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**TROPHODYNAMIC ANALYSIS OF PCB CONGENERS
AND OTHER CHLORINATED HYDROCARBONS IN THE
LAKE ONTARIO ECOSYSTEM**

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EXECUTIVE SUMMARY AND MANAGEMENT PERSPECTIVE

The concentration of PCB congeners and several other chlorinated organics has been measured in most compartments of the Lake Ontario ecosystem. The biomagnification of PCB and several other organics occurred as one moved up the food chain from water to plankton to fish. In addition to increasing in concentration, the chlorine content of the PCBs increased from 52% in the water to 56.3% in salmonids. Most of the selective PCB fractionation occurred at the lower end of the food chain (water to plankton to mysid). More research is required in this neglected area to develop a better understanding of what factors control chemical uptake at the bottom of the food chain.

The bioaccumulation factors were observed to increase linearly with octanol-water partition coefficient of the chemicals. Thus some predictions can be made on the relative tendency of chemicals to accumulate based on their physical/chemical properties. Bioaccumulation factors for the study chemicals were at least a factor of ten higher than would be predicted from bioconcentration from water alone showing that contaminated food is the major source of these chemical residues in fish. Better models in food chain transfer of organics to fish are required. Finally the major PCB congeners in salmonids have been identified.

RÉSUMÉ ET PERSPECTIVES DE GESTION

Nous avons mesuré la concentration des congénères de PCB et de plusieurs autres organochlorés dans la plupart des compartiments de l'écosystème du Lac Ontario. Il y a bioamplification des PCB et de plusieurs autres composés organiques en remontant la chaîne alimentaire à partir de l'eau jusqu'au plancton et aux poissons. Les concentrations de PCB augmentent, mais il y a également une augmentation de la teneur en chlore des PCB qui passe de 52 % dans l'eau à 56,3 % chez les salmonidés. Le fractionnement sélectif des PCB se produit surtout au début de la chaîne alimentaire (de l'eau au plancton et aux mysididés). De plus amples recherches devront être effectuées dans ce domaine négligé si on veut mieux comprendre quels sont les facteurs qui influencent la fixation des composés chimiques au début de la chaîne alimentaire.

Les facteurs de bioaccumulation augmentent de façon linéaire avec le coefficient de partage octanol/eau de ces composés chimiques. On peut donc faire quelques prévisions concernant la tendance relative de ces composés chimiques à s'accumuler à partir de leurs propriétés physico-chimiques. Les facteurs de bioaccumulation des composés chimiques à l'étude sont au moins 10 fois plus élevés que les facteurs calculés à partir de la bioconcentration dans l'eau, ce qui indique que les aliments contaminés constituent la principale

source de ces composés chimiques dans le poisson. Il nous faut de meilleurs modèles de transfert des composés organiques aux poissons par la chaîne alimentaire. Enfin, on a identifié les principaux congénères de PCB chez les salmonidés.

Analyse trophodynamique des congénères de PCB et d'autres hydrocarbures chlorés dans l'écosystème du lac Ontario.
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ABSTRACT

The bioaccumulation of PCB congeners and some other chlorinated organics in the Lake Ontario ecosystem has been studied. In addition to the classical biomagnification of PCBs and some of the other organics, the chlorine content of the PCBs was observed to increase with trophic level. Most of the differential PCB fractionation seemed to occur at the lower end of the food chain (water to plankton to mysid). At the higher trophic levels (mysid to smelt to salmonid), the PCB seemed to be distributed as a uniform composition mixture. The bioaccumulation factor of these hydrophobic organics increased linearly with octanol-water partition coefficient of the chemicals at all trophic levels. The environmental bioaccumulation of these chemicals in salmonids was at least an order of magnitude higher than that predicted from bioconcentration from water alone, showing that contaminated food is the major source of these chemical residues in fish.

RÉSUMÉ

Nous avons étudié la bioaccumulation des congénères de PCB et d'autres organochlorés dans l'écosystème du lac Ontario. En plus de la bioamplification classique des PCB et d'autres composés organiques, nous avons observé que la teneur en chlore des PCB augmente avec le niveau trophique. Le fractionnement différentiel des PCB semble se produire surtout au début de la chaîne alimentaire (de l'eau au plancton et aux mysididés). Aux niveaux trophiques plus élevés (des mysididés à l'éperlan et aux salmonidés), les PCB semblent être répartis en un mélange de composition uniforme. Le facteur de bioaccumulation de ces composés organiques hydrophobes augmente de façon linéaire avec leur coefficient de partage octanol-eau à tous les niveaux trophiques. La bioaccumulation de ces composés chimiques chez les salmonidés est au moins 10 fois plus élevée que celle qui peut être calculée à partir de la bioconcentration dans l'eau, ce qui indique que les aliments contaminés constituent la principale source de ces résidus chimiques dans le poisson.

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INTRODUCTION

The contamination of Lake Ontario with organochlorine chemicals has been thoroughly documented (1-4). Even though the worst contamination of the lake from the Niagara River occurred in the 1960's and early 1970's (5), fish from the lake are still highly contaminated and many exceed health guidelines for PCBs (6). Some work has been reported for a few PCB congeners in bottom and suspended sediments (4) but, in general, past PCB data is limited to total PCBs (7). Also past research has mainly dealt with a single lake compartment such as sediment (7) and very little data is available for many of the other components of the lake (8, 9). In the marine environment a few studies have reported total PCBs (10, 11) and PCB congeners (12, 13) in several ecosystem compartments.

Several models have been advanced to predict the fish bioconcentration of chemicals from water (14, 15). Some models also incorporate a food chain component in their calculations (16, 17). Testing of and development of further sophistication of these models has been hampered by a lack of comprehensive field information for chemicals with diverse physical/chemical properties. In this paper we report concentration data for PCB congeners and of several other chlorinated hydrocarbons in a variety of sample matrices collected from Lake Ontario over the last five years. Samples from all trophic levels in the planktonic (water-plankton-mysid-alewife and smelt-salmonid) and the benthic (water-sediment/suspended sediment - amphipod/oligochaete-sculpin-salmonid) food chains have been analyzed.

EXPERIMENTAL

Water samples from Lake Ontario were collected from the locations shown in Fig. 1 in April, 1984 when the lake was well mixed. Samples were pumped from a depth of 10 m with a March pump through teflon and stainless steel hose. The water was then passed through a Wesphalia continuous-flow centrifuge to remove the particulates and into a 200 L stainless steel extractor, and extracted on site with dichloromethane. Field testing of this large volume liquid-liquid extractor has been reported elsewhere (18). The surrogate spikes 1,3-dibromobenzene; 1,3,5-tribromobenzene; 1,2,4,5-tetrabromobenzene; 2,3,5,6-tetrachlorobiphenyl and octachloronaphthalene were added to the drum when the sample was collected and carried right through the extraction, cleanup and analytical procedure. Recoveries for the surrogate chemicals in these samples was in the 60-80% range.

Bottom surficial sediments (0-3 cm) were collected using a 0.25 m² box corer from the sedimentation basins of the lake (Fig. 1) in May, 1981. Suspended sediments were integrated samples collected using sediment traps (19) from near the centre of the Niagara, Mississauga and Rochester basins (Fig. 1). Overwinter samples collected from November to April for each year from 1982 to 1986 were used to approximate chemical concentrations on suspended sediments, since material in the water column at this time of year is mainly resuspended bottom sediment (4). Collections from six depths (20, 40, 60, 100, 140 and 180 m) at each site were combined to give one sample per site for each year.

Plankton samples from each of the major basins (Fig. 1) were collected in July, 1982 by centrifuging 5000 L of water from a depth of 10 m using a Westfalia centrifuge. Although this sample would contain a mixture of phytoplankton and zooplankton, phytoplankton should predominate. One mysid (Mysis relicta) sample was collected from the Niagara Basin of the lake in July, 1981 in nets trawled near the bottom. A second mysid sample was collected incidentally in a sediment trap in the Rochester Basin in October, 1984. Amphipods (Pontoporeia affinis) and oligochaete (mainly Tubifex tubifex and Limnodrilus hoffmeisteri) worms were collected from sediment box cores at 5 km intervals about 10 km from the mouth of the Niagara River (Fig. 1) in June, 1985.

