Effects of Pyrethroid Insecticides on Nontarget Invertebrates in Aquatic Ecosystems[1]

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ABSTRACT This review presents data on the impacts of pyrethroid insecticides on nontarget aquatic invertebrates. Toxicological information on both photolabile and photostable pyrethroids against insects and mammals has been evaluated. A detailed analysis is also provided on the contamination of aquatic habitats by pyrethroids through direct, purposeful use in pest control, and indirect routes such as spray drift, run-off and erosion processes.

Based on laboratory data, some of the photostable and more effective compounds could be ranked in order of decreasing toxicity to nontarget species as: permethrin = fenvalerate < cypermethrin < deltamethrin. In field studies, depending on their use pattern in agricultural, silvicultural and public health pest control programs, nontarget aquatic insects such as Ephemeroptera, Odonata, Plecoptera, Hemiptera, Coleoptera and Trichoptera, and crustacean groups such as Cladocera, Ostracoda, Copepoda, Amphipoda, Isopoda and Decapoda, were more severely affected by exposure to pyrethroids than other invertebrates. In most of these cases, however, the population recovery of affected species to pretreatment levels was noticed within weeks to months after application. Moreover, the impact of these transient effects of pyrethroids on nontarget fauna resulted in short-term reductions in the populations of dependent fish species in aquatic ecosystems.

KEY WORDS Pyrethroids, nontarget, aquatic, invertebrates.

Chemical insecticides constitute one of the most reliable and needed components of pest control programs in agriculture, forestry, home-garden, and public health. The use of insecticides in agricultural and forest ecosystems can result in indirect contamination of aquatic habitats through drift, wind and soil erosion, and rain. In control programs of disease vectors, chemical insecticides are directly applied to extensive portions of aquatic habitats in order to control the aquatic stages of pests and disease-vector insects such as mosquitoes, chironomid midges and blackflies. Some nontarget biota in aquatic environments are as vulnerable as the target organisms to the toxic action of insecticidal chemicals. In some cases the action of pesticides may be even more severe on nontarget insects, and invertebrates that are phylogenetically close to insects.

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Natural pyrethrins, and especially the newer photostable pyrethroids, have demonstrated high efficacy against pest and disease vector insects with low toxicity to mammals. The impact of these new neurotoxic pyrethroids on the well-being of nontarget aquatic invertebrates has been the subject of a number of recent studies. The toxicity and risks of pyrethroids to nontarget organisms have been reviewed by Mulla et al. (1979), Hill (1985), and Smith and Stratton (1986). However, these articles do not thoroughly examine the impact of pyrethroids on nontarget aquatic invertebrates in field situations. The purpose of the present review, therefore, is to synthesize, analyze and update the information on the impact of pyrethroids on nontarget invertebrates in aquatic ecosystems with special emphasis on use patterns of these materials.

PYRETHROIDS

In the wake of insect resistance to various organophosphorus compounds, carbamates and natural pyrethrins, a new group of synthetic analogues of pyrethrins - pyrethroids, was developed and evaluated against insect pests in agricultural, forestry, animal health and public health sectors. Of these compounds, allethrin was the first pyrethrin-like compound developed in the early 1950's. Like natural pyrethrins, allethrin showed the same order of toxicity as pyrethrins to insects coupled with low toxicity to mammals; it was also susceptible to catabolic enzymes and sunlight (Chen and Casida 1969). In the early 1960's new pyrethroids were synthesized and developed for insect control, thereby replacing natural pyrethrins (Barthel 1961). During the early stages of their development, several of these compounds, *e.g.*, allethrin, bioallethrin, cismethrin, resmethrin, bioresmethrin, and tetramethrin, were shown to have good knockdown properties against the housefly (Hayashi and Hatsukade 1968). Resmethrin appeared to be almost 20 times more toxic to the house fly than natural pyrethrins (Elliott et al. 1967). Tetramethrin, which was originally synthesized by Kato et al. (1964), appeared to have more powerful knockdown properties than insect killing action as compared with some of the other compounds (Nishiwaza 1971). Nonetheless, most of these pyrethroids such as allethrin, bioallethrin, cismethrin, resmethrin, bioresmethrin, and tetramethrin, lacked stability in the air and sunlight (Elliott et al. 1973) and were not suitable for use in outdoor situations, especially aquatic habitats, thus posing little or no hazard to aquatic fauna.

