RRB 90-19

PESTICIDE RESIDUES IN FRESHWATER AND MARINE ZOOPLANKTON: A REVIEW WITH IMPLICATIONS FOR TROPHIC TRANSFER AND TOXICITY

by

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March 1990
NWRI Contribution #90-60

ABSTRACT

A review of the scientific literature on pesticide residues in freshwater and marine zooplankton indicates that despite the great number of pesticides in current use, only residues of the persistent organochlorine insecticides, many of which have been restricted or removed from general use in North America, have been determined. Much of this information is outdated. In addition, with the exception of the Great Lakes on which limited information is available, reports on residues in freshwater zooplankton are rare. Information on residues of the newer, less persistent but heavily used pesticides is lacking. As an alternative to field sampling and chemical analysis of endemic populations of zooplankton, scientists have modelled the bioaccumulation of pesticides in zooplankton using either laboratory microcosms or mathematical equations. However, the extent and importance of trophic transfer to higher food levels through this intermediary group of organisms is still controversial. In addition, the relationship between accumulation of pesticides and toxicity to zooplankton remains unresolved.

RÉSUMÉ

Une étude de la littérature scientifique sur les résidus de pesticides dans le zooplancton marin et d'eau douce montre que, malgré le grand nombre de pesticides couramment utilisés, seuls les résidus d'insecticides organochlorés persistants, dont l'usage de bon nombre a été limité ou dont l'usage général a été interdit en Amérique du Nord, ont été étudiés. Une grande partie de ces informations est périmée. De plus, à l'exception des Grands Lacs pour lesquels les données accessibles sont peu nombreuses, les rapports sur les résidus dans le zooplancton d'eau douce sont rares. Nous ne disposons pas d'informations sur les résidus de pesticides plus récents, moins persistants mais grandement utilisés. Des scientifiques ont établis des modèles de bioaccumulation des pesticides dans le zooplancton à l'aide de microcosmes expérimentaux ou d'équations mathématiques comme solution de rechange à l'échantillonnage sur le terrain et à l'analyse des populations endémiques de zooplancton. Toutefois, la portée et l'importance du transfert trophique à des niveaux supérieurs de la chaîne alimentaire par ce groupe intermédiaire d'organismes sont encore contestées. En outre, le rapport entre l'accumulation des pesticides et la toxicité pour le zooplancton n'est pas encore élucidé.

MANAGEMENT PRESPECTIVE

A review of the scientific literature on pesticide residues in freshwater and marine zooplankton indicates that, despite the great number of pesticides in current use, only residues of the organochlorine insecticides are often reported and much of this information is outdated. In addition, with the exception of the Great Lakes on which limited information is available, reports on residues in freshwater zooplankton are rare. Information on the residues of the newer, less persistent but heavily used pesticides are required. This paper also reviews information on the uptake and transfer kinetics of pesticides in zooplankton, either in laboratory microcosms or through the use of mathematical equations. Despite advances in the modelling of pesticide uptake by zooplankton, the extent and importance of trophic transfer to higher food levels through this intermediary group of organisms is still controversial. In addition, the relationship between accumulation of pesticides and toxicity to zooplankton remains unresolved. This paper provides a baseline to the available literature from which future research should proceed.

PERSPECTIVE-GESTION

Une étude de la littérature scientifique sur les résidus de pesticides dans le zooplancton marin et d'eau douce montre que, malgré le grand nombre de pesticides couramment utilisés, seuls les résidus d'insecticides organochlorés sont souvent signalés et une grande partie de ces informations est périmée. De plus, à l'exception des Grands Lacs pour lesquels les données accessibles sont peu nombreuses, les rapports sur les résidus dans le zooplancton d'eau douce sont rares. Des informations sur les résidus de pesticides plus récents, moins persistants mais grandement utilisés sont nécessaires. Le présent article porte également sur les informations concernant la fixation et la cinétique de transfert des pesticides dans le zooplancton, au moyen de microcosmes expérimentaux ou par le biais d'équations mathématiques. Malgré les progrès de la modélisation de la fixation des pesticides par le zooplancton, la portée et l'importance du transfert trophique à des niveaux supérieurs de la chaîne alimentaire par ce groupe intermédiaire d'organismes sont encore contestées. En outre, le rapport entre l'accumulation des pesticides et la toxicité pour le zooplancton n'est pas encore élucidé. Cet article constitue les données de base de la littérature existante à partir desquelles les recherches devraient être effectuées.