Slimy sculpin (a five-fish composite of 8-10 g fish) (Cottus cognatus) was collected near Grimsby in the spring of 1986. A 12-fish composite of alewife (≈ 32 g) and a 20-fish composite of larger rainbow smelt (≈ 16 g) (Osmerus mordax) were collected near Vineland in May, 1982. Smaller smelt (≈ 12 g each), which were obtained from Port Credit in April, 1986, consisted of six eight-fish composites. A total of 60 salmonids were collected and analyzed separately. Ten coho salmon (3330 ± 520 g) (Oncorhynchus velinus namaycush), ten rainbow trout (3380 ± 870 g) (Salmo gairdneri) and ten lake trout (2410 ± 770) (Salvelinus namaycush) were collected in the fall of 1981 from the Credit River. Ten coho salmon (1190 ± 190 g), ten rainbow trout (1140 ± 120 g) and ten brown trout (1430 ± 360 g) (Salmo trutta) were obtained in April, 1982 from Vineland.

The analytical procedures have been described in detail elsewhere (20). Briefly, all samples were soxhlet extracted with acetone/hexane, back extracted with water to remove the acetone, and concentrated to the appropriate volume using Snyder and/or Kuderna-Danish condensers. Cleanup consisted of passage through a small pasteur pipette (8 mm ID) packed with 1 cm Na_2SO_4 , 4 cm 40% H_2SO_4 silica gel, and 2 cm of Florisil (deactivated with 5% water). Extracts of the biological samples were pretreated with H_2SO_4 to remove the bulk of the lipids prior to column cleanup, and sediment extracts were treated with mercury to remove sulfur interferences after column cleanup.

Quantification was carried out using dual capillary columns (30 m DB5 and DB17) and electron capture detector (350°C) in a Varian 4600 gas chromatograph. The carrier gas was helium (linear velocity 20 cm/s) and an extremely slow program rate 50 to 250°C at 1°C per minute was used to optimize separations. A mixture of four Aroclor 1221, 1016, 1254 and 1262 obtained from EPA were used in the ratio 10:5:3.5:3 for instrument calibration. The composition of the mixture was obtained from Mullin (21) who has all 209 PCB congeners (22). To confirm peak identities and quantities by this procedure, a series of 50 commercially-available PCB congeners and 51 PCB congeners obtained from the National Research Council of Canada, Marine Analytical Chemistry Standard Program, Atlantic Research Laboratory, Halifax, Nova Scotia were run and excellent agreement between the secondary and primary standards was found. Selected samples were also run by GC/MS for quantitative and qualitative confirmation.

RESULTS AND DISCUSSION

The trophic relationships among organisms examined in this study (see Fig. 2) have not been well defined in the Lake Ontario ecosystem. All salmonid species feed primarily on alewives, and, to a lesser extent, on smelt (23). Small lake trout feed mainly on sculpins, and some alewives and smelt during certain times of the year (24). Studies on Lake Michigan alewives indicate mysids are their primary prey species followed by amphipods (25). Other studies on sculpins in Lake Michigan indicate amphipods were the primary prey species, with mysids and chironomids contributing less (26). Smelt in Great Lakes waters feed mainly on mysids (27). Mysids feed mainly on zooplankton, while amphipods and oligochaetes utilize detrital matter.

The results of the study are tabulated in Table I. The PCBs are listed as International Union of Pure and Applied Chemistry (IUPAC) numbers (28) and less common abbreviations for the other chemicals are: chlorobenzenes, CB, Q=penta, H=hexa; chlorotoluene, CT, P=2,3,4,5,6 penta; α benzenehexachloride, α BHC; hexachlorobutadiene, HCBd; octachlorostyrene, OCS. The PCBs 1,3,4,7,10, 19 were also measured out not detected in any of the samples. Although the data sets for some compartments are much more extensive than for others, there is sufficient data in the table to give a reasonable approximation of the contaminants in each lake component. Even though the samples were not collected at the same time, no significant concentration changes were apparent in the sediment trap collections

chlorinated contaminants in fish from the lake (29). Thus we feel the data is representative of the current status of Lake Ontario since the lake is slow to react to external influence (mean residence time 7.8 yr) and no major environmental control programs have been implemented in the 1980's.

The PCB concentration increase from water to lower organisms to small fish to salmonids demonstrates the classical biomagnification process (Fig. 3). The PCB concentration increases with trophic level and with organism lipid content (plankton 0.5% lipid, mysids 3%, amphipods 3%, oligochaetes 1%, sculpin 8%, alewife 7%, smelt 4% and salmonids 11%). Not only does total PCB content increase with trophic level but the chlorine content of the PCBs increases at the higher trophic levels (Table I). The percentage chlorine of the PCBs increase from 52% for the lakewater to 56.1% for the salmonids. The PCBs in sculpin, which are small bottom-living fish that feed on benthic invertebrates, had the highest chlorine content, 57%.

Figure 4 depicts visually the increase in chlorine content of PCBs in the ecosystem. The tri- and tetrachlorobiphenyls comprise a much higher percentage of the PCBs in the water and lower trophic levels than in the salmonids and small fish. The percentage of penta- and octachlorobiphenyls in all samples is fairly uniform, but the hexa- and hepta-homologues comprise a much larger fraction of the PCBs in the small fish and salmonids than in the water and lower trophic levels. These fractionation processes lead to an increase in PCB

chlorine content at the higher levels of the food chain. These observations are confirmed by looking at several structurally-related congeners in Fig. 5. The tri-, tetra- and penta-congeners comprise a much higher fraction in the water than in the other trophic levels, whereas, the hexa- and hepta- congeners are preferentially higher at the upper trophic levels. No consistent trend with trophic level was found for the octa- congener (#194).

Of the chlorinated hydrocarbons studied, pp-DDE and mirex exhibited the highest concentrations in the salmonids (Table I). Most of the lower chlorinated benzenes, the chlorinated toluenes and hexachlorabutadiene were not detected in the fish, likely because of low bioconcentration factors (30, 31). There were some interesting differences in the behaviour of the hexachloro-substituted cyclic nonaromatic compounds α -BHC and lindane compared to hexachlorobenzene. α -BHC and lindane had among the highest water concentrations, a factor of 20 and 2, respectively, higher than HCB. In contrast in the bottom sediments, α -BHC and lindane were about 1/100 times the HCB concentrations. Although HCB would be expected to partition more strongly into sediments, α -BHC and lindane exhibit a much lower tendency to be adsorbed than would be predicted from their water solubilities and/or octanol-water partition coefficients. The concentration ratios of α -BHC and lindane to HCB approach one in the biota samples. Thus, these ratios can be used to differentiate between samples containing mainly sediment and those which may contain a significant amount of biologically-generated material.

The ratio of photomirex to mirex also varies greatly in the lake compartments. Mudambi and Hassett (32) have observed the conversion of mirex to photomirex (mirex minus one chlorine atom) in sunlight irradiated Lake Ontario water. The lowest photomirex/mirex ratios (0.13) and (0.09) were observed in bottom sediments and in sediment-dwelling oligochaete worms. Much higher ratios were found in water and the other trophic levels. This ratio for suspended sediments (0.25) is somewhat higher than for bottom sediments, probably because some of this material was resuspended to the photic zone in the lake. With more information on quantum yields and environmental conversion rates of mirex to photomirex, it may be possible to use their ratio for estimating the degree and rates of mirex recycling in Lake Ontario (32). Most mirex sources to the lake have been severely curtailed (5) and it is likely that the major current source of mirex to the biota in the lake is the bottom sediments.

Several investigators (14, 15, 30, 33) have shown that there is an excellent correlation between fish bioconcentration factor (BCF) and a chemical's octanol-water partition coefficient (K_{ow}). The BCF, chemical concentration in fish/chemical concentration in water at equilibrium, is normally measured in the laboratory by exposing fish to a controlled water concentration of the chemicals of interest. In the environment the fish are exposed to chemicals both in the water they respire and from the food they ingest, so a more appropriate term is bioaccumulation factor (BAF), chemical concentration in organism/chemical concentration in lakewater (34). The log BAF of the

salmonids is plotted versus $\log K_{ow}$ in Fig. 6 for the tri-through octachlorobiphenyls and for the other chlorinated hydrocarbons in the study yielding the equation:

$$\log \text{BAF} = 1.07 \log K_{ow} - 0.21 \quad r^2 = 0.86 \quad (1)$$

(n = 18, 95% confidence limit of slope 0.84 - 1.30)

The octanol-water partition coefficients used for this correlation were taken from the literature and were tabulated in our earlier publication (33). The BAF equation can be compared to the BCF equation by Mackay (15) also shown on the graph.

$$\log \text{BCF} = 1.0 \log K_{ow} - 1.32 \quad (2)$$

(from reference 15)

The two lines are approximately parallel but the $\log \text{BAF}$ line is about 1 log unit or one order of magnitude higher than the $\log \text{BCF}$ line. Thus, although the same trends for accumulation are predicted by both equations, consideration of only chemical uptake from water underestimates fish residues by at least a factor of ten. This clearly demonstrates that the consumption of contaminated food is the major source of chemical residues in fish for this group of hydrophobic organics.

The BAF for each PCB isomeric group was calculated by dividing the sum of the PCBs in that group in salmonids by the sum for the group in lakewater. The range of the BAFs of the various PCB

congeners within each isomeric group, which is of the order of a factor of 20, is shown in Fig. 6 by the barred lines. This variation in BAF indicates that chlorine substitution pattern of the isomer plays an important role in the bioaccumulation process.

The partitioning process for the various planktonic food chain linkages for the pentachlorobiphenyls is shown in Fig. 7. Trends observed for this group of PCB isomers are similar to those of the other PCB homologue groups. The considerable variation in BAFs for the pentachlorobiphenyls in salmonids is evident from the uppermost section of the figure. Interestingly, the most significant differential partitioning of the congeners appears to occur at the lower end of the food chain (water to plankton to mysid). Although there are significant changes in the absolute concentration of the congeners higher in the food chain (mysid to smelt to salmonid), the concentration increases are seen to be fairly uniform for the various congeners at this level. Thus at the upper chain levels, the PCBs appear to move as a uniform composition mixture. A cursory comparison of the PCB congeners which exhibit higher or lower than average bioaccumulation for a given isomeric class does not reveal any obvious structure/accumulation relationships. Components lacking adjacent unchlorinated positions may be more highly accumulated. It is likely that controlled experimental work on the water/sediment/suspended sediment, plankton/water and mysid/plankton partitioning will be required to develop generalized structural correlations. Emphasis should be placed at the lower end of the food chain where most of the selective partitioning apparently occurs.

The bioaccumulation factors have been correlated to octanol-water partition coefficients for the various trophic levels in Table II. A reasonable linear correlation is observed for each organism and these relationships are plotted for both the planktonic and benthic food chains in Fig. 8. The plot shows a typical stepwise biomagnification of the chemicals as one moves up the food chain. The slopes of the lines for the lower organisms are much lower than for the fish (Table II). This may point to somewhat different partitioning processes at these trophic levels.

The analysis of bottom and suspended sediments has been included in Table I for completeness, since the sediments are an important source of chemicals to the biota and water in the lake (35). At present models for predicting the partitioning of chemicals between bottom sediments and pore water, and between suspended sediments and water are in early stages of development. At some future date it may become possible to use the sediment concentration data presented here to make better predictions of the "dissolved" chemical concentrations in the water column and in pore water which, in turn, could be used to improve bioaccumulation estimates.

Connor (36, 37) and Breck (38) have suggested that concentrations of chemicals in bottom sediments could be used directly to predict residue levels in fish. Value of $C_{\text{fish}}/C_{\text{sediment}}$ of 45 or 21 (depending on the literature equation used for K_{oc} and BCF) were predicted for PCBs in fish over sediments with an organic carbon content of 1%. For Lake Ontario, where sediments averaged $2.7 \pm 1.4\%$

organic carbon, the $C_{\text{fish}}/C_{\text{sediment}}$ ratio is 7.5 for total PCB and ranged up to about 20 for some of the individual congeners. A very large data scatter for this ratio for the PCB congeners and the chlorinated organics was observed with no consistent pattern or correlation to chemical properties. Thus a simple correlation between fish and sediment concentrations is probably not presently feasible. A much better understanding of the partitioning processes involved would appear to be needed before such correlations are possible.

Recently Baker et al. (39) have shown that an important fraction of PCBs operationally defined as "dissolved" by centrifugation or filtration separations may be bound to colloidal matter. In Lake Ontario with the dissolved organic carbon concentrations at about 2 mg/L, according to Baker's model, as much as 50% of the chemicals measured in Table I as dissolved could be bound to colloidal matter. Yin and Hassett (40) have shown that as much as 80% of the operationally-defined "dissolved" fraction of mirex in Lake Ontario is bound to organic matter. Thus the BAFs reported in Table I could be higher if the "true dissolved" concentration of the chemicals was known and used in the calculation. This difficulty in assessing the true state of organics in water reemphasizes the importance of developing a better understanding of the partitioning process. Defining the equilibrium between chemicals dissolved - bound to dissolved organics - bound to colloidal matter - and bound to suspended sediments and how this effects uptake by lower trophic levels should be a fruitful research area in coming years.

The analysis of individual PCBs is difficult and time consuming. This study shows that there is a considerable difference in PCB composition between, water, sediments and biota. Twelve PCB congeners (153, 101, 84, 138, 110, 180, 87+97, 149, 187+182 and 105) constitute over half the PCBs in fish. Health effects research should focus on these important congeners so that more accurate fish consumption guidelines can be established. Congener-specific PCB analysis is not required for all applications but, because of differential partitioning, it seems to be vital for pathways research.

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FIGURE CAPTIONS

- Fig. 1 Lake Ontario sampling sites.
W = water, . = bottom sediments, SS = suspended sediments,
P = plankton, M = mysids, Am = amphipods, O = oligochaetes,
F = various fish species.
- Fig. 2 The food chain in Lake Ontario.
- Fig. 3 PCB biomagnification in food chain.
- Fig. 4 Isomeric composition (%) at the various trophic levels.
- Fig. 5 Percentage composition of structurally related PCB congeners in the lake compartments.
- Fig. 6 Log bioaccumulation factor for salmonids versus log octanol-water partition coefficient.
■ PCB isomeric groups ○ other chlorinated organics
- Fig. 7 Bioaccumulation relationships for various planktonic food chain linkages.
- Fig. 8 Log bioaccumulation factor for the various trophic levels in the planktonic and benthic food chains versus log octanol-water partition coefficient.

FIG. 1

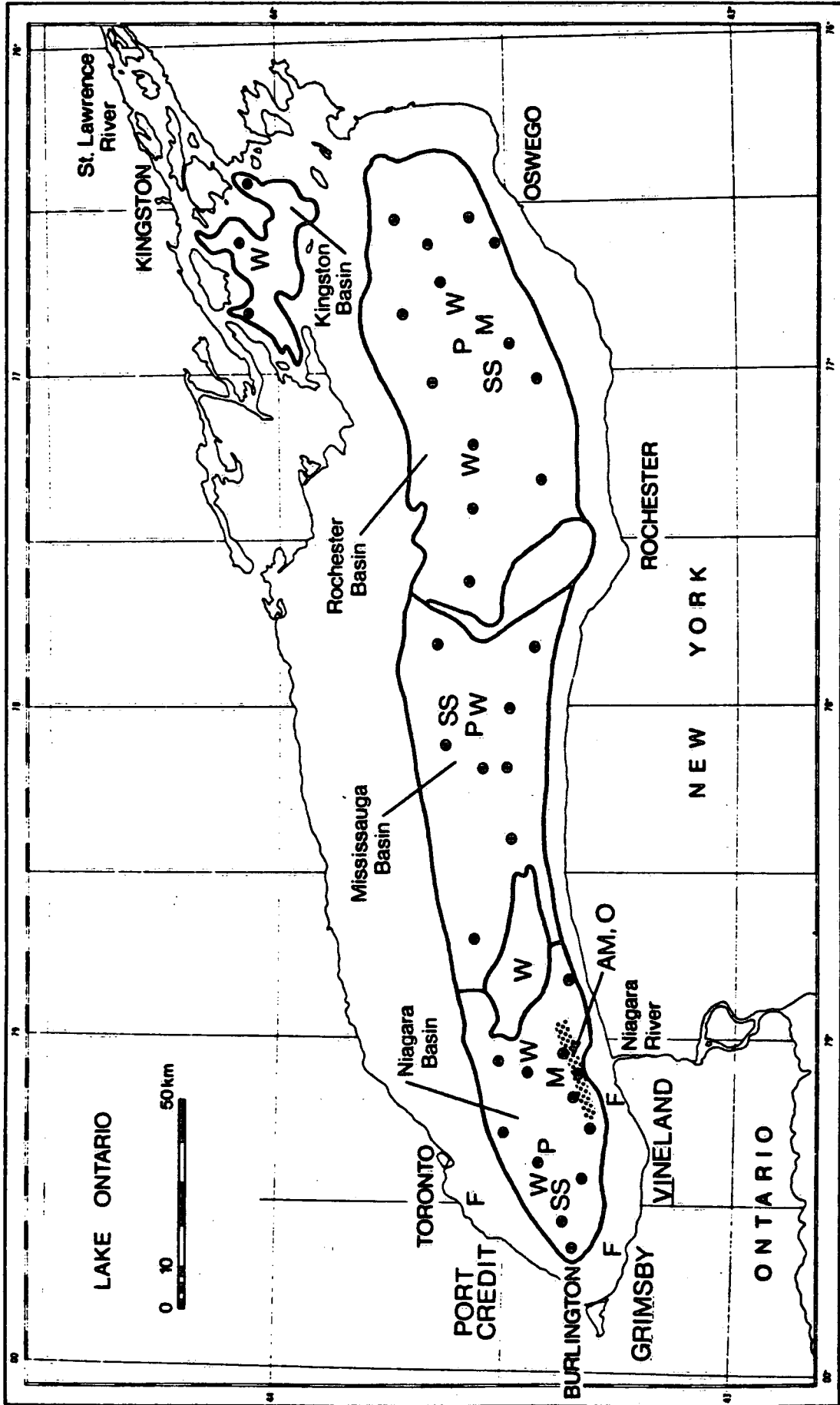


FIG.2

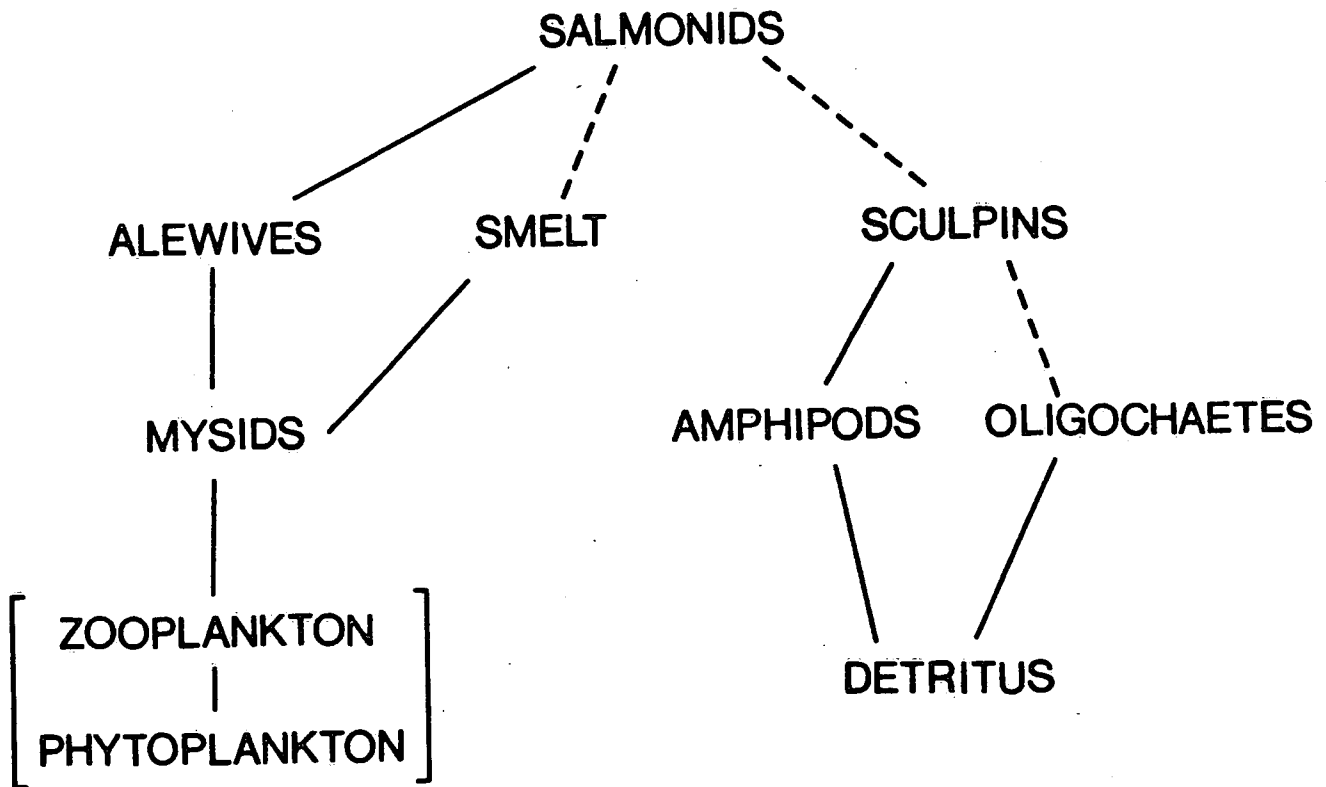


FIG. 3

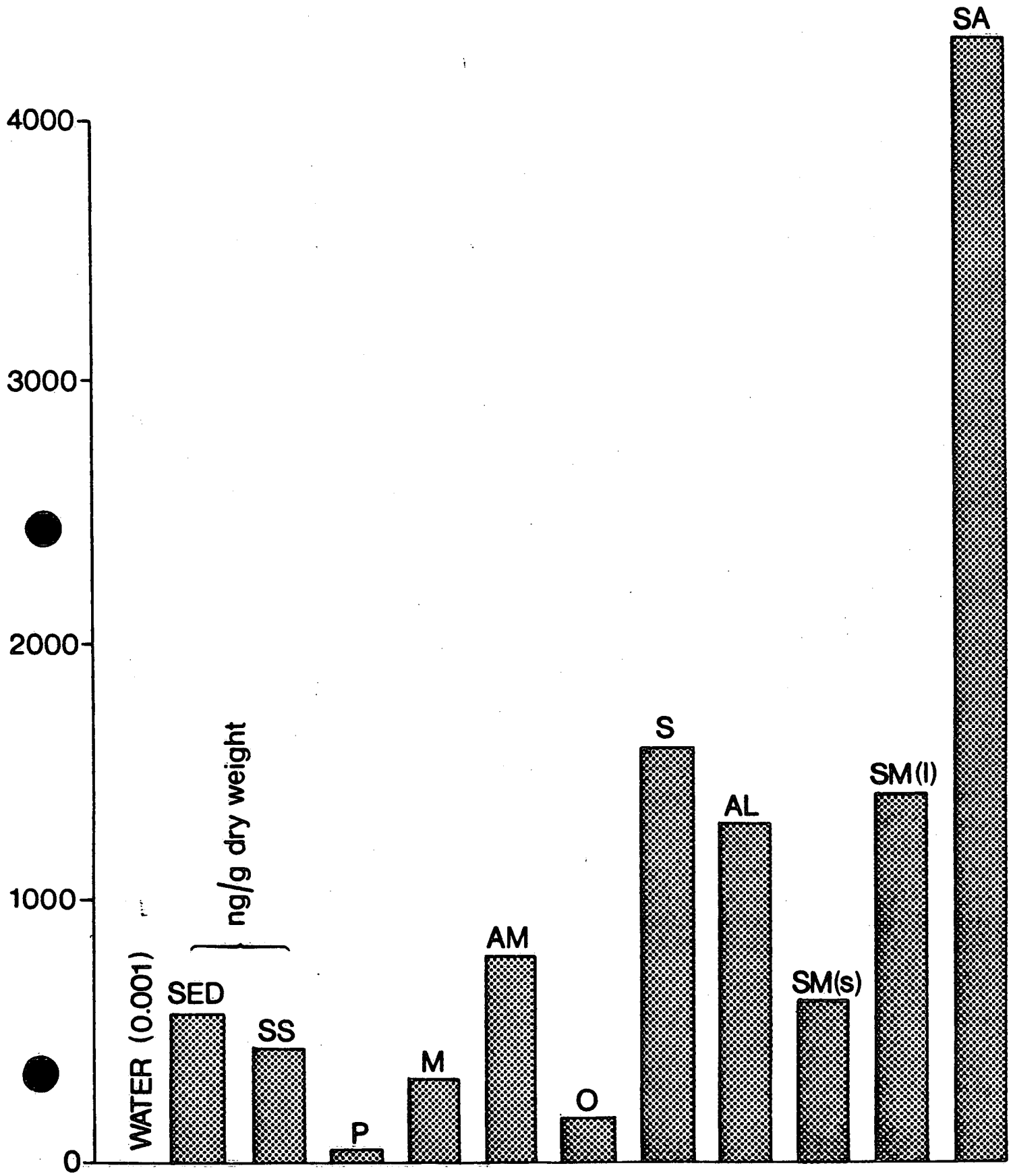
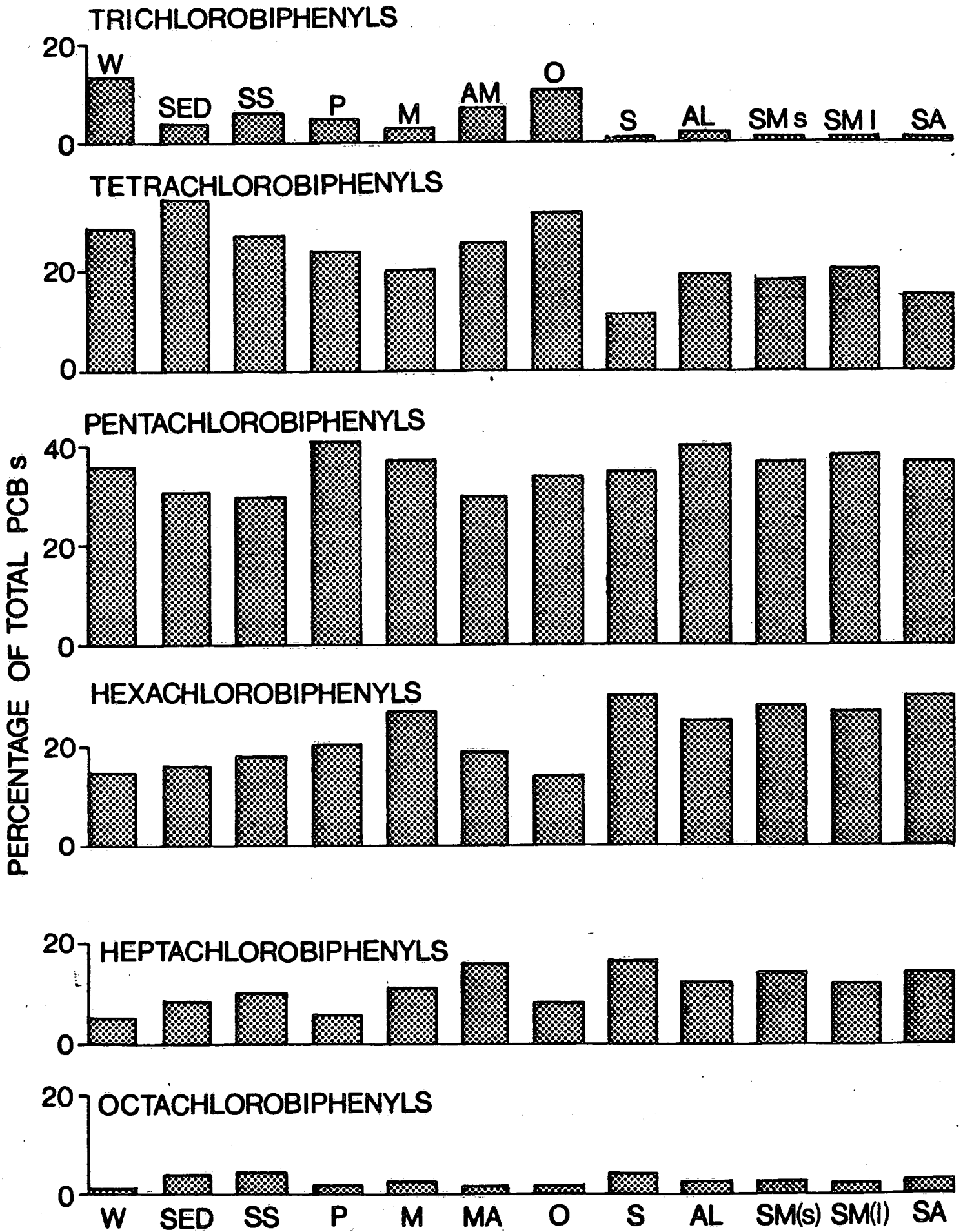


FIG. 4



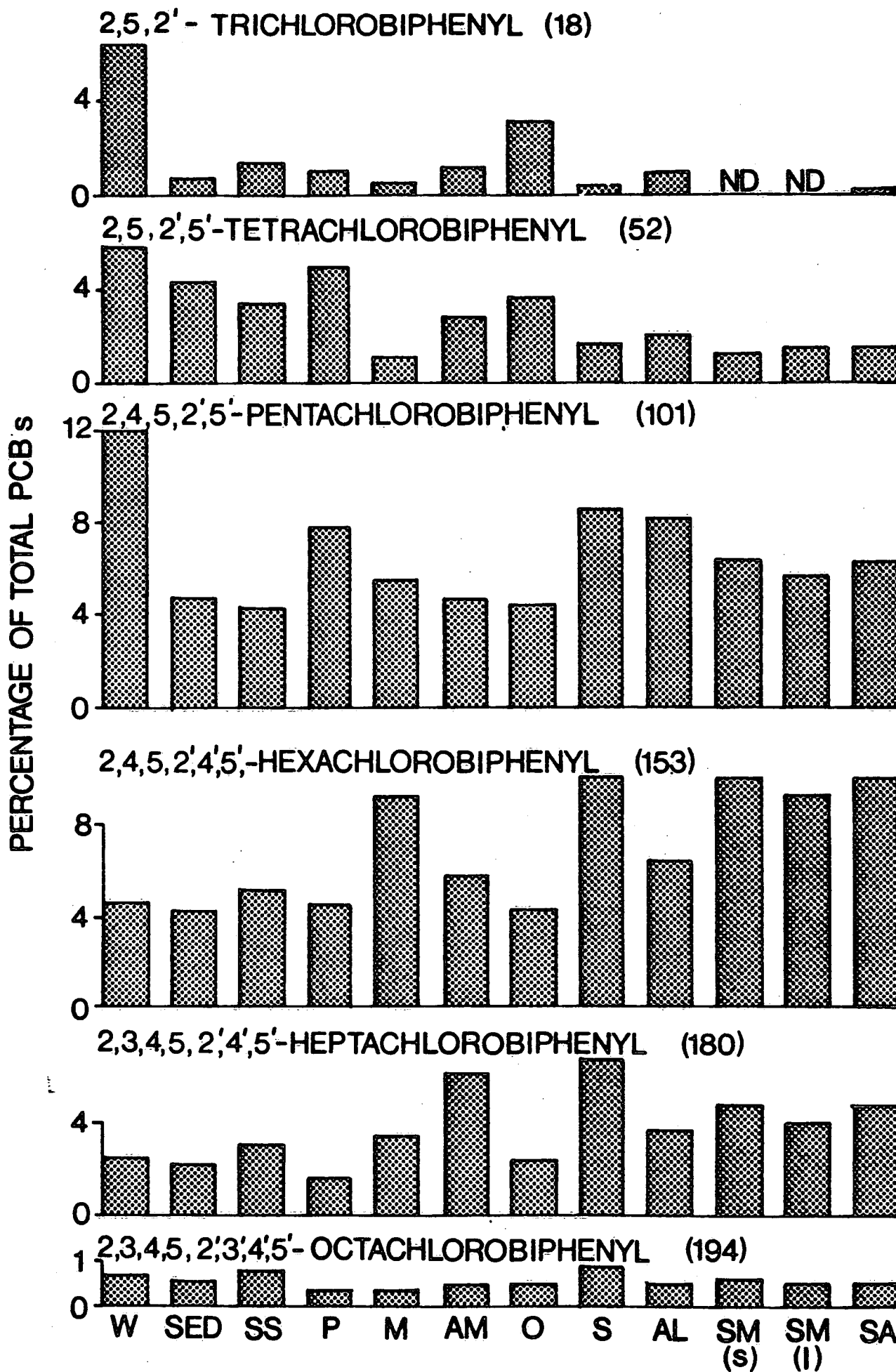


FIG. 6

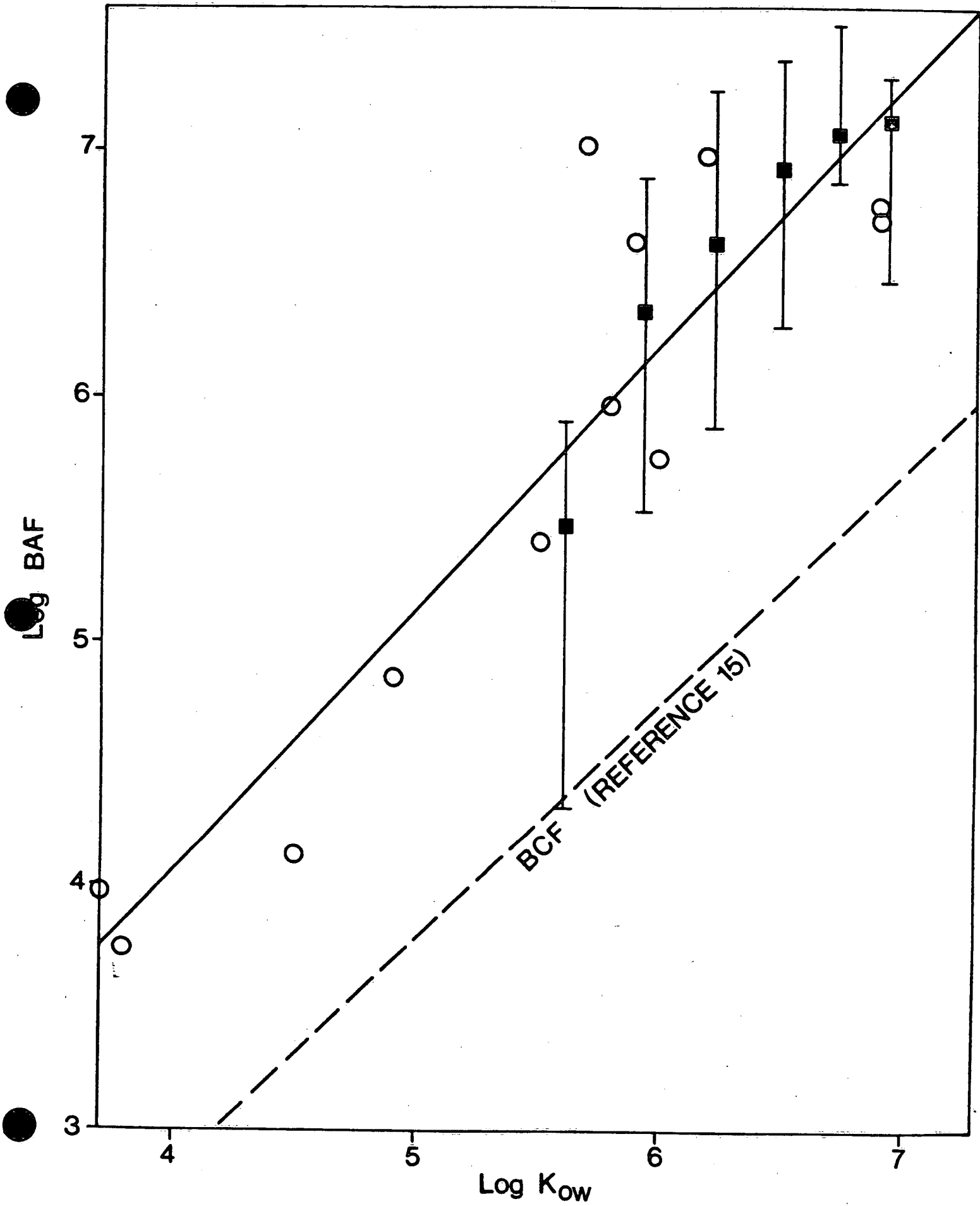


FIG. 7

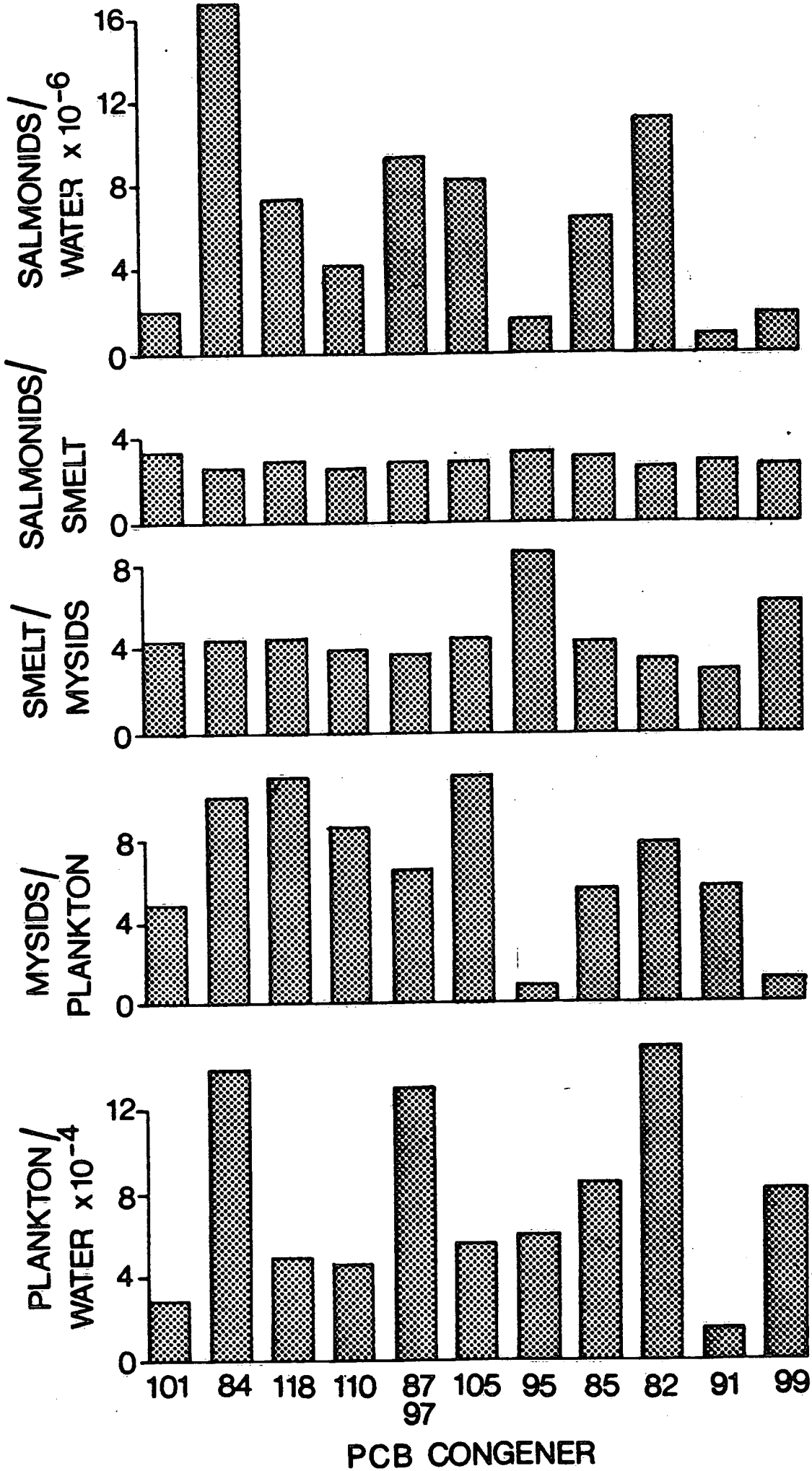


FIG. 8

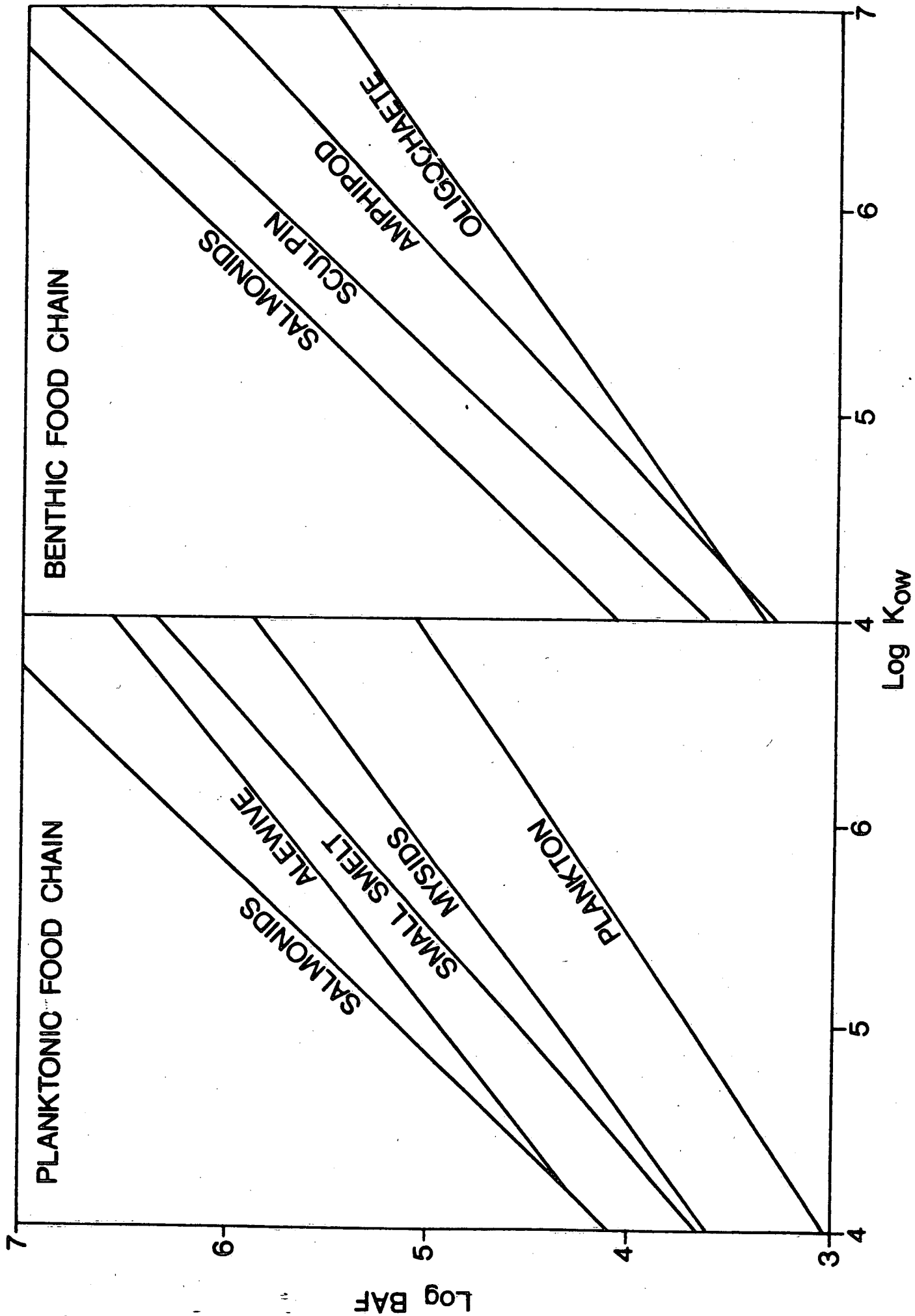


TABLE I PCB Congeners and Some Chlorinated Hydrocarbons in Lake Ontario Compartments Concentration ± Standard Deviation Percentage of Total PCBs in Brackets.

Compound	Sample											
	Water (n=7) pg/L	Bottom Sediments (n=38)	Suspended Sediments (n=10)	Plankton (n=3)	Myxids (n=2)	Amphipods (n=6)	Oligochaetes (n=6)	Sculpin (Composite) (n=6)	Alewife (Composite) (n=6)	Seal Swelts (n=6)	Larger Swelts (Composite) (n=60)	Fish (n=60)
	ng/g dry weight											
8	18±30(1.7)	ND*	4.8±4.5(1.1)	0.5±0.2 (1.1)	ND	ND	0.7±1.0(0.4)	ND	ND	ND	ND	ND
6	ND	ND	0.4±0.5(0.1)	0.08±0.04(0.2)	ND	ND	ND	ND	ND	ND	ND	ND
5	ND	ND	0.1±0.3(0.02)	0.2±0.2 (0.4)	ND	ND	ND	ND	ND	ND	ND	ND
12	ND	ND	0.1±0.1(0.02)	0.04±0.08(0.1)	ND	ND	ND	ND	ND	ND	ND	ND
13	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Total	18±30(1.7)	ND	5.4±5.1(1.2)	0.8±0.5 (1.6)	ND	ND	0.7±1.0(0.4)	ND	ND	ND	ND	ND
ng/g wet weight												
Dichlorobiphenyls												
28+31	46±25 (4.2)	17±7.1(2.4)	14±3.7(3.2)	0.8±0.07(1.6)	6.4±1.8(2.0)	30±32 (3.8)	7.0±5.9(4.0)	7.8 (0.5)	14 (1.0)	6.3±0.7(1.0)	14 (1.0)	36±20 (0.8)
18	72±22 (6.6)	4.0±4.3(0.7)	5.8±3.0(1.3)	0.5±0.1 (1.0)	1.7±0.1(0.5)	9.6±7.5(1.2)	5.6±3.5(3.2)	5.2 (0.3)	12 (0.4)	ND	ND	4.3±7.7(0.1)
22	6.7±12 (0.6)	2.0±1.3(0.3)	2.3±0.8(0.6)	0.2±0.07(0.4)	0.5±0.7(0.2)	3.4±3.4(0.4)	1.4±1.1(0.4)	ND	ND	ND	ND	1.7±2.4(0.04)
26	ND	0.1±0.2(0.02)	0.2±0.2(0.05)	0.05±0.04(0.1)	ND	2.3±3.2(0.3)	0.8±0.7(0.3)	ND	ND	ND	ND	0.7±0.8(0.02)
16	3.4±9.1(0.3)	ND	0.7±0.8(0.2)	0.2±0.08(0.4)	ND	2.4±2.6(0.3)	0.3±1.0(0.3)	ND	ND	ND	ND	0.3±0.5(0.01)
33	14±14 (1.3)	0.5±1.2(0.09)	2.1±1.7(0.5)	0.2±0.07(0.4)	0.4±0.6(0.1)	3.1±3.9(0.4)	1.8±1.4(1.0)	ND	ND	ND	ND	0.3±0.5(0.01)
17	8.5±9.7(0.8)	0.5±1.1(0.09)	0.9±1.3(0.2)	0.2±0.05(0.4)	0.2±0.3(0.06)	1.5±2.8(0.3)	1.0±0.7(0.6)	ND	ND	ND	ND	0.2±0.4(0.01)
25	ND	0.2±0.4(0.03)	0.2±0.3(0.05)	0.02±0.01(0.04)	ND	1.2±1.4(0.2)	0.4±0.5(0.2)	ND	ND	ND	ND	0.2±0.4(0.01)
24+27	ND	0.4±0.6(0.07)	1.0±0.8(0.2)	0.06±0.06(0.1)	ND	1.7±2.3(0.2)	0.2±0.3(0.1)	ND	ND	ND	ND	0.2±0.4(0.01)
32	0.5±1.4(0.05)	0.4±0.6(0.07)	1.0±0.8(0.2)	0.06±0.06(0.1)	ND	1.7±2.3(0.2)	0.2±0.3(0.1)	ND	ND	ND	ND	0.2±0.4(0.01)
Total	150±90 (14)	22±11 (3.6)	27±11 (6.1)	2.1±0.5 (4.3)	9.4±3.7(2.9)	58±48 (7.3)	19±14 (11)	13 (0.8)	26 (1.9)	6.3±0.7(1.0)	14 (1.0)	44±34 (1.0)
Trichlorobiphenyls												
66	31±18 (2.9)	46±17 (7.9)	27±11 (6.1)	1.6±0.5 (3.3)	15±3.5(4.6)	30±16 (3.8)	8.3±5.3(4.7)	53 (3.2)	61 (4.5)	27±2.9(4.4)	72 (5.1)	160±110(3.7)
70+76	45±38 (4.2)	23±18 (4.0)	25±8 (5.2)	2.1±0.6 (4.5)	20±6.4(6.1)	32±22 (4.0)	9.4±6.7(5.3)	32 (1.9)	50 (3.7)	29±2.8(4.7)	72 (5.1)	140±95 (3.2)
56+60+81	9.7±26 (0.9)	33±13 (5.7)	19±8.8(4.3)	1.1±0.3 (2.2)	11±5.3(3.4)	25±20 (3.2)	6.5±5.5(3.7)	18 (1.1)	32 (2.4)	16±1.9(2.6)	39 (2.8)	74±58 (1.4)
52	63±52 (5.8)	25±12 (4.3)	15±3.2(3.4)	0.5±0.4 (4.9)	3.5±1.0(1.1)	22±10 (2.8)	6.3±4.4(3.6)	28 (1.7)	27 (2.0)	7.6±2.5(1.2)	18 (1.3)	62±45 (1.4)
47+48	41±5.5(3.8)	12±4.8(2.1)	3.4±1.6(0.8)	0.5±0.4 (1.0)	1.7±2.4(0.5)	14±13 (1.8)	3.6±3.8(2.0)	4.1 (0.2)	18 (1.3)	7.8±4.0(1.3)	24 (1.7)	60±50 (1.4)
44	50±32 (4.6)	23±7.5(4.0)	12±3.2(2.7)	1.7±0.4 (3.5)	4.2±1.6(1.3)	26±11 (3.3)	6.9±5.1(3.9)	16 (1.0)	23 (1.7)	4.5±3.6(0.7)	15 (1.1)	38±29 (1.0)
74	10±8.1(0.9)	2.7±0.6(0.5)	4.6±1.4(1.0)	0.4±0.1 (0.8)	4.0±1.8(1.2)	8.2±6.1(1.0)	2.2±1.8(1.3)	12 (0.7)	12 (0.9)	6.2±0.7(1.0)	14 (1.0)	55±29 (0.9)
49	24±11 (2.2)	11±6.8(1.4)	5.8±1.4(1.3)	0.9±0.2 (1.8)	2.3±0.3(0.7)	16±7 (2.0)	3.5±2.9(2.0)	10 (0.6)	14 (1.0)	2.4±1.9(0.4)	9.0 (0.6)	31±22 (0.7)
64	9.3±9.7(0.9)	9.4±3.7(1.6)	4.0±2.5(0.9)	0.5±0.1 (1.0)	3.6±1.3(1.1)	8.4±3.2(1.1)	2.4±2.0(1.4)	9.2 (0.6)	11 (0.8)	4.4±0.4(0.7)	11 (0.8)	28±20 (0.6)
42	3.3±3.7(0.3)	4.7±2.5(0.8)	2.6±0.8(0.6)	0.2±0.07(0.4)	1.5±0.7(0.5)	4.6±4.7(0.6)	1.2±1.2(0.7)	2.8 (0.2)	5.0 (0.4)	1.8±0.9(0.3)	5.1 (0.4)	10±6.3(0.2)
53	4.6±5.9(0.4)	0.2±0.5(0.03)	0.5±0.5(0.1)	0.2±0.09(0.4)	ND	2.4±2.1(0.3)	0.7±0.7(0.4)	ND	ND	ND	ND	1.5±1.9(0.03)
40	3.6±6.2(0.3)	3.1±1.2(0.5)	1.4±0.4(0.3)	0.2±0.03(0.4)	ND	3.2±2.4(0.4)	1.1±1.1(0.6)	ND	ND	ND	ND	0.8±1.2(0.02)
41+71	ND	0.3±0.7(0.05)	0.3±0.3(0.07)	0.04±0.01(0.1)	ND	1.9±2.2(0.2)	0.4±0.4(0.2)	ND	ND	ND	ND	0.7±1.2(0.02)
46	ND	1.1±0.8(0.2)	0.1±0.2(0.02)	ND	ND	1.7±1.7(0.2)	0.3±0.7(0.2)	ND	ND	ND	ND	ND
45	ND	200±77 (34)	120±37 (27)	12±2.6 (24)	66±24 (20)	200±12 (25)	34±36 (31)	190 (11)	250 (19)	110±16 (18)	280 (20)	650±470(15)
Total	300±200 (28)	200±77 (34)	120±37 (27)	12±2.6 (24)	66±24 (20)	200±12 (25)	34±36 (31)	190 (11)	250 (19)	110±16 (18)	280 (20)	650±470(15)
Pentachlorobiphenyls												
101	130±36 (12)	27±10 (4.7)	19±5.1 (4.3)	3.8±1.2 (7.8)	18±4.2(5.5)	37±11 (4.7)	7.7±5.1(4.4)	140 (8.5)	110 (8.1)	39±7.2(6.3)	79 (5.6)	270±190(6.2)
84	15±19 (1.4)	21±11 (3.6)	15±5.1 (3.4)	2.1±0.7 (4.3)	21±10 (6.4)	24±5 (3.7)	4.9±2.4(2.8)	110 (6.7)	68 (5.0)	39±5.3(6.3)	95 (6.7)	260±210(6.0)
118	34±12 (3.1)	15±13 (2.6)	21±7.7 (4.8)	1.7±0.5 (3.5)	19±6.4(5.8)	21±10 (2.6)	4.3±1.7(2.4)	94 (5.7)	58 (4.3)	37±6.8(6.0)	87 (6.2)	250±210(5.8)
110	55±25 (5.1)	37±13 (6.4)	25±8.0 (5.7)	2.8±0.7 (5.3)	22±7.1(6.7)	28±12 (3.5)	7.5±3.3(4.3)	76 (4.6)	78 (5.8)	35±5.4(5.7)	88 (6.2)	230±150(5.3)
87+97	21±26 (1.9)	20±10 (3.9)	17±6.0 (3.9)	2.7±0.9 (5.5)	18±3.5(5.5)	61±33 (7.7)	18±11 (10)	42 (2.5)	22 (1.6)	37±10 (6.0)	69 (4.9)	200±120(4.6)
105	14±5.1(1.3)	10±8.4(1.7)	12±4.9 (2.7)	0.8±0.2 (1.6)	8.5±3.5(2.6)	12±8 (1.5)	2.6±1.4(1.5)	39 (2.4)	27 (2.0)	15±2.0(1.4)	38 (2.7)	110±82 (2.5)
95	52±44 (4.8)	14±4.6(2.4)	12±2.9 (2.7)	3.1±0.7 (6.3)	2.8±1.0(0.9)	22±3.9(2.8)	4.9±2.4(2.8)	31 (1.9)	40 (3.0)	11±3.7(1.8)	24 (1.7)	80±53 (1.8)
85	9.4±14 (0.9)	9.8±4.0(1.7)	5.6±2.0 (1.3)	0.8±0.1 (1.6)	4.4±1.3(1.3)	8.1±4.8(1.1)	1.6±0.8(0.9)	17 (1.0)	22 (1.6)	6.9±0.4(1.1)	19 (1.3)	58±48 (1.3)
92	5.4±14 (0.5)	2.9±1.2(0.5)	6.9±2.3 (1.6)	1.0±0.5 (2.0)	0.4±0.2 (0.8)	1.2±6.1(1.5)	4.1±3.9(2.3)	15 (0.9)	22 (1.6)	2.2±3.4(0.4)	9.4 (0.7)	53±57 (1.3)
82	2.6±6.7(0.2)	2.9±1.2(0.5)	2.0±0.8 (0.5)	0.4±0.2 (0.8)	3.1±1.3(1.0)	2.7±1.4(0.3)	0.5±0.3(0.3)	6.3 (0.4)	10 (0.9)	4.6±0.8(0.7)	11 (0.8)	29±17 (0.7)
91	40±8.4(3.7)	5.2±2.2(1.0)	3.6±0.9 (0.8)	0.8±0.2 (1.2)	3.4±1.6(1.0)	5.8±2.7(0.7)	1.2±1.1(0.7)	7.0 (0.4)	12 (0.9)	3.2±2.5(0.5)	10 (0.7)	29±18 (0.7)
99	11±14 (1.0)	7.2±2.8(1.4)	4.7±1.4 (1.1)	0.9±0.2 (1.8)	1.2±1.6(0.4)	8.6±2.4(1.1)	2.6±1.9(1.5)	ND	ND	0.8±2.0(0.1)	7.4 (0.5)	20±13 (0.5)
Total	390±190(36)	180±76 (31)	130±43 (30)	20±5.1 (41)	120±42 (37)	240±100(30)	60±35 (34)	580 (35)	540 (40)	230±36 (37)	540 (38)	1600±1200(37)

TABLE II Bioaccumulation Relationships for Various Trophic Levels.

Trophic Level	Equation	95% Confidence Limit of Slope	n	r ²
Plankton	$\log \text{BAF} = 0.68 \log K_{ow} + 0.33$	0.55 - 0.81	26	0.83
Mysids	$\log \text{BAF} = 0.77 \log K_{ow} + 0.53$	0.59 - 0.94	25	0.77
Amphipods	$\log \text{BAF} = 0.61 \log K_{ow} + 0.61$	0.48 - 0.74	27	0.79
Oligochaetes	$\log \text{BAF} = 0.73 \log K_{ow} + 0.44$	0.51 - 0.94	26	0.67
Sculpins	$\log \text{BAF} = 1.08 \log K_{ow} - 0.70$	0.84 - 1.32	21	0.83
Alewives	$\log \text{BAF} = 0.83 \log K_{ow} + 0.81$	0.59 - 1.06	17	0.78
Small Smelt	$\log \text{BAF} = 0.92 \log K_{ow} - 0.02$	0.66 - 1.17	16	0.80
Large Smelt	$\log \text{BAF} = 0.99 \log K_{ow} - 0.22$	0.74 - 1.25	17	0.82