	0.192	0.678	-0.038
Sc	-0.138	-0.012	0.261	Ba	0.152	0.560	-0.028
				K_2O_3	0.132	0.335	-0.418
				CaO	0.116	0.151	-0.077
				La	0.095	0.653	-0.141
				Sc	0.060	0.535	-0.230
% Variance	56.7	23.1	10.0		50.3	25.1	12.6

The STEP2 variables (Fig. 5a) are able to distinguish between the sites forming the three groups in Gp 3 on the first and second canonical coefficients as well as the Gp 1 sites, and the first two coefficients account for almost 80% of the variance. The concentration of arsenic and silt content contribute most to the first coefficient and sites that have silty sediments with a high As concentration (20.5μg.g As) score high on CAN1. The variables contributing most on CAN2 are water depth and sodium concentration, with shallow water and high sodium concentration sites scoring high on CAN2. The sites from Gp 2 are poorly discriminated either from each other or from Gp 3 sites by these functions. The use of the third canonical function provided little more discrimination of the sites and only accounted for 10% of the variance (Table 6).

The second variable set (COREL) used the 12 variables correlated with the ordination vectors (Table 4). The first three canonical coefficients explained 88% of the variance (Table 6). The first two functions again discriminated between the sites forming the different groups in Gp 3 and did discriminate to a greater degree between Gps 2 and 3. However, they could not discriminate between Gps 2a and 2b (Fig. 5b), nor were they able to discriminate the Gp 1 sites. The iron concentration (Fe_2O_3), water depth and concentration of aluminium (Al_2O_3) contributed most to the first coefficient, and cobalt and lanthanum to the second canonical function (Table 6). The Gp 3b sites are in the deepest water with the highest iron concentration and the Gp 3c sites have the highest aluminium concentration. Gp3a and Gp2a are discriminated on the second function by cobalt and lanthanum where higher values of the two elements are positively related with CAN2, thus, sites at the top of the plot have high levels of cobalt (19.3μg.g Co). Again the third function explained little of the variance (12.6%) and did not assist in discriminating the site groups (Table 6).

Discriminant analysis was also used to determine whether either of the two sets of variables could predict the biological site classification (Table 7). Both variable sets showed a similar ability to correctly predict the biological classification, 65% and 69% of the sites were correctly predicted to the six groups by STEP and COREL variables, respectively, and 75% and 80% of the sites were correctly predicted to the three groups. The 12 variables were slightly better at predicting and distinguishing between the sites comprising Gp 3, and the 8 variables (STEP) at predicting the Gp 2 sites. This confirms the differentiation between the sites from the canonical scores (Fig. 5). Overall the STEP variables are a slightly better predictor set as fewer variables are required in the discriminant model and as they were derived from a stepwise model are better at accounting for the variance in the biological data. On the other hand the COREL variables which are derived from a correlation analyses may better account for the observed effects in the benthic community.

Table 7. Classification of sites using two variable sets.

Group (n)	STEP (8 var) No. Correct	(%)	COREL (12 var) No. Correct	(%)
1 (3)	3	100.0	2	66.7
2a (26)	17	65.4	17	65.4
2b (10)	7	70.0	6	60.0
2 (36)	29	80.6	27	75.0
3a (8)	5	62.5	6	75.0
3b (8)	3	37.5	6	75.0
3c (3)	3	100.0	3	100.0
3 (19)	14	73.7	15	78.9
Avg. (6 gps)	38	65.5	40	69.0
Avg. (3 gps)	46	79.3	44	75.9
Wilks Lambda (Prob)	0.1282	(0.0001)	0.1516	(0.0075)

DISCUSSION

These data provide the first comprehensive survey of Lake Superior since the 1973 study of Cook (1975). The three earlier whole lake surveys of the benthic community of Lake Superior were conducted in 1871, 1968 and 1973. The earliest survey Smith and Verrill, 1871; Smith,1874) described the lake as having a variable shallow water (55-73 m) community determined by bottom type, and a uniform deep-water fauna that included *Pontoporeia affinis (P. hoyi), Mysis relicta, Pisidium* sp. , *Chironomus* sp., oligochaetes and *Hydra* sp. Adams and Kreger (1969) identified three benthic communities: nearshore, shoal and pelagic. Their nearshore zone extended from 2 - 10 km from the southern shore and was between 60 - 90 m water depth. They described the shoal zone as areas with topographic features typical of shallow water (30 m), such as a sandy substratum. Their third zone they described was the pelagic, which is equivalent to the deep-water zone and incorporates the majority of the lake basin. This pelagic or deep-water zone was described by Adams and Kregear (1969) as being dominated by *Pontoporeia affinis (P. hoyi)*, oligochaetes, chironomids and sphaeriids. The survey described by Cook (1975) is the most extensive to date and included 382 stations. Cook (1975) intuitively defined nine lake zones which have largely been confirmed by subsequent pattern analysis of his data.

A re-analysis of the Cook data using K-means analysis on 382 sites shows that 375 of 382 sites formed 2 clusters (Table 8). The remaining seven sites formed three small clusters characterised by large numbers of amphipods, oligochaetes and particularly nematodes. The community represented by Gp 5 is formed from 66 sites with an average depth of water of 106 m and differs from the deeper water (171 m) Gp 1 sites by greater numbers of amphipods (*Pontoporeia*) and oliogochaetes (largely *Stylodrilus heringianus*) The Gp 5 community occurred mainly in the nearshore and the Gp 1 community in the deeper water central portions and the western shore (Fig. 6a). The major difference between the zones identified by Cook (1975) and those identified by this re-analysis is a modification in their spatial location. For example, Cook described three zones in Duluth Basin, the Apostle Islands and the north-shore of the Keewenaw Peninsula (Zones 1-3, Cook 1975), these now comprise one zone (Fig. 6a - Zone 5a). More important than the spatial adjustments of the nearshore zones described by Cook is the fact that all the nearshore zones are represented by a single type of community.

Table 8. Major Taxa in five clusters formed form 1973 benthic sampling by Cook (1975 - expressed as no. m^2).

Variable	Gp1 n=309	Gp2 n=1	Gp3 n=3	Gp4 n=3	Gp5 n=66
Amphipoda	90	699	1156	296	310
Oligochaeta	66	1588	2956	436	458
Pelecypoda	15	0	522	32	234
Chironomidae	8	0	257	8	40
Water Depth	171				106

A comparison of the re-defined 1973 zones with those established from 1991 data (Fig. 6) suggests little change in the spatial dynamics. The open lake zone is largely unchanged, the 1973 Zone 5a has expanded to the north to include the Duluth Basin. Zone 5e has reduced in size to include just Whitefish Bay and the east side of Michipicoten Island. However, these changes could also be due to a difference in resolution between 382 and 68 stations. Moreover, they indicate that the huge extra effort involved in sampling over 300 more stations provides little extra resolution. There is no suggestion from these data of any significant change in the distribution of the benthic community and no evidence of significant impact, from the benthic community, on the offshore waters of the lake from local pollution sources.

The differences in the numbers of organisms found between 1973 and 1991 are summarised in Table 9. In order to compare the results between surveys data are expressed in terms of abundance per square meter. While there are major differences in the total numbers collected, with much greater numbers being found in 1991, qualitative differences are small. This is particularly noticeable for the sites considered as representing the offshore community, where there is an approximately ten fold increase frm the numbers observed in 1973.

While this may be a real difference the most likely explanation is that the box core used in the 1991 survey is a much more efficient sampling device than the shipek sampler used by Cook. The fact that the proportion of individuals is unchanged suggests that the difference is a sampling artifact. The fact that the spatial pattern in the distribution of the organisms is similar and there is little qualitative difference in the benthic community suggests that the benthic fauna has changed little in the last 18 years and these data, particularly the more quantitative numbers from 1991 can be used as a reference point for future monitoring of Lake Superior and indicate that the Great Lakes Water Quality Agreement ecosystem objective is being met.

Table 9. Comparison of major taxa between 1973 and 1991 (expressed as numbers per m^2)

Taxa	Abundance <100m water depth		Abundance >100m water depth		Offshore Gp	
	1973	1991	1973	1991	1973	1991
Amphipoda	264	1650	105	608	90	907
Oligochaeta	336	786	116	501	66	760
Pelecypoda	226	505	11	104	15	146
Chironomidae	52	255	8	52	8	29

The observed spatial differences in the benthic fauna can largely be explained by physical and chemical characteristics of the environment. Using discriminant analysis the biological classification of the sites was predicted by two different sets of variables (Table 6). Almost 80% of the sites were classified to one of three groups correctly and over 65% of the sites were correctly classified to one of six groups. Of the two predictor variable sets water depth, the concentrations of iron, chromium and scandium were common to both. Dermott (1978) used a similar multivariate approach to examine the 1973 data collected by Cook (1975). Using canonical analysis Dermott found water depth, mean particle size, concentration of iron and redox potential (Eh) to be associated with the major groups of organisms. The fact that with a much greater number of measured variables the same ones appear important suggests there is a real relationship between these variables and the structure of the benthic community, rather than it being a fortuitous correlation, which is a concern with this type of analysis. The importance of water depth in the structuring of the benthic community has been well documented (Berg, 1938; Brinkhurst, 1974; Rawson, 1930; Welch,1935) through the role of water depth in determining temperature and thus growth and reproduction, as well as controlling the physical structure of the sediment substrate. The role of sediment particle size distribution particularly on burrowing organisms is also documented (Cole and Wegmann, 1983; Culp *et al.*, 1983; McCall, 1979). The manner in which the iron concentration and other major and trace elements effect the community is not as clearly understood, but could be through the microbial cycle.

The value of the benthic community for monitoring ecosystem integrity is well established (Reynoldson, 1985; Wiederholm, 1980; Wright *et al.*, 1988)). Through the Great Lakes Water Quality Agreement benthic community structure was identified as an appropriate indicator for Lake Superior and an ecosystem objective established for the benthic community of the lake based on densities of *P. hoyi.* However, no implementation of a monitoring programme for the objective has yet been established. These data provide a basis for the establishment of such a programme, both for the identification of sampling sites and the determination of expected numbers at given sites based on environmental characteristics. The following considerations must be made when selecting a long term monitoring strategy:

1. The offshore zone is geographically well defined and encompasses a large portion of the lake but CANNOT be standardized based on distance from shore or water depth of water. The average water depth for this zone is 148.7 m but ranges between 33 m and 262 m and incorporates features other than water depth in determining its extent. Because of its general uniformity a relatively few stations should suffice in describing this area. Using Elliott's (1977) method for determining an appropriate n where:

n= required number of sample sites
s= standard deviation
x= sample arithmetic mean
D= desired standard error

$$n=\frac{s^2}{D^2x^2}$$

As the monitoring will be used to determine trends in the amphipod populations those data from the 1991 survey for the offshore zone were used to determine an appropriate number of sites for various required standard errors:

Desired Standard Error	Required number of sites
25%	15
50%	7
75%	3

100%	1

Detection of a change of 50% in amphipod numbers will be more than sufficient resolution as an objective for a monitoring programme and therefore seven stations in the offshore zone are sufficient. These should be randomly selected from the 21 sites comprising the offshore zone and sampled once annually for 5 years to detect normal year to year variation. A reduced frequency may then be considered.

2. The nearshore zones are spatially distinct and more variable, five distinct geographical nearshore zones were defined (Fig. 3) that were similar to those identified from the 1973 data (Fig. 6a) and are therefore considered robust. In order to determine an appropriate number of sites for each zone, the same approach was used. The mean and variance used was that obtained for the amphipods from the sites in the Gp 3 community in the same zone for which a number of sampling sites was determined: the following number of sites are proposed in the various nearshore zones to detect a 50% change in the numbers of amphipods:

Zone	No. of Sites
A	11
B	4
D	1
E	1

F 3

As in the offshore these should be randomly selected from either existing sites or newly located stations and should be sampled annually for five years at which time an estimate of annual variation and a revised schedule may be devised.

Conclusion

Data presented in this report demonstrate:

1. That the current ecosystem objective for *Pontoporeia hoyi* is being met in Lake Superior.

2. That there has been little change in the benthic community over the past 18 years.

3. That there is a strong relationship between the benthic community and environmental characteristics and that the structure of the benthic community can be predicted from a few environmental measurements.

4. That a comprehensive monitoring network for the Lake Superior ecosystem objective can be assured with relatively few sites, seven in the offshore and twenty in the nearshore zones.

References

Adams, C.E. and R.D. Kregear. 1969. Sedimentary and faunal environments of eastern Lake Superior. *Proc. 12th Conf. Great Lakes Res. 1969*:1-20.

Belbin, L. (in press). SSH: Semi-strong hybrid scaling. Classification Soceity.

Berg, K. 1938. Studies on the bottom animals of Esrom Lake. *K. danske Vidensk. Selsk. Naturv. Math. Afd.* 8:1-255.

Brinkhurst, R.O. 1974. *The Benthos of Lakes.* MacMillan Press, London. 190pp.

Cole, R.A. and D.L. Weigmann. 1983. Relationships among zoobenthos, sediments, and organic matter in littoral zones of western Lake Erie and Saginaw Bay. *J.Great Lakes Res.* 9:568-581.

Culp, J.M., S.J. Walde and R.W. Davies. 1983. Relative importance of substrate particle size and detritus to stream benthic macroinvertebrate microdistribution. *Can. J. Fish. Aquat. Sci.* 40:1568-1574.

Cook, D.G. 1975. A preliminary report on the benthic macroinvertebrates of Lake Superior. *Environment Canada. Fisheries and Marine Service. Tech. Rep.* 572. 41pp.

Dermott, R. 1978. Benthic diversity and substrate-fauna associations in Lake Superior. *J. Great Lakes Res.* 4:505-512.

Duncan, G.A. and G.G. LaHaie. 1979. Size analysis procedures used in the sedimentology laboratory, NWRI. *CCIW, Hydraulics Division Manual,* September, 1979.

McCall, P.L. 1979. The effects of deposit feeding oligochaetes on particle size and settling velocity of Lake Erie sediments. *J. Sed. Petrol.* 49:813-818.

Mudroch, A. 1985. Geochemistry of the Detroit River sediments. *J. Great Lakes Res.* 11:193-200.

Rawson, D.S. 1930. The bottom fauna of Lake Simcoe and its role in the ecology of the lake. *Univ. Toronto Stud. Biol., Publ. Ont. Fish. Res. Lab.* 34:1-183.

Reynoldson, T.B. 1985. The utility of benthic invertebrates in water quality monitoring. *Wat. Qual. Bull.* 10:21-27.

Smith, S.I. 1874. Sketch of the invertebrate fauna of Lake Superior. *Rep. U.S. Comm. Fish 1872-73*:690-707.

Smith, S.I. and A.E. Verrill. 1871. Notice of the invertebrate dredged in Lake Superior in 1871, by the U.S. Lake Survey, under the direction of Gen, C.B. Comstock, S.I. Smith, naturalist. *Am. J. Sci.* 2:448-454.

Welch, P.S. 1935. *Limnology.* McGraw-Hill Book Co., New York-London. 471 pp.

Wiederholm, T. 1980. Use of benthos in lake monitoring. *J. Water Poll.Control Fed.* 52:537-547.

Wright, J.F., P.D. Armitage, M.T. Furse and D. Moss. 1988. A new approach to the biological surveillance of river quality using macroinvertebrates. *Verh. Internat. Verein. Limnol.* 23:1548-1552.

APPENDIX

Range of Values for Measured Variables

Variable	Min	Max	1	2a	2b	3a	3b	3c
Depth (m)	12.8	276	158.7	148.7	101.6	58.7	168.1	70.3
SiO_2 (%)	41.1	92.5	65.3	60.5	65.5	75.8	67.12	62.27
TiO_2 (%)	0.08	1.10	0.45	0.64	0.66	0.55	0.50	0.58
Al_2O_3 (%)	1.9	15.4	10.8	12.32	11.77	8.75	8.89	12.38
Fe_2O_3 (%)	0.9	17.2	5.0	6.80	5.75	4.14	9.50	6.84
MnO (%)	0.01	1.02	0.25	0.26	0.21	0.12	0.40	0.30
MgO (%)	0.2	5.0	2.40	2.61	2.27	1.54	2.76	2.40
CaO (%)	0.2	17.8	3.40	2.55	3.04	1.81	1.74	2.44
Na_2O (%)	0.26	3.03	1.24	1.58	1.77	1.50	1.08	2.26
K_2O (%)	0.14	3.32	2.42	2.73	2.75	2.35	2.17	2.25
P_2O_5 (%)	0.01	0.47	0.09	0.23	0.18	0.10	0.15	0.22
LOI (%)	0.2	19.7	8.2	9.03	6.84	3.46	5.29	8.64
TN µg.g	107	4006	1497	1937	1412	747	1304	2686
TP µg.g	0.5	2176	328	1068	995	595	949	1032
TOC µg.g	0.07	3.57	1.31	2.01	1.55	0.85	1.16	2.62
Sc µg.g	2.5	10.0	4.7	6.92	5.70	4.19	4.44	4.33
V µg.g	10.0	109.0	58.0	75.42	66.6	54.5	52.0	71.33
Cr µg.g	5.0	90.0	55.0	60.07	49.00	35.2	36.00	58.67
Co µg.g	1.0	27.0	14.7	19.31	15.50	10.00	13.38	18.33
Ni µg.g	3.0	70.0	40.0	47.58	38.40	27.38	31.75	44.00
Cu µg.g	2.0	342.0	73.7	122.96	69.60	38.25	71.12	96.33
Zn µg.g	13.0	274.0	108.0	154.81	119.10	81.25	108.50	179.33
As µg.g	2.5	49.0	2.5	4.76	2.50	4.56	4.44	20.5
Sr µg.g	7.0	100.0	41.3	40.00	33.50	24.50	36.38	34.33
Y µg.g	3.0	20.0	11.7	15.6	14.4	10.0	13.12	13.00
Mo µg.g	0.5	8.0	4.0	3.3	3.0	2.8	2.7	3.0
Ag µg.g	0.1	0.9	0.13	0.3	0.2	0.2	0.2	0.4
Cd µg.g	0.1	3.6	1.1	1.5	1.4	0.8	1.2	2.5
Ba µg.g	35.0	267.0	143.3	160.7	139.4	92.0	117.6	145.7
La µg.g	7.0	49.0	30.3	35.6	32.2	21.9	27.5	29.3
Pb µg.g	1.0	132.0	41.7	62.4	39.9	23.6	35.2	69.7
Gravel (%)	0	40.2	0	0.8	4.0	1.3	0	0
Sand (%)	0.2	100.0	7.1	14.5	25.5	52.4	27.8	4.8
Silt (%)	0.0	70.2	45.7	27.0	22.7	20.2	29.1	53.0
Clay (%)	0.0	80.14	47.2	57.6	47.8	26.2	43.1	42.2

FIELD ID.	Silica (SiO_2) %	Titanium (TiO_2) %	Alumina (Al_2O_3) %	Total Iron (Fe_2O_3) %	Manganese (MnO) %	Magnesium (MgO) %	Calcium (CaO) %	Sodium (Na_2O) %	Potassium (K_2O) %	Phosphorou (P_2O_5) %	L.O.I. %	Whole rock Total %	Total Nitrogen PPM	Total Phosphorus PPM	TOC PPM	Aluminum PCT
Station 1																
Station 2																
Station 3																
Station 6																
Station 8	71.85	0.59	11.13	4.8	0.09	1.77	1.59	1.71	2.55	0.08	3.32	99.47	180	516	0.22	2.57
Station 11	76.31	0.34	10.68	2.91	0.009	1.21	1.95	3.03	2.03	0.11	2.05	100.71	354	530	0.35	1.08
Station 12	65.99	0.54	10.23	6.44	0.22	1.83	1.2	1.11	2.27	0.38	9.48	99.7	2700	1688	2.69	2.57
Station 17	92.52	0.11	3.42	0.93	0.01	0.22	0.44	0.59	0.97	0.005	0.19	99.41	107	6	0.07	0.35
Station 22	67.7	0.46	10.2	4.63	0.11	1.68	1.09	1.12	2.63	0.1	10.05	99.77	402	1437	0.85	1.37
Station 23	78.32	0.3	8.7	3.38	0.05	1.28	0.84	1.05	2.5	0.07	3.62	100.11	491	600	0.41	2.2
Station 25	79.54	0.28	6.75	3.98	0.1	0.91	0.86	0.96	1.82	0.37	4.07	99.65	402	1437	0.85	1.37
Station 28	53.17	0.55	10.14	4.37	0.15	3.41	9.03	1.08	2.67	0.18	14.21	98.96				
Station 30	59.54	0.63	12.22	5.81	0.1	2.22	1.62	1.52	2.5	0.32	12.02	98.51	1159	1004	3.57	2.97
Station 31	63.52	0.49	11.62	7.03	0.47	1.87	2.26	2.42	2.18	0.29	8.56	100.71	2764	948	2.66	1.89
Station 34	64.73	0.56	12.26	5.23	0.18	1.92	1.94	2.09	2.42	0.2	8.2	99.72	2635	1465	2.29	2.56
Station 35	67.39	0.51	12.22	4.55	0.15	1.73	2.29	2.59	2.22	0.17	6.97	100.78	2555	823	2.12	1.9
Station 39	74.61	0.54	10.12	3.75	0.08	1.34	1.6	1.9	2.76	0.14	3.4	100.24	204	865	0.64	1.65
Station 43	55.14	0.68	14.42	7.21	0.63	2.84	1.61	1.4	3.1	0.16	12.34	99.54	4006	558	3.43	3.71
Station 50	85.32	0.3	5.91	1.66	0.09	0.38	0.27	0.26	3.32	0.08	1.41	99	454	335	0.38	0.6
Station 51	90.2	0.19	4.32	1.29	0.02	0.22	0.24	0.38	2.6	0.05	0.39	99.89	110	0.5	0.09	0.42
Station 62	62.87	1.02	13.04	6.67	0.13	2.44	1.7	1.67	2.69	0.18	7.74	100.16	2114	851	1.88	3.06
Station 68	59.61	0.94	12.72	7.59	0.15	2.68	1.68	1.41	2.8	0.27	9.81	99.67	2988	1297	2.54	3.06
Station 69	57.53	1.01	12.29	7.97	0.17	2.87	1.9	1.56	2.66	0.17	10.83	98.97	2856	1116	3.08	3.07
Station 70	87.7	0.49	5.29	1.42	0.06	0.23	0.24	0.47	3.29	0.03	0.53	99.75	166	140	0.15	0.39
Station 84	48.17	0.56	14.72	6.84	0.1	4.14	8.16	1.72	3.18	0.12	12.14	99.85	378	419	0.42	4.18
Station 84A	41.08	0.37	8.71	2.93	0.06	5.02	17.76	1.61	2.01	0.08	19.73	99.38	179	600	0.09	1.59
Station 89	60.24	0.45	10.43	3.39	0.1	3.79	5.25	2.15	2.59	0.1	10.61	99.05	1167	1214	1.82	1.33
Station 92	64.35	0.57	13.43	6.22	0.12	1.92	1.89	2.2	3.19	0.18	5.65	99.71	1481	1046	1.21	2.48
Station 95	54.09	0.6	14.93	7.26	0.35	2.88	1.71	1.54	3.25	0.25	11.75	98.6	3525	474	3.2	4.11
Station 95A	60.52	0.6	14.16	6.03	0.13	2.35	1.86	1.96	3.25	0.17	8.33	99.37	2102	628	2.22	3.28
Station 100	65.93	0.57	12.67	4.66	0.12	1.81	2.04	2.31	2.89	0.17	6.73	99.9	1100	949	2.06	2.11
Station 101	69.29	0.47	12.4	3.92	0.08	1.48	2.07	2.68	2.72	0.18	3.56	98.85	836	879	0.81	1.65
Station 102	56.91	0.63	13.94	7.09	0.54	2.56	1.79	1.61	3.06	0.31	11.12	88.56	3265	1953	3.06	3.66
Station 105	61.2	0.64	13.3	5.99	0.14	2.43	2.09	2	2.93	0.19	8.77	99.67	2371	990	2.52	3.21
Station 106	56.42	0.6	13.79	7.28	0.45	2.65	1.82	1.68	3.06	0.47	10.51	98.73	2959	2023	2.67	4.09
Station 113	54.65	0.62	15.35	7.35	0.28	2.89	1.67	1.63	3.25	0.3	11.57	99.57	2978	1325	3.03	4.14
Station 121	57.94	1.1	11.12	6.34	0.13	2.38	2.33	2.09	2.05	0.09	3.19	99.39	331	572	0.46	2.36
Station 125	68.56	0.63	15.11	6.82	0.14	2.71	1.62	1.52	3.23	0.2	9.84	99.76	2454	781	2.55	4.37
Station 127	50.04	0.63	14.85	7.3	0.11	3.48	6.46	1.71	3.19	0.11	10.86	98.74	708	656	0.87	4.13
Station 130	63.1	0.88	13.74	7.69	0.13	3.28	2.09	1.91	2.94	0.13	4.95	100.85	441	670	0.47	3.41
Station 133	54.87	0.62	14.12	8.02	0.76	2.88	2.03	1.71	3	0.44	10.5	98.95	2810	2176	2.6	3.79
Station 135	61.29	1.09	11.96	8.09	0.14	4.27	4.29	2.03	2.2	0.11	3.61	99.07	419	711	0.44	2.47
Station 136	57.08	0.67	13.41	7.23	0.34	3.04	2.4	1.81	2.68	0.24	10	98.89	3101	1228	2.76	3.31
Station 137	63.91	0.99	13.31	7.74	0.09	2.94	2.08	1.87	2.54	0.08	3.37	98.93	381	488	0.29	2.57
Station 138	54.9	0.64	13.77	8.86	0.52	3.33	2.11	1.59	2.71	0.27	11.72	100.43	3315	1507	3.2	3.73
Station 139	55.9	0.73	13.3	8.95	0.29	3.6	2.76	1.76	2.36	0.19	10.39	100.23	2741	1325	3.08	3.4
Station 140	57.18	0.62	13.3	7.9	0.51	2.95	2.04	1.72	2.64	0.35	11.33	100.54	3488	1562	3.01	3.37
Station 149	55.96	0.62	13.94	8.54	0.7	2.95	1.92	1.64	2.81	0.45	11.33	100.86	2786	1953	2.96	3.59
Station 152	54.78	0.67	14.64	7.5	0.3	2.97	1.89	1.77	3.07	0.28	10.4	98.27	2763	1214	2.57	4.2
Station 155	72.74	0.8	9.73	5.67	0.07	1.59	1.64	2	2.41	0.11	2.66	99.43	515	530	0.5	1.69
Station 157	53.76	0.66	14.65	7.48	0.26	2.89	1.67	1.47	3.05	0.29	12.17	98.34	2762	921	3.19	4.31
Station 164	83.37	0.6	6.89	2.61	0.04	0.6	0.98	1.14	2.65	0.04	0.82	99.74	171	265	0.15	0.84
Station 165	88.61	0.51	3.97	2.47	0.03	0.37	0.58	0.53	1.79	0.02	0.54	99.42	162	195	0.1	0.43
Station 169	54.02	0.63	14.89	7.66	0.51	2.94	1.67	1.5	3.29	0.33	11.76	99.2	2923	1869	3.07	4.02
Station 171	54.92	0.88	16.21	8.11	0.1	3.27	1.67	1.53	3.48	0.13	8.94	99.04	1639	879	1.39	5.28
Station 177	62.85	0.81	12.72	7.1	0.12	2.4	2.42	2.2	3.08	0.1	5.48	99.28	1280	725	0.37	2.75
Station 180	59.01	0.34	7.18	16.75	0.74	4.54	2.45	0.75	1.2	0.26	6.62	99.85	1267	1576	1.81	2.19
Station 185																
Station 187																
Station 189	56.24	0.66	12.68	8.43	0.56	2.63	1.57	1.23	2.63	0.36	11.72	98.72	3655	460	3.24	3.59
Station 192	77.72	0.95	8.65	3.82	0.13	0.9	1.38	1.85	2.14	0.08	2.13	99.75	368	753	0.42	1.34
Station 193																
Station 196	73.35	0.88	10.03	4.28	0.07	1.3	1.16	1.64	2.45	0.04	4.33	99.54	961	265	1.18	1.75
Station 201	59.53	0.36	7.43	15.94	0.73	4.26	2.25	0.68	1.27	0.25	6.63	99.34	1698	1507	1.79	2.2
Station 203	71.64	0.08	1.96	16.91	0.83	4.09	2.48	0.31	0.14	<0.01	0.89	99.33	381	656	0.28	0.52
Station 207	59.43	0.34	6.66	17.2	1.02	4.46	2.33	0.63	1.12	0.29	5.86	99.35	1326	1786	1.39	2.02
Station 212	91.19	0.14	3.99	1.05	0.02	0.23	0.26	0.32	2.41	<0.01	0.49	100.12	148	112	0.11	0.35
Station 218	60.63	0.85	12.26	8.3	0.35	2.61	11.72	1.25	2.63	0.25	8.66	99.51	1511	990	2.17	2.91

Total Iron PCT	Manganese PPM	Magnesium PCT	Calcium PCT	Sodium PCT	Potassium PCT	Scandium PPM	Vanadium PPM	Chromium PPM	Cobalt PPM	Nickel PPM	Copper PPM	Zinc PPM	Arsenic PPM	Strontium PPM	Yttrium PPM	Molybdenun PPM	Silver PPM
3.39	698	1.13	0.79	0.15	0.53	6	61	48	13	33	22	68	2.5	35	13	1	0.1
1.69	734	0.54	0.56	0.12	0.15	2.5	35	26	7	20	19	42	2.5	31	7	3	0.1
4.88	2064	1.22	0.77	0.1	0.41	6	63	46	18	39	146	141	2.5	28	15	2	0.4
0.61	83	0.1	0.19	0.11	0.13	2.5	13	6	1	3	2	15	2.5	15	3	3	0.1
3.25	969	0.55	0.45	0.09	0.25	2.5	56	42	14	34	116	123	8	27	14	2	0.3
2.46	458	0.81	0.49	0.11	0.47	2.5	42	37	10	27	30	64	2.5	24	9	0.5	0.1
3.25	969	0.55	0.45	0.09	0.25	2.5	39	25	9	23	48	59	2.5	20	9	2	0.4
4.18	899	1.45	0.92	0.11	0.44	7	79	56	18	48	201	193	2.5	33	18	2	0.6
4.95	4324	1.05	0.87	0.1	0.25	2.5	57	45	19	41	107	158	49	33	12	4	0.3
3.78	1669	1.2	0.88	0.11	0.4	6	67	53	16	41	111	138	2.5	35	16	3	0.4
3.02	1297	0.95	0.8	0.1	0.26	2.5	55	45	14	34	96	127	10	31	13	1	0.2
2.74	647	0.78	0.66	0.12	0.27	2.5	49	29	10	25	31	71	2.5	30	13	3	0.1
4.86	5686	1.81	1.01	0.11	0.47	2.5	80	69	23	60	174	186	2.5	36	19	3	0.2
1.2	846	0.18	0.17	0.07	0.21	2.5	17	8	5	8	25	27	2.5	9	6	1	0.1
0.91	100	0.1	0.11	0.09	0.23	2.5	17	7	2	4	3	13	6	9	5	2	0.1
4.71	1103	1.68	1.07	0.1	0.48	8	86	57	21	56	140	145	2.5	34	20	2	0.5
5.63	1290	1.83	1.1	0.09	0.42	8	95	55	23	51	195	160	2.5	32	20	5	0.6
5.88	1468	1.94	1.17	0.1	0.39	9	106	56	24	55	342	212	11	32	20	3	0.9
0.92	486	0.09	0.13	0.08	0.19	2.5	23	8	4	7	21	20	6	7	7	2	0.2
4.85	848	2.93	6.7	0.15	0.87	9	81	90	20	57	45	123	2.5	73	13	6	0.1
2	501	3.74	15.25	0.13	0.3	2.5	36	36	6	26	19	46	2.5	100	9	8	0.1
2.1	850	2.64	3.73	0.09	0.24	2.5	38	37	7	24	47	96	2.5	32	10	6	0.1
3.47	1063	1.17	0.84	0.1	0.43	7	59	55	16	39	54	105	2.5	34	15	2	0.2
5.17	3317	1.93	1.08	0.12	0.75	9	83	61	24	59	164	195	2.5	42	18	1	0.3
4.38	1276	1.55	0.98	0.12	0.57	8	75	67	19	50	94	143	9	39	18	5	0.3
3.07	961	1.03	0.84	0.1	0.36	6	55	51	13	34	89	137	2.5	32	13	3	0.2
2.53	661	0.83	0.71	0.1	0.27	2.5	45	43	11	28	28	66	2.5	27	11	3	0.1
5.27	5230	1.74	1.1	0.12	0.65	9	82	76	23	58	179	225	2.5	43	18	5	0.1
4.5	1368	1.64	1.12	0.13	0.54	8	81	73	20	54	138	191	8	42	17	5	0.4
6.11	5022	2.02	1.2	0.15	0.72	10	92	87	27	63	139	204	8	47	19	4	0.1
5.34	2607	1.95	1.05	0.12	0.74	9	83	83	24	66	130	183	2.5	41	18	3	0.2
4.66	1162	1.73	1.34	0.11	0.22	7	92	53	24	65	236	89	2.5	37	15	4	0.9
5.38	1383	1.98	1.08	0.14	0.82	10	88	84	24	58	100	274	2.5	44	19	5	0.4
5.27	980	2.42	5.27	0.15	0.84	10	82	86	22	60	63	145	2.5	68	16	8	0.1
4.91	1003	1.95	0.96	0.16	0.65	8	102	68	22	54	49	116	2.5	38	13	0.5	0.1
5.98	7454	1.92	1.18	0.14	0.68	9	84	80	25	59	108	166	2.5	46	17	3	0.1
4.37	880	1.67	1.25	0.19	0.39	6	109	68	21	70	48	94	2.5	37	11	4	0.3
4.97	3115	1.79	1.16	0.16	0.55	8	83	69	21	54	133	199	2.5	42	15	2	0.5
4.6	667	1.35	0.71	0.14	0.37	6	101	57	20	56	36	111	2.5	23	10	2	0.3
6.31	4897	2.07	1.12	0.17	0.62	9	102	88	24	62	111	269	10	40	15	6	0.6
6.19	2470	2	1.23	0.21	0.47	8	102	86	22	57	86	253	2.5	39	14	4	0.7
5.57	4657	1.8	1.09	0.15	0.56	8	84	72	23	57	147	224	7	40	15	2	0.3
5.83	6200	1.83	1.09	0.14	0.61	9	81	71	23	54	142	195	2.5	42	16	4	0.1
5.72	2908	2.07	1.18	0.15	0.74	10	93	86	26	68	117	185	2.5	44	19	4	0.3
3.73	558	0.74	0.73	0.15	0.31	2.5	74	32	12	24	31	74	11	24	14	3	0.2
5.71	2485	2.06	1.12	0.13	0.76	10	89	84	26	61	152	202	2.5	43	20	1	0.3
1.68	274	0.27	0.47	0.11	0.19	2.5	42	18	6	12	37	27	2.5	21	8	2	0.2
1.61	171	0.13	0.28	0.09	0.15	2.5	40	12	3	6	7	28	2.5	12	6	2	0.1
5.39	4568	1.88	1.02	0.12	0.73	9	82	78	24	56	117	171	2.5	41	18	3	0.2
6.36	974	2.52	1.23	0.15	1.03	12	106	104	30	75	97	189	2.5	51	20	2	0.2
4.73	893	1.28	1.1	0.17	0.37	6	78	40	15	41	66	139	2.5	49	20	3	0.2
5.56	2218	1.44	1.08	0.12	0.32	2.5	49	32	14	28	98	157	17	56	14	4	0.1
5.99	5023	1.71	1.03	0.12	0.6	8	82	61	22	53	168	219	2.5	40	18	3	0.3
2.57	1109	0.5	0.72	0.1	0.24	2.5	64	25	8	19	26	52	8	28	16	2	0.4
2.83	487	0.73	0.59	0.09	0.28	2.5	59	29	10	24	42	89	2.5	23	17	2	0.4
5.45	2454	1.38	1	0.11	0.32	2.5	50	31	15	27	93	159	11	51	14	3	0.4
3.02	835	0.41	0.53	0.08	0.08	2.5	10	6	5	5	16	22	6	30	4	3	0.1
5.67	4754	1.32	1.02	0.11	0.29	2.5	44	26	13	25	73	136	2.5	55	13	5	0.1
0.7	178	0.09	0.12	0.08	0.18	2.5	14	5	2	4	3	15	2.5	7	7	0.5	0.1
5.16	2815	1.47	0.93	0.12	0.42	7	76	44	19	43	66	169	2.5	36	17	3	0.3

Cadium	Barium	Lanthanum	Lead	Particle Size Distribution			
PPM	PPM	PPM	PPM	% Gravel	% Sand	% Silt	% Clay
				0	99.21	0.4	0.39
				0	55.89	29.05	15.06
				0	98.59	0.71	0.7
				0	89.39	5.31	5.3
0.9	149	33	17	2.14	69.13	5.54	23.2
0.2	56	17	1	0	9.47	44.73	45.8
2	166	31	74	0	8.13	33.35	58.52
0.1	35	9	1	0	15.34	48.86	35.8
0.1	126	30	61	0	20.16	15.11	64.73
0.2	126	24	11	0	98.15	0.93	0.92
1.4	124	20	17				
				0	73.57	12.16	14.27
2.9	158	37	111	0	1.66	32.95	65.39
3.4	143	28	82	0	8.33	64.1	27.58
1.8	145	39	73	0	12.39	35.95	51.66
1.5	93	29	73	0	4.74	60.31	34.94
0.1	95	25	10	0	67.09	10.05	22.86
2	170	41	95	0	1.24	18.06	80.7
1.8	54	15	1	0	76.94	12.52	10.54
0.3	44	12	1	0	99.92	0.04	0.04
0.3	138	37	55	0	1.89	47.06	51.05
1.7	149	37	57	0	3.57	34.71	61.72
2.3	149	35	94	0	2.44	55.67	41.88
1.4	48	14	1	0	99.71	0.15	0.14
1.1	225	41	29	0	4.72	70.15	25.13
0.1	82	23	5	0	3.16	52.43	44.41
1.8	73	25	37	0	2.43	7.16	90.14
1.3	138	37	31	0	1.9	42.83	55.27
1.4	194	44	91	0	0.46	15.06	84.48
0.8	175	43	50	0	1.15	27.92	70.93
1.8	103	34	71	0	4.98	42.6	52.42
0.8	83	28	10	0	29.73	37.82	32.46
3	183	44	132	0	0.22	23	76.78
0.9	151	42	102	0	5.81	38.56	55.63
2	245	49	88	0	1.76	20.58	77.66
1.2	215	46	70	0	0.64	28.88	70.48
0.4	63	21	21	0	30.8	52.05	17.15
1	227	47	52	0	5.16	16.04	78.8
2.1	228	48	39	0	9.58	9.83	80.59
1.3	196	36	30	40.18	59.08	0.37	0.37
1.1	239	43	55	0	1.26	20.8	77.94
0.1	126	28	22	10.28	58.99	10.79	19.94
1.5	172	38	108	0	1.35	35.62	63.03
0.7	105	25	17	15.37	51.49	14.14	18.99
3.2	267	39	85	0	0.49	20.07	79.45
2.7	201	31	54	0	1.44	34.55	64.01
2.5	210	37	113	0	0.16	20.48	79.36
1.8	212	38	84	0	0.85	18.95	80.21
2.2	231	48	62	0	1.38	15.43	83.19
0.4	79	25	9	2.27	37.25	19.41	41.07
1.3	224	47	83	0	11.35	50.67	37.98
0.6	47	15	1	0	98.29	1.36	1.35
0.1	37	12	1	0	99.54	0.23	0.23
0.3	212	44	62	0	1.2	13.7	85.1
1.4	264	55	57				
1.6	120	44	33	0	19.8	37.76	42.44
3	140	25	58	0	0.59	26.1	73.31
				0	100	0	0
3.6	215	36	113	0	3.41	19.39	77.2
0.7	65	22	7	0	45.43	43.11	11.46
1.6	83	27	25	0	10.83	53.07	36.11
1.7	126	25	63	0	1.03	27.9	71.07
0.8	38	7	1	0	0.54	58.43	41.02
2.4	130	23	48	0	0.74	31.51	67.75
0.1	38	11	1	0	100	0	0
1.8	174	32	46	0	0.85	42.26	56.89

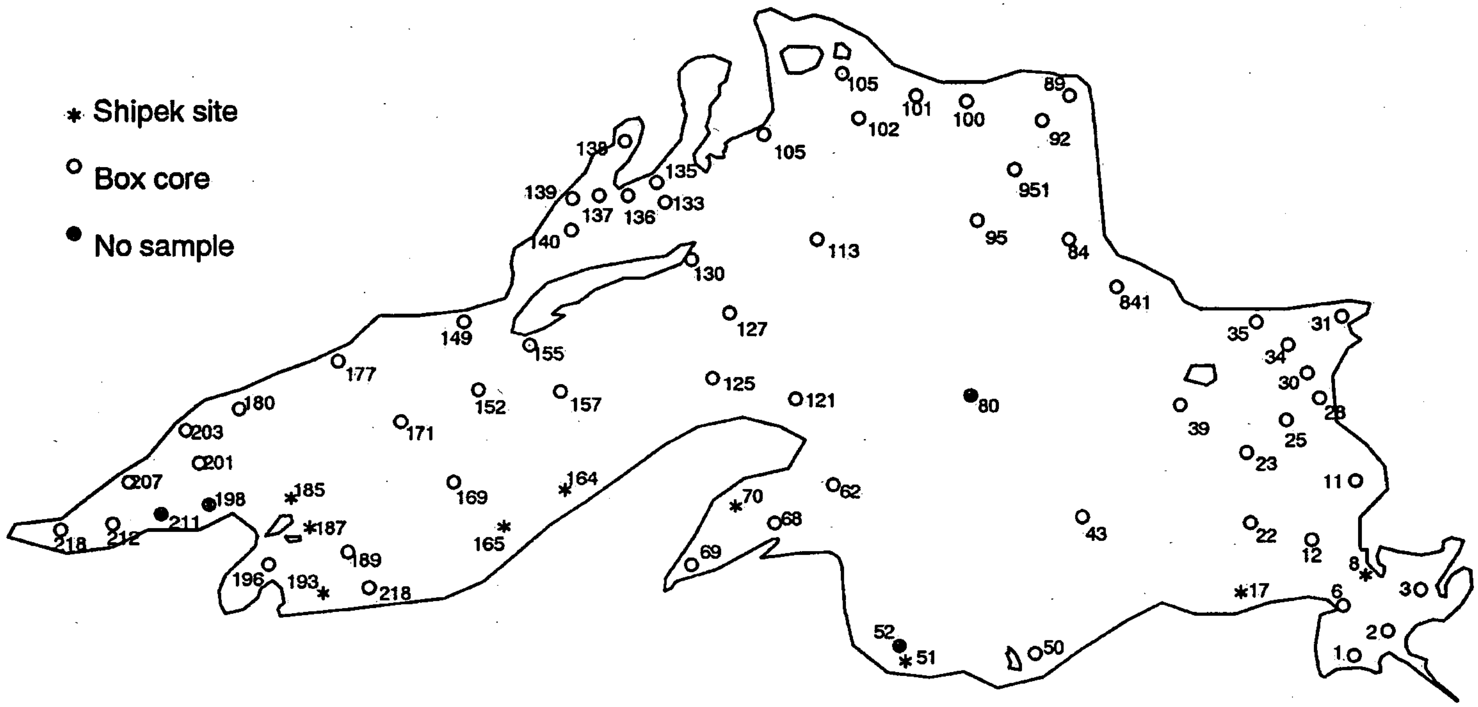


Fig. 1 Sampling Sites in Lake Superior (1991)

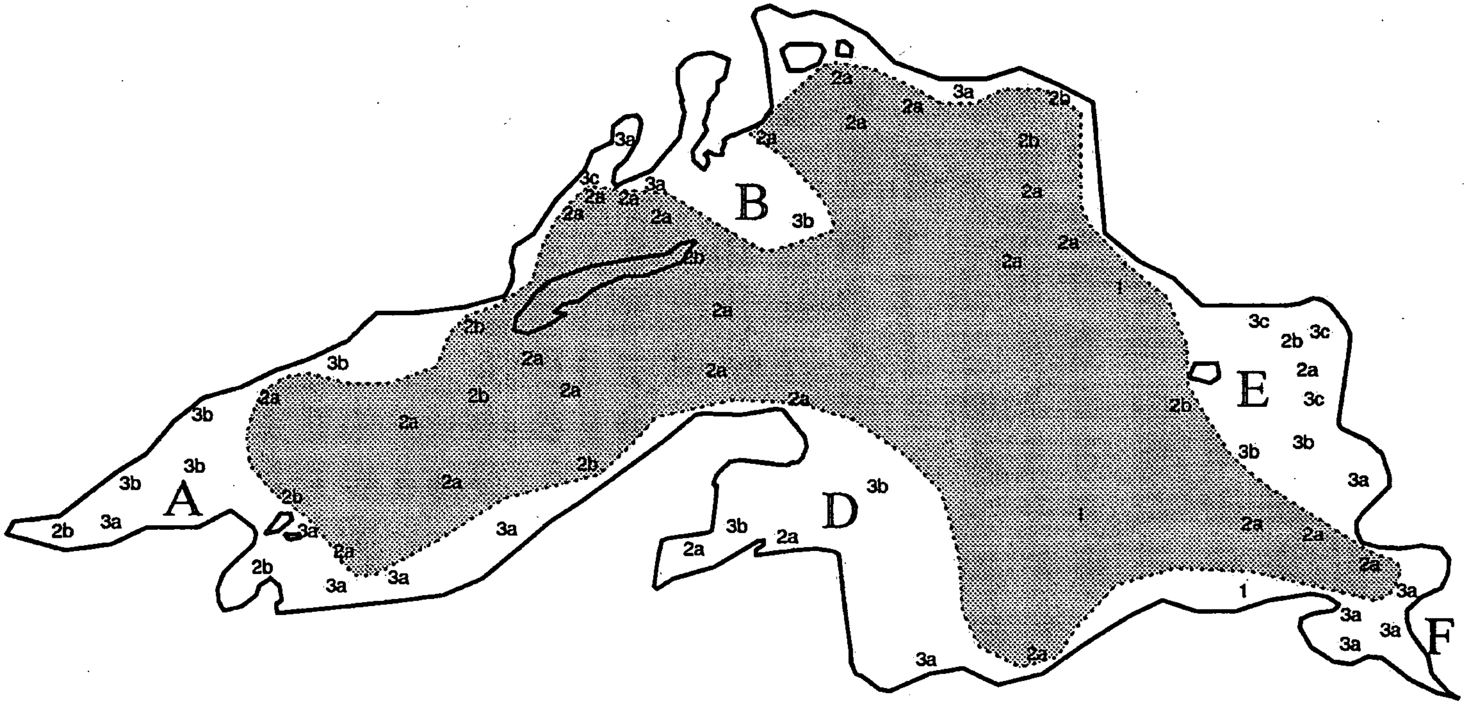


Fig. 3 Lake Superior Zones defined by classification analysis of the benthic community

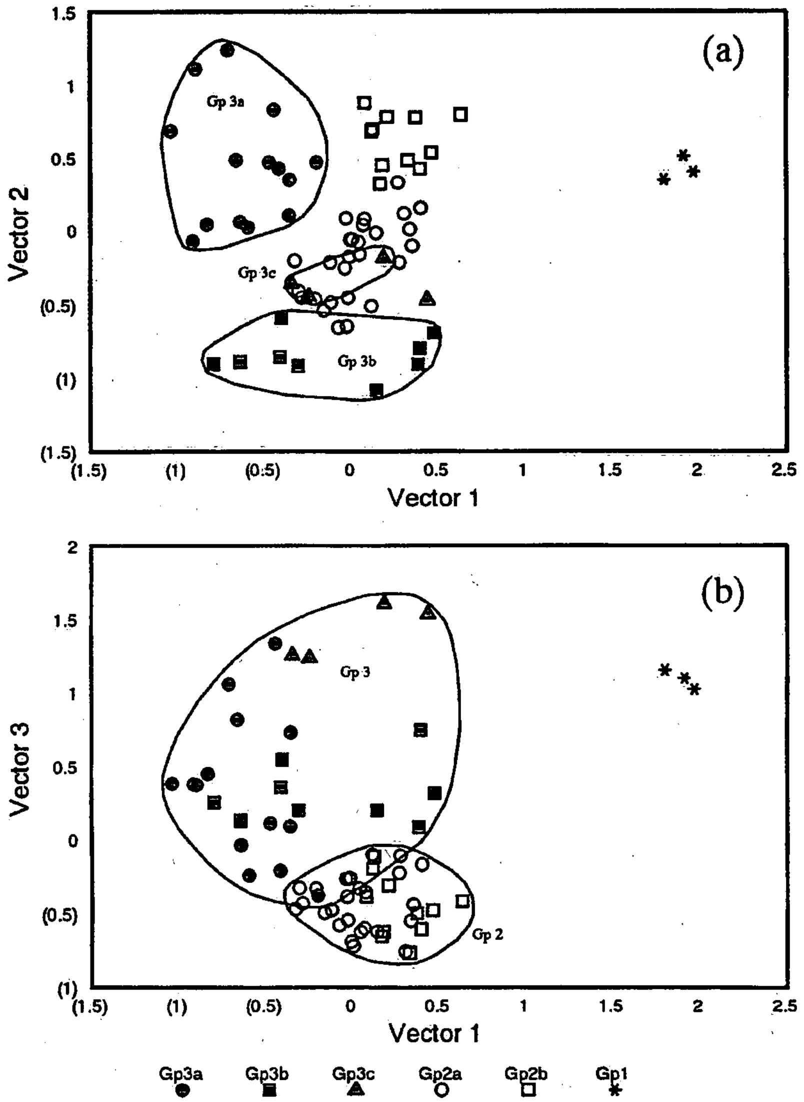


Fig. 4 Ordination of benthic community in Lake Superior

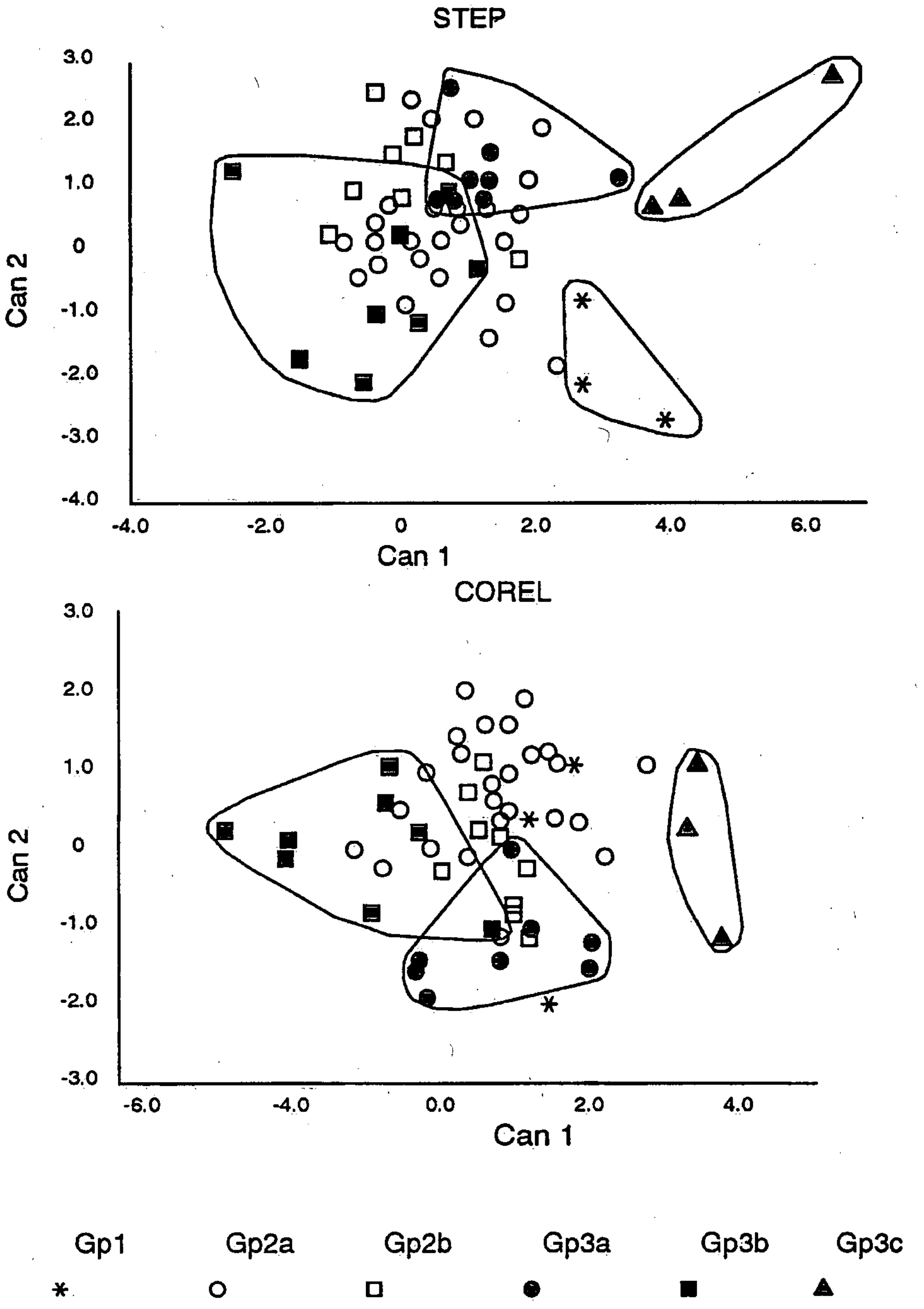
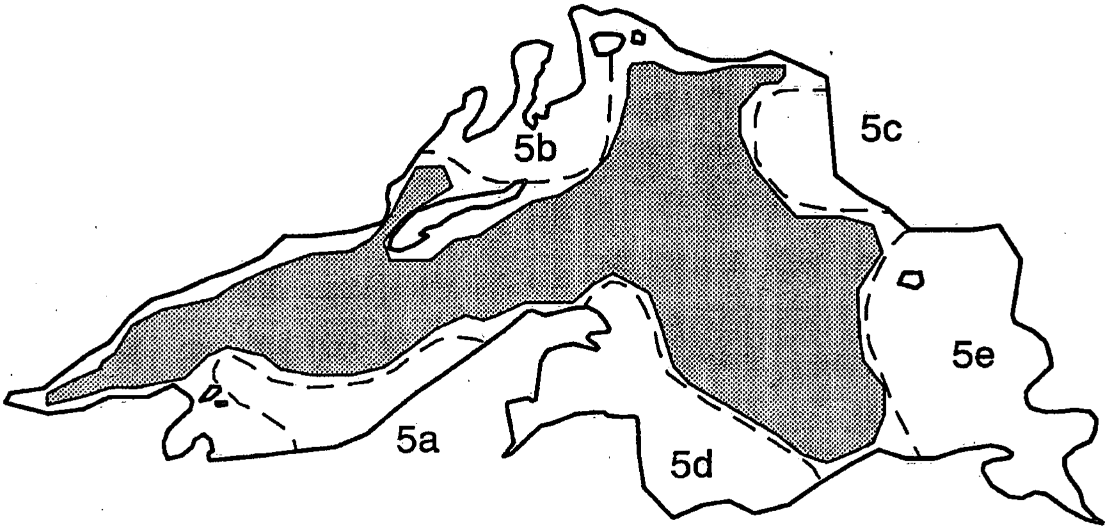


Fig. 5 Discriminant Plots for Lake Superior site groups using 2 sets of environmental variables

a) 1973 (382 sites)



b) 1991 (68 sites)

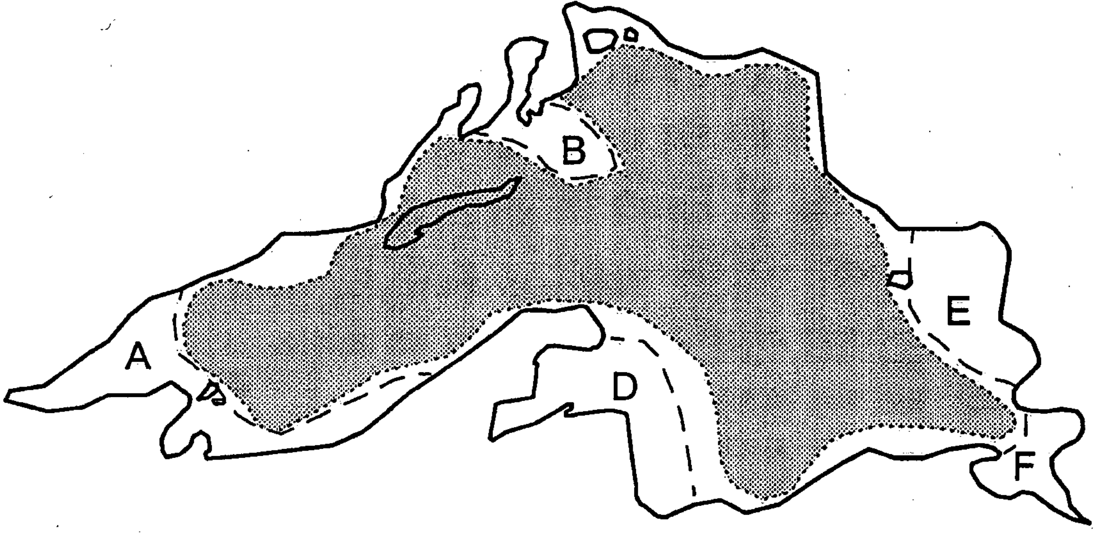


Fig. 6 Distribution of lake zones defined by classification analysis of the benthic community from two data sets.

Environment Canada Environnement Canada

Canada

Canada Centre for Inland Waters
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
L7R 4A6 Canada

National Hydrology Research Centre
11 Innovation Boulevard
Saskatoon, Saskatchewan
S7N 3H5 Canada

St. Lawrence Centre
105 McGill Street
Montreal, Quebec
H2Y 2E7 Canada

Place Vincent Massey
351 St. Joseph Boulevard
Gatineau, Quebec
K1A 0H3 Canada

Centre canadien des eaux intérieures
Case postale 5050
867, chemin Lakeshore
Burlington (Ontario)
L7R 4A6 Canada

Centre national de recherche en hydrologie
11, boul. Innovation
Saskatoon (Saskatchewan)
S7N 3H5 Canada

Centre Saint-Laurent
105, rue McGill
Montréal (Québec)
H2Y 2E7 Canada

Place Vincent-Massey
351 boul. St-Joseph
Gatineau (Québec)
K1A 0H3 Canada