INTRODUCTION

Zooplankton are important and abundant components of both marine and freshwater ecosystems. They represent an integral link between the primary producers, invertebrates and fish in aquatic food webs by providing food for predators and by recycling essential nutrients through feeding on living and detrital material. Zooplankton are known to accumulate persistent lipophilic chemicals, particularly the organochlorine pesticides, to concentrations greater than those found in their surrounding environment and there is concern that this accumulation contributes to increased pesticide residues in higher trophic levels. For example, zooplankton, benthic amphipods, forage fish and top predators in the Great Lakes food-web have been found to contain progressively greater amounts of dieldrin, chlordane, and ΣDDT, corresponding to their trophic level (Whittle and Fitzsimons, 1983). Such accumulation is known to occur either by direct uptake from the water by surface adsorption and diffusion (Johnson et al., 1971; Crosby & Tucker, 1971; Sanders et al., 1981) or via ingestion of contaminated organic matter (Canton et al., 1975; Hansen et al., 1980; Harding, 1986). This concept of food chain amplification gained notoriety in the 1960's when it was observed that residues of DDT and its metabolites increased in a stepwise fashion from one trophic level to another in freshwater and estuarine environments (Hunt and Bischoff, 1960; Woodwell et al., 1967).

There is considerable confusion in the scientific literature over the extent to which food chain transfer of persistent

chemicals influences the potential for bioaccumulation in organisms of a higher trophic level (for a review, see Biddinger and Gloss, 1984). Pesticides with low water solubility and high stability are known to have a high affinity for lipid or fat tissues (Esser, 1986) and organisms at higher trophic levels have greater lipid pools than organisms of lower trophic levles (Ellgehausen et al., 1980). Thus, amplification of pesticides in aquatic ecosystems at increased trophic levels may be simply a function of the partitioning of chemicals between water and lipids in the bodies of these animals (Hamelink et al., 1971; Hamelink & Waybrant, 1976; Clayton et al., 1977). The issue has yet to be resolved. Nevertheless, the presence of lipophilic pesticides in zooplankton is made more critical by the suggestions by McNaught (1982b) and Harding (1986) that zooplankton play a major role in retaining and redistributing these compounds in the water column thus making the water column the main repositiory of persistent chemicals rather than the deep sediment.

A review of the scientific literature for reports of pesticides in zooplankton indicates that field populations of zooplankton have been analysed far less frequently for tissue residues of pesticides than fish, particularly salmonids (Hellawell, 1986). This is probably due to 1) the difficulty in separating zooplankton from other particulate organic matter collected by plankton nets 2) the size of sample required for quantitative detection and analysis of pesticides, and 3) a lack of comprehension about the economic benefit of zooplankton to

humans and their health.

RESIDUES IN MARINE ZOOPLANKTON

Marine zooplankton have been sampled more frequently than their freshwater counterparts and several reviews have been published tabulating concentrations of residues (see Kerr & Vass, 1973; Harding, 1986). Table 1 summarizes the ranges of pesticide residues reported in marine bulk plankton samples. Differences in concentrations of chemicals between aquatic organisms are diminished by basing concentrations on lipid weights rather than wet weight (Phillips, 1978); thus, data are recorded as both whole wet weight ($ng.g^{-1}$) and lipid weight ($ng.g^{-1}$) where available.

Despite the great number of pesticides in current use, most published data report only residues of the organochlorine insecticides or the non-pesticidal polychlorinated biphenyls (PCBs). Much of these data pre-date the banning of DDT and other organochlorine pesticides in North America. In addition, most field biomonitoring surveys only analyze biota for a standard list of high-priority pollutants. This list does not usually include the less persistent, more water-soluble pesticides which are transitory and likely found in biota only immediately following agricultural application. The high stability and persistence, low water solubility and high lipid solubility of organochlorines plus their continuous flux between sediment and water (Larsson, 1985) are all factors which allow these chemicals to remain in the water

column long after their use has been discontinued and thus reports on residues as recent as 1987 still record substantial levels of these compounds in aquatic organisms. In addition, developing countries are still using many of these chemicals.

Table 1 indicates that there are large differences in the contamination of zooplankton by pesticides in different areas of the world. However, the species composition of planktonic populations changes seasonally and geographically and this may explain some of the variability. The accidental incorporation of pesticides into plankton as they pass through the contaminated surface microlayer, rich in organic matter and lipids may also increase the variation (McNaught, 1982a). The physiological condition of the organisms, particularly seasonal fluctuations of lipid content with food availability and sexual cycle (Phillips, 1978; Gardner et al., 1985) may all affect residue levels of pesticides in zooplankton.

RESIDUES IN FRESHWATER ZOOPLANKTON

Reports of pesticide residues in freshwater zooplankton are limited and are mainly from government biomonitoring surveillance programs, especially of the Great Lakes. These programs are designed to assess temporal trends as well as the spatial distribution of contaminants within and between these lakes (Shear, 1984) but much of the information on zooplankton has not been updated (Table 2). Residues of organochlorines tend to be highest

in Lake Ontario with the exception of toxaphene in Lake Michigan. Whittle and Fitzsimons (1983) compared organochlorine body burdens in surface zooplankton and the mysid, Mysis relicta, from the eastern and western basins of Lake Ontario and found that mean levels of ΣDDT and dieldrin in the western basin (where the Niagara River enters) either equalled or exceeded the eastern basin values although the results were not statistically significant. The Niagara River is a known source of many persistent pesticides such as chlordane, lindane, dieldrin, endrin, heptachlor epoxide and DDT (Fox et al., 1983) and is a likely contaminant of Lake Ontario. Mirex, which is a known contaminant of fish in Lake Ontario (Kaiser, 1974; Whittle and Fitzsimons, 1983), has not been detected in net plankton. Samples of net plankton from the Upper Great Lakes (Lakes Huron and Superior) have been analyzed for 15 organochlorines and 17 organophosporus pesticides in addition to PCBs (Glooschenko et al., 1976). In this study, only PCBs could be quantified; dieldrin and p,p'-DDE were reported in trace amounts throughout the sampling region but no other pesticides were detected. High levels of toxaphene in Lake Michigan are likely due to atmospheric deposition of this chemical (Rice and Evans, 1984).

Data on natural levels of pesticides in zooplankton in smaller bodies of water in North America are rare and only one report can be cited. Hannon et al., (1970) reported on the ecological distributions of several chlorinated hydrocarbons (ΣDDT, dieldrin, aldrin, heptachlor epoxide, heptachlor and lindane) in Lake Poinsett, South Dakota. Insecticide residue levels in plankton

ranged from 0.75-5.0 $ng.g^{-1}$ wet weight representing an average bioconcentration factor of 37. The potential for the biomagnification of contaminants in aquatic ecosystems is often expressed as the bioconcentration factor (BCF) i.e., the ratio of the concentration of the chemical in the organism to the concentration in the environment at equilibrium and is a quantitative measure of the accumulation property of the chemical (Esser, 1986). The residues in Lake Poinsett zooplankton represented 1-34% of the total composition of insecticides present in the lake ecosystem, with DDT, DDD and DDE accounting for most of the residues. Other persistent organochlorine insecticides such as endrin or toxaphene were not detected in the zooplankton in this lake.

RESIDUES IN MESOCOSM STUDIES

An alternative approach to biomonitoring surveys in understanding the dynamics of pesticides in zooplankton is to experimentally treat natural bodies of water or man-made enclosures (mesocosms) with pesticides (Kaushik et al., 1985) and study the fate and distribution of these chemicals in the biota. Hughes et al. (1970) studied the fate of the chlorinated hydrocarbon toxaphene applied to several Wisconsin lakes for rough fish control and determined concentrations of the chemical in water, suspended solids, net plankton, fish and sediment. Residues of toxaphene were found to range from 0.250-0.317 $ng.g^{-1}$ in net plankton

representing an apparent bioconcentration factor of 1.4×10^5.

The fate of DDE and lindane added to the epilimnion of a seasonally thermally-stratified, flooded limestone quarry was followed for one year (Hamelink & Waybrant, 1976). DDE was rapidly distributed throughout the water column due to adsorption to suspended sediment from runoff generated by a rainstorm (concentrations of DDE in the water column declined 69% within five days possibly due to settling of this material). Zooplankton rapidly took up high concentrations of DDE (Table 3) for five days and then gradually lost residues as the insecticide concentrations declined in the water. In contrast, lindane remained in the epilimnion until fall turnover with water concentrations declining by only 50% by day 123. Zooplankton also took up lindane (Table 3) but concentrations were not as high as those of DDE. In addition, bioconcentration factors for zooplankton at equilibrium were considerably lower for lindane ($3-4 \times 10^2$) than for DDE ($2-6 \times 10^{-1}$).

The trend in pesticide usage in agriculture in the industrialized nations has been away from persistent compounds that bioaccumulate. However, little is known about other common pesticides that potentially can contaminate aquatic ecosystems with the exception of the study by Klaassen & Kadoum (1979). In this study, the distribution and retention of the herbicide, atrazine, and the carbamate insecticide, carbofuran, in a pond system was determined following surface application. A concentration of 0.3 mg.atrazine $litre^{-1}$ resulted in residues of 165-285 $ng.g^{-1}$ in the

zooplankton throughout the two-year observation period. However, bioconcentration factors were low because levels of atrazine in the water were high (195 $\mu g.litre^{-1}$). Treatment of ponds with 0.025 and 0.050 $mg.litre^{-1}$ of carbofuran resulted in no detectable residues in the biological components (including zooplankton) of the pond systems. Lake column studies using man-made lake column simulators treated with several concentrations of atrazine resulted in similar residues in both the biota, including daphnids, and the water (Millard et al., 1979).

The major advantage of measuring pesticide residues in endemic populations of zooplankton is that field samples give an indication of the true biological availability of ambient levels of pesticides over time at the site of collection. However, the effects of species, age, size and chemical content of organisms, reproductive stage, and environmental variables such as temperature, levels of suspended particulate matter, etc., on uptake are had to differentiate (Ellgehausen et al., 1980).

RESIDUES IN MICROCOSM STUDIES

A simplified approach to the determination of pesticide uptake by zooplankton is to conduct experiments in the laboratory where a variety of static, continuous flow, recirculating and/or compartmentalized model ecosystems (microcosms) have been developed to estimate the potential hazards of pesticides in the aquatic

environment under controlled, replicated conditions (Canton et al., 1975; Isensee & Yockim, 1980). Cladocerans, particularly Daphnia magna, have been the organisms most extensively studied either as individual populations or as components of simplified food chains. These studies (Table 4) indicate that lipophilic pesticides such as the organochlorines and to a lesser extent the newer insecticides, such as the synthetic pyrethroids (e.g., fenvalerate), are bioconcentrated/bioaccumulated by zooplankton over a short time period. Other insecticides (e.g., organophosphates and carbamates), herbicides (with the exception of trifluralin) and fungicides remain at low to non-detectable levels in daphnids and show no tendency to concentrate. These results may help to explain why natural zooplankton do not contain detectable residues of pesticides other than the organochlorines.

MODELING RESIDUES IN ZOOPLANKTON

The residue levels of pesticides in zooplankton, as in many other aquatic organisms, can be predicted from kinetic equations that have been developed to model the behavior of contaminants in the aquatic environment (Ellgehausen et al., 1980; Spacie & Hamelink, 1985; Connell, 1986; Harding, 1986). Residues are the observed consequence of both the uptake and clearance processes at a specific time (Kerr & Vass, 1973). The simplest equations are as follows:

Uptake

a) Uptake phase

$$C_B = C_W \, k_1/k_2 \, (1-e^{k2t}) \qquad (1)$$

b) Steady-state equilibrium

$$C_B = BCF \, C_W \qquad (2)$$

where

C_B = concentration of pesticide in animal

k_1 = uptake rate constant

k_2 = depuration rate constant

t = time

C_W = concentration of pesticide in water

BCF = bioconcentration factor = k_1/k_2 as $t \rightarrow \infty$

Depuration

$$C_B = C_T \, e^{-k2t} \qquad (3)$$

where

C_T = total concentration of pesticide in the organism or population at the start of depuration

The uptake equation (1) describes a curvilinear increase in body burden with an asymptotic approach to a "plateau" (i.e., steady-state). Elimination is assumed to follow first-order kinetics. The organism is treated as a single homogenous compartment and assumptions include i) no growth has taken place ii) uptake is from water only (bioconcentration) and iii) uptake is proportional to pesticide concentration. Harding & Vass (1977, 1979) determined the uptake kinetics for p,p'-DDT in the marine

copepod, Calanus finmarchicus, and based on these results, suggest that the equilibrium concentrations of residues in natural zooplankton can be predicted from water contaminant levels alone. For example, the model estimates approximate concentrations of 6.5 $ng.g^{-1}$ wet weight for C. finmarchicus from a water concentration of 0.1 $ng.litre^{-1}$, a value which falls well within the range of observed DDT concentrations in marine crustacean zooplankters. Hawker and Connell (1986) described linear relationships for daphnids between the logarithms of the equilibrium bioconcentration factors (BCFs) or the reciprocal clearance rate constants ($1/k_2$) and the logarithm of the octanol-water partition coefficient (K_{ow}) for various lipophilic chemicals. Using these relationships, calculations of the time required for organochlorines to reach a steady-state equilibrium in zooplankton may be determined and bioconcentration factors predicted.

It has been hypothesized that uptake of pesticides dissolved in water is of greater importance than ingestion of contaminated food particularly in the lower trophic levels (Hall et al., 1986). Reinert (1972), Canton et al. (1975) and Hanson (1980) all conclude that greater residues of organochlorines were picked up directly from water than from contaminated algal food ingested by daphnids. Day & Kaushik (1987a) found that accumulation of fenvalerate was not significantly affected by increasing concentrations of Chlamydomonas reinhardii to which the pesticide was known to adsorb.

The kinetic equations used to describe the flux of

contaminants between zooplankton and water can be expanded to include pesticides assimilated through feeding on contaminated food as well as growth of the organism over the exposure time (Thomann, 1981) as follows:

$$X = \frac{(k_1 C_w + \alpha R C_f)\, W_o}{K'} [e^{gt} - e^{-k2t}] + X_o e^{-k2} \qquad (4)$$

where

X = total body weight of residue (μg)

W = body weight

α = assimilation efficiency of pesticide from food (μg absorbed per μg ingested)

R = weight specific ration for feeding rate (g ingested per g of body weight per day)

C_f = concentration of contaminant in food ($\mu g.g^{-1}$)

$K' = k_2 + g$

g = growth rate constant

X_o and W_o = total residue and body weight at the beginning of the observation period

Harding et al. (1981) developed a version of this equation to model the accumulation of p,p'-DDT by C. finmarchicus feeding on contaminated phytoplankton, Thalassiosira weisflogii. Model simulations indicate that it is not necessary to invoke direct uptake from water to arrive at published levels of DDT in copepods. In this model, organochlorine retention from food in rapidly growing copepeods exceeds clearance rates early in life but this reverses at some point due to decreasing specific ingestion rates

as copepods grow to adult size. The maximum bioaccumulation derived from food is predicted to be directly proportional to organochlorine assimilation efficiency and is related to environmental temperature. The model estimates that populations of C. finmarchicus will reach an equilibrium with environmental DDT concentrations within 4-12 generations, depending on temperature and food and water contamination. The authors suggest that this equilibrium is partially due to carry-over of residues in copepod eggs.

These models are helpful in predicting the residues of persistent pesticides to be expected in zooplankton; however, they are understandably simplistic. More experimental research in both the laboratory and field under a variety of environmental conditions and using pesticides with differing physicochemical characteristics will be necessary before generalized equations can be accepted. Suspended particulate organic matter and dissolved or colloidally dispersed organic macromolecules, such as humic substances in natural waters, have been shown to exert significant sorptive forces towards hydrophobic chemicals (Esser, 1986; McCarthy & Black, 1988), and little information is available on how these molecules affect the uptake of contaminants by zooplankton (Thomann, 1981; Baker et al., 1981).

RELATIONSHIP BETWEEN RESIDUE LEVELS AND TOXICITY

Although there is a great deal of literature on the acute

(Lewis & Weber, 1985) and chronic (Canton & Adema, 1978; Parkhurst et al., 1981) toxicity of pesticides to zooplankton, there is very little known about the level of residues of pesticides in zooplankton which affect the long-term survival of these organisms, especially under field conditions. Harding & Vass (1979) reported that p,p'-DDT was acutely lethal in the laboratory to C. finmarchicus at body concentrations greater than 80 ng. mg^{-1} dry weight. Day & Kaushik (1987a) found that at water concentrations of 0.420 and 0.084 µg fenvalerate.$litre^{-1}$, Daphnia galeata mendotae accumulated residues of 0.75-1.08 and 0.51-0.87 $\mu g.g^{-1}$ wet weight respectively which may be responsible for the sublethal toxic effects observed in other studies (Day & Kaushik 1987b,c). For example, filter-feeding rates of D. galeata mendotae decreased significantly after 24 h exposure to ≥0.05 µg fenvalerate.$litre^{-1}$. In addition, survival, average brood size, and average number of broods per female daphnid were reduced during chronic life-cycle toxicity tests at concentrations of 0.01-0.1 µg fenvalerate. $litre^{-1}$. Impairment of metabolic activity by pesticides with subsequent toxicological effects on physiological processes i.e., rates of filtration, could lead to a reduced chance for reproduction and survival under field conditions. Treatment of large volume, in situ lake enclosures with fenvalerate resulted in short-term changes in the feeding behavior of zooplankton at a nominal concentration of 0.05 µg.$litre^{-1}$ and reductions in the densities of several species of zooplankton at higher concentrations (Day et al., 1987).

Few studies have provided a direct link between the site of action of a pesticide and the observed toxic effects. However, Schultz and Kennedy (1976) found that sublethal concentrations of the herbicide amitrole in D. magna caused organelle swelling and folding of the outer membranes of muscle mitochrondria and resulted in immobilization. Several researchers have observed that exposure of daphnids to some pesticides (e.g., parathion, 2,4-D and 1,4-benzoquinone) results in decreased activities of certain enzymes (e.g., aliesterases, cholinesterases, and glutathione transferases (Dortland, 1978; Dierickx, 1987). Heisig-Gunkel and Gunkel (1982) studied the effects of body composition of Daphnia pulicaria on the bioaccumulation of atrazine at several temperatures. At low temperatures (i.e., 8°C), atrazine residues were found mainly bound to protein whereas with increasing temperatures (12-20°^C), association of the pesticide with protein decreased and accumulation in lipid became of greater importance.

SUMMARY AND CONCLUSIONS

The interrelationship of a pesticide in the environment, its detection in organisms such as zooplankton and the observation of effects, either lethal or sublethal, are schematisized in Figure 1. Environmental variables, physiological condition of the organisms, physicochemical characteristics of the pesticide and the presence of dissolved and particulate organic matter will all act as modifiers on the overall bioaccumulation and toxicological

effects of any contaminant (McCarthy & Black, 1988). At very low levels of pesticides in the environment, there may be no residues detected in the organisms and no biological effects (Figure 1a). As concentrations increase or under conditions of continuous input, levels of detectable pesticides in zooplankton may cause biological effects that are either acute or chronic, resulting ultimately in death. Conversely, the organisms may experience a toxic effect but residues may either be below the level of analytical detection or not bioaccumulated to any extent. The measurement of residues under these circumstances does little in the determination of environmental hazard but ecological damage may still be occurring. Many pesticides may not be particularly persistent nor bioaccumulative yet they may exert a toxic effect on aquatic organisms (e.g., organophosphate insecticides, synthetic pyrethroids, etc.). Pesticides which fall into this category present a problem in the assessment of environmental damage from pesticide contamination. Techniques to detect the effects of very low concentrations of non-lipophilic pesticides in natural waters on biota need to be further developed e.g., biochemical techniques which detect changes at the cellular level and can be related to reductions in growth and/or reproduction.

Finally, organisms may not be affected by the pesticide because they can tolerate or store large concentrations of the chemical in their bodies (Figure 1b). The presence of lipophilic and persistent organochlorine insecticides in routine biomonitoring may fall into the latter category. The long-term biological

effects of these residues on zooplankton are unknown. The main environmental hazard resulting from residues of pesticides in zooplankton may prove to be as a repository for transfer of these chemicals to higher trophic levels where their detrimental effects, at least in the well-known case of DDT, have been demonstrated.

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TABLE 1. RESIDUES OF PESTICIDES DETECTED IN MARINE NET PLANKTON

Pesticide	Mesh Size µm	Whole Body Wet Weight ($ng.g^{-1}$)	Lipid Weight ($ng.g^{-1}$)	Location	Reference
DDT	--	160	--	--	Robinson et al., 1967
	>239	40	--	Atlantic Ocean near Long Island	Woodwell et el., 1967
	>333	<0.01-9.5	120-1250	N. Atlantic	Grice et al., 1972
	>300	0.2-34	--	Gulf of Mexico, Caribbean	Giam et al., 1973
	>300	2-107	20-8000	N. Atlantic	Williams & Holden, 1973
	>300	1.3	560	North Sea off Holland	Ten Berge & Hildebrand 1974
	>333	2-3	258-3681	Gulf of Mexico	Baird et al., 1975
	>280	1-11	--	Mediterranean Sea	Fowler & Elder, 1981
	>300	1.7	0.44	NW Pacific	Tanabe et al., 1984
	>300	--	50-85	N. Pacific & Bering Sea	Kawano et al., 1986
	>300	55-320	3125-38,000	Eastern Arabian Sea	Kannan & Sen Gupta 1987
	>250	45-341	--	Mediterranean Sea	Sanchez-Pardo & Rovira, 1985
p,p'-DDT	>300	0.82	0.34	N. Pacific & Bering Sea	Kawano et al., 1986
	>250	22-204	--	Mediterranean Sea	Sanchez-Pardo & and Rovira, 1985

TABLE 1. (continued)

Pesticide	Mesh Size μm	Whole Body Wet Weight $ng.g^{-1}$	Lipid Weight $ng.n^{-1}$	Location	Reference
p,p'-DDE	>300	0.19	0.11	North Sea off Holland	Ten Berge & Hildebrand 1974
	>280	<0.5	--	Mediterranean Sea	Fowler & Elder, 1981
	>250	16-94	--	Mediterranean Sea	Sanchez-Pardo & Rovira 1985
HCH	>300	0.26	0.067	NW Pacific	Tanabe et al., 1984
	>300	--	100-190	N. Pacific & Bering Sea	Kawano et al., 1986
	>250	2-30	--	Mediterranean Sea	Sanchez-Pardo & Rovira 1985
Chlordane	>300	--	40-72	N. Pacific & Bering Sea	Kawano et al., 1986
Dieldrin	>300	<1-230	--	N. Atlantic	William & Holden, 1973
	--	160	--	Off North U.K.	Robinson et al., 1967
	>333	<1-16	<1-6742	Gulf of Mexico	Baird et al., 1975
	>300	1-48	650	North Sea off Holland	Ten Berge & Hildebrand 1974
Endrin	>300	0.60	0.24	North Sea off Holland	Ten Berge & Hildebrand 1974

TABLE 2. RESIDUES OF PESTICIDES DETECTED IN GREAT LAKES NET PLANKTON AND THE MYSID, *Mysis relicta*.

Pesticide	Plankton Type Mesh Size μm	Lake				Reference
		Ontario	Erie	Michigan	Superior	
		Lipid Weight of Pesticide ($ng.\ g^{-1}$)				
DDT 1983	Net plankton	60-80	41	-	tr*	Whittle & Fitzsimons, 1983 Borgmann & Whittle 1983
	Mysis relicta	59-280	-	-	tr-53	Rathke & McRae, 1989 Veith *et al.*, 1977 Glooschenko *et al.*, 1976
p,p'-DDT	Net plankton	30-40	14.3	-	tr	Whittle & Fitzsimons, 1983 Rathke & McRae, 1989
	Mysis relicta	48-140	-	-	-	
Dieldrin 1983	Net plankton	17-19	23	-	tr	Whittle & Fitzsimons, 1983
	Mysis relicta	-	-	-	<1	Veith *et al.*, 1977
Chlordane	Net plankton	20	10	-	-	NRCC, 1974
Toxaphene	Net plankton	-	-	85-560		Rice & Evans, 1984
	Mysis relicta	-	-	190-432		

*tr = trace

TABLE 3. INSECTICIDE CONCENTRATION ($ng.g^{-1}$) AND BIOCONCENTRATION FACTORS RELATIVE TO WATER FOR DDE AND LINDANE IN ZOOPLANKTON. (after Hamelink and Waybrant, 1976).

Day	DDE Residue	BCF	Lindane Residue	BCF
<0	5		ND*	
1	58	1.31×10^3 TR*		
5	775	5.16×10^4	26.1	414
21	223	6.32×10^4	10.0	170
42	120	3.64×10^4	22.6	448
60	60	2.86×10^4	9.3	314

*ND = nondetectable
*TR = trace

TABLE 4. BIOCONCENTRATION OF PESTICIDES BY DAPHNIDS IN MICROCOSMS

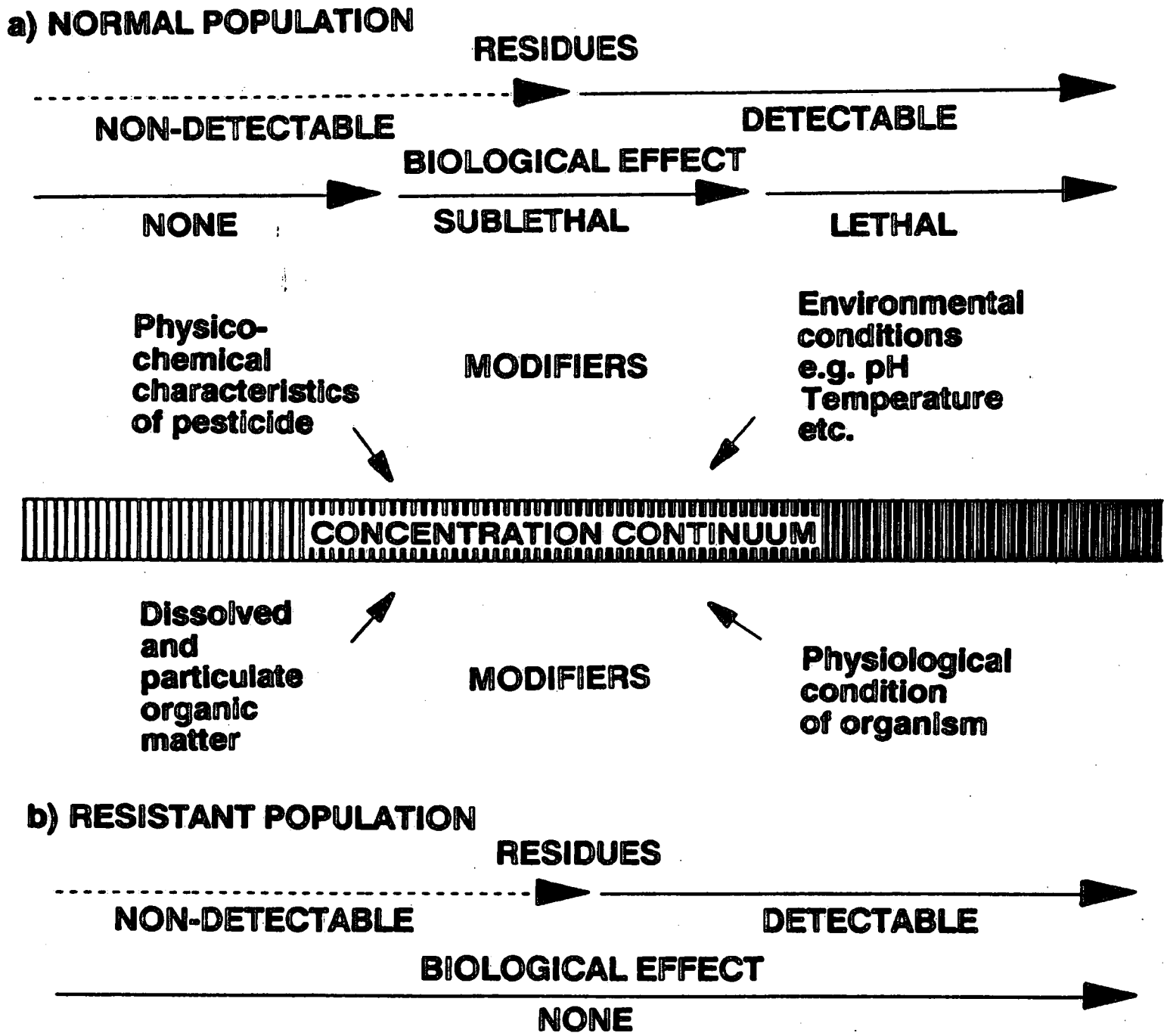
Pesticide	Type of Microcosm	Days of Exposure	Wet Weight Residues in Daphnids ($ng.g^{-1}$)	BCF	Reference
Insecticides					
DDT	Static Recirculating	7	30	2500	Ohkawa et al., 1980
	Continuous flow	3	9170	>100,000	Johnson et al., 1971
Dieldrin	Static terrestrial-water	33	5	2535	Sanborn, 1974
Chlordane	Static	3	130	12,000	Moore et al., 1977
Lindane	Static	3	2	173	Sanborn, 1974
Fenvalerate	Static, recirculating	7	239	683	Ohkawa et al., 1980
Parathion	Static, terrestrial-water	33	ND*	-	Sanborn, 1974
Carbaryl	Static, terrestrial-water	33	ND	-	Sanborn, 1974
Carbofuran	Static, terrestrial-water	33	ND	-	Sanborn, 1974
Herbicides					
Atrazine	Static, terrestrial-water	33	0.0013	<1	Sanborn, 1974 Francis et al., 1985
	Static, wetland	42	279	50	Huckins et al., 1986
Simazine	Static, recirculating	30	0-0.3	0.7	Yockim et al., 1980
Dicamba	Static,	33	ND	-	Sanborn, 1974 Francis et al.,

TABLE 4. (continued)

Pesticide	Type of Microcosm	Days of Exposure	Wet Weight Residues in Daphnids $ng.g^{-1}$	BCF	Reference
Herbicides					
Alachlor	Static, terrestrial-water	33	ND	-	Francis et al., 1985
Linuron	Static,	33	ND	-	Francis et al., 1985
Trifluralin	Static, recirculating	30	0-19.6	0-1293	Yockim et al., 1980
	Static, wetland	42	566	943	Huckins et al., 1986
	Static, terrestrial-water	33	ND	-	Sanborn, 1974
Fungicides					
Captan	Static, terrestrial-water	33	ND	-	Sanborn, 1974
Hexa-chlorobenzene	Static, terrestrial-water	33	0.6	0	Sanborn, 1974
Penta-chlorophenol	Static, terrestrial-water	30	ND	165	Metcalf & Sanborn, 1975

*ND = non-detectable

FIGURE 1. THE RELATIONSHIP AMONGST THE CONCENTRATION OF A PESTICIDE IN THE ENVIRONMENT, THE DETECTION OF RESIDUE LEVELS IN ORGANISMS AND THE OBSERVATION OF EFFECTS (LETHAL OR SUBLETHAL).


a) NORMAL POPULATION
RESIDUES
NON-DETECTABLE
DETECTABLE
BIOLOGICAL EFFECT
NONE
SUBLETHAL
LETHAL
Physico-chemical characteristics of pesticide
MODIFIERS
Environmental conditions e.g. pH Temperature etc.
CONCENTRATION CONTINUUM
Dissolved and particulate organic matter
MODIFIERS
Physiological condition of organism
b) RESISTANT POPULATION
RESIDUES
NON-DETECTABLE
DETECTABLE
BIOLOGICAL EFFECT
NONE