The synthetic pyrethroids developed in the early years had good insecticidal properties with low mammalian toxicity, but their instability in air and light remained a major problem in long-range control programs. In 1973, however, phenothrin was synthesized, and was found to be more photostable than allethrin, furamethrin, resmethrin, and tetramethrin. It had stronger insecticidal activity than resmethrin but lower knockdown activity than the other compounds (Fujimoto et al. 1973). Studies on modifying the photo-labile moieties, i.e., acid and alcohol moieties, resulted in the synthesis of other photostable insecticides such as deltamethrin (= decamethrin, Elliott et al. 1974), cypermethrin (Elliott et al. 1975), fenvalerate (Ohno et al. 1976), and cyfluthrin (Behrenz et al. 1983). Some of the above mentioned pyrethroids with data on their toxicity to both insects and mammals are presented in Table 1.

Table 1. General chemical and toxicological information on pyrethroids.

Common name	Code number or other name(s)	Chemical description	Mammalian toxicity[a,b]	Insect toxicity[c]
Natural pyrethrin	–	–	900	1,100 [d]
Allethrin	Allyl homolog of Cinerin I, ENT 1750 Pynamin	[(±)-3-allyl-2-methyl-4-oxocyclopent-2-enyl (±) *cis, trans*-chrysanthemate)	1,500 (685 - 2430)	940 [e]
Bioallethrin	Pynamin-Forte®, Esbiol®	[(±)-3-allyl-2-methyl-4-oxocyclopent-2-enyl (±)*trans*-chrysanthemate]	–	420 [d]
Bioresmethrin	FMC 18739, NRDC 107, RU 11484, SBP 1390, Chryson Forte®, Resburthrine	[5-benzyl-3-furylmethyl(+)*trans*-chrysanthemate]	> 8,000	9 [d]
Cismethrin	NRDC 119, RU 12063 Cismethrin	[5-benzyl-3-furylmethyl(+)*cis*-chrysanthemate]	100	22 [d]
Cyfluthrin	FCR 1272, Oko®, Mafu®, Baythroid-H	[(cyano-(4-fluoro-3-phenoxyphenyl)-methyl-3(2,2-dichloroethanyl)-2,2-dimethylcyclopropanecarboxylate]	500	1 [d]
Cypermethrin	CCN 52, FMC 30980, NRDC 149, PP 383 WL 43467, AMMO®, Barricade®, Cymbush®, Fastac, Folcord®, Imperator®, Kafil Super®, Polytrin®, Ripcord®, Stockade®	[RS-α-cyano-3-phenoxybenzyl,IRS,*cis,trans*-3-(2,2-dichlorovinyl)-2,2-dimethylcyclo-propanecarboxylate]	500 310	210 [b]
Deltamethrin (= decamethrin)	NRDC 161, FMC 45498, RU22974, OMS 1998 Butoflin®, Butox®, Decis®	[S-α-cyano-3-phenoxybenzyl, 1R,cis-3-(2,2-dibromovinyl)-2,2-dimethylcyclopropane-carboxylate]	70 - 140 135 - 535	1 [d]
Fenpropathrin	S-3206, SD 41706 WL 41706, Danitrol®, Meothrin®, Rody®	[α-cyano-3-phenoxybenzyl-2,2,3,3-tetra-methylcyclopropanecarboxylate]	107 - 164	0.27 [f]

Table 1. Continued.

Common name	Code number or other name(s)	Chemical description	Mammalian toxicity[a,b]	Insect toxicity[c]
Fenvalerate	S-5602, SD 43775, Pydrin®, Sumicidin®	[α-cyano-3-phenoxybenzyl,2-(4-chlorophenyl)-3-methylbutyrate]	450	38 [b]
Fluvalinate	–	[N-[2-chloro-4-(trifluoromethyl)phyenyl-DL-valine-α-cyano-(3-phenoxphenyl)methyl ester]	–	
Kadethrin	RU 15525	[5-benzyl-3-furylmethyl,1R,*cis*-2,2-dimethyl-3-(2'-oxo-3'-thiacyclopentylidene-methyl)-1-cyclopropanecarboxylate]	140 - 1,300	34 [b]
Permethrin	FMC 33297, NRDC 143, OMS 1821, PP 557, S-3151, SBP 1513, WL 43479, Ambush®, Coopex®, Ectiban®, Eksmin®, Kafil®, Outflank®, Permasect®, Pethrine®, Picket®, Pounce®, Pramex®, Qamlin®, Stomoxin®	[3-phenoxybenzyl,1R,*cis,trans*-3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropanecarboxylate]	2,000 430 > 5,000	60 [b]
Phenothrin	ENT 27972, OMS 1810, S-2539, Pesguard®, Sumithrin®, Wellcide®	[3-phenoxybenzyl,1R,*cis,trans*-chrysanthemate]	> 10,000	30 [b]
Resmethrin	FMC 17370,NRDC 104, SBP-1381m/Restrin®, Chryson®	[5-benzyl-3-furylmethyl(+)*cis,trans-chrysanthemate]*	3,000 > 2,500 - > 5,000	22 [e]
Tetramethrin	FMC 9260, Phthalthrin, Neo-Pynamin®	[3,4,5,6-tetrahydrophthalimidomethyl(±) *cis, trans*-chrysanthemate]	> 5,000	210 [d]
Tralomethrin	RU 25474	[RS-α-cyano-3-phenoxybenzyl,IRS,*cis*-3(1,2,2,2-tetramoethanyl)-2,2-dimethylcyclopropanecarboxylate]	–	–

[a] Oral LD_{50} to rat, mg/kg.
[b] Elliott et al. (1978), Miyamoto, (1976), Riley (1985), and Worthing and Walker (1983).
[c] Expressed in ng/fly (LD_{50}).
[d] Behrenz et al. (1983).
[e] Calculated from *b* and *d* sources.
[f] LC_{50} (ppb) to fourth instar-larvae of *Culex quinquefasciatus* Say (Mulla et al. 1982).

The advent of photo-stable pyrethroids in the mid-1970's opened a new chapter in the history of world pest control. Since 1976 there has been a multifold increase in the worldwide usage of pyrethroid insecticides. According to Herve (1985), the user-value of pyrethroids in terms of millions of U.S. dollars was 10 in 1976, 80 in 1977, 220 in 1978, and 300 in 1980. In nonagricultural uses of pyrethroids, such as veterinary, animal houses, public health, household and industry, the user-value of pyrethroids amounted to U.S. $100 million in 1980 and this value was estimated to increase threefold in 1985 (Herve 1985).

MODE OF ENTRY OF PYRETHROIDS INTO AQUATIC ECOSYSTEMS

The entry of insecticides into the environment can occur in several ways. Direct sources of environmental contamination by insecticides include purposeful applications to control insect pests in agriculture, horticulture, silviculture (DeBoo 1980, Hull 1982, Herve 1985) and pests and disease vectors in public health (Elliott et al. 1978, Mulla et al. 1978, 1979, 1980, 1982, Baldry et al. 1981). The indirect entry or transport of pesticides into the environment is possible through wind, water, and food or feed (Westlake and Gunther 1966). A brief synopsis by Mulla et al. (1981) identifying the direct and indirect sources of pesticide entry into the environment, is given as follows:

I Direct sources:
- A) Applications to control insect pests in agriculture, forestry, turf, home-garden, and floriculture
- B) Application to livestock against pests and disease vectors
- C) Soil applications against subterranean pests
- D) Water treatments to control weeds, mosquitoes, midges, blackflies, trash fish, etc.
- E) Residual structural applications to control mosquitoes and other pests of humans and animals

II. Indirect entry from main sources:
- A) Drift (air), rain, and snow
- B) Animal dips
- C) Soil erosion through wind, water, etc.
- D) Sanitation system carrying pesticides from washing and cleaning of equipment and containers
- E) Industrial wastes from pesticide manufacturing plants
- F) Dumping of pesticides
- G) Spilling of pesticides
- H) Decaying pesticide-laden plant debris
- I) Dead animals and animal excreta

In public health, larvicides such as cypermethrin, deltamethrin, fenpropathrin, fenvalerate and permethrin are used against mosquitoes (Mulla et al. 1978, 1982) and deltamethrin and permethrin could be used against blackflies (Muirhead-Thompson 1977, 1978, 1981a,b, Mohsen and Mulla 1981, Bellec et al. 1983). In forestry, permethrin was extensively tested in the control of spruce budworm in the pine forest ecosystem in Canada (DeBoo 1980). Ponds and streams in the pine forest were directly exposed to aerial application of permethrin. In agricultural crop situations, irrigation water in canals and ditches around fields can receive direct spray deposits from aerial applications of pyrethroid chemicals such as cypermethrin, deltamethrin and permethrin in cotton pest control (Davis et al. 1977, Ruscoe 1979, Herve 1985).

Of the indirect modes of entry into aquatic habitats, insecticide drift by wind and erosion or transport of pyrethroid-contaminated sediment through the agency of wind and water, are more common than other routes. Contamination of ponds, streams and water ditches adjacent to cotton, potatoes, sugar beet and vineyards by cypermethrin and permethrin through spray-drift or runoff, was demonstrated in field trials (Crossland et al. 1982). Although there is no documented evidence on the erosion or transport of pyrethroid-contaminated soil particles through wind, the transport of pyrethroid residue in runoff has been documented in actual field situations. According to Wauchope (1978) total losses for the majority of commercial pesticides from crop surfaces are 0.5% or less of the amount applied unless heavy rainfall conditions occur within 1-2 wk after application. Transport of pyrethroid residues in runoff to a great extent depends on the hydrosolubility of the compound in question; as well as the distance between the site of application and the receiving aquatic habitat. Pyrethroid residue in the water phase is more bioavailable than that in the adsorbed state on particulate matter; this results in a higher residue uptake by aquatic organisms from water than from food alone (Hill 1985). Generally insecticides with water solubility of 10 ppm or more are lost mainly in water phase, while those with low hydrosolubility remain adsorbed on sediment (Wauchope 1978). For pyrethroids such as deltamethrin and cyfluthrin with water solubility of 0.1 ppm (Roussel-Uclaf 1982) and 1-2 ppm (Behrenz et al. 1983), respectively, residue adsorbed on sediment will be more subject to transport by wind and water than solubilized residue in the water phase. In a later study, Carroll et al. (1981) demonstrated that under a wide range of rainfall and runoff conditions, permethrin concentration and loss in the runoff were low and not high enough to be harmful to aquatic organisms. In this study, permethrin was applied to the cotton crop at 0.112 kg/ha on ten different occasions in August and September 1976 and 1977. In the 1976 cotton season (80 cm rainfall), permethrin concentration in runoff did not exceed 0.2 ppb and the total amount recovered was $< 0.01\%$ of the quantity applied. During the higher (103 cm) rainfall year (1977), the runoff concentrations of permethrin were less than 1.0 ppb and the total amount recovered was $<1\ \%$ of the quantity applied.

IMPACT OF PYRETHROIDS ON NONTARGET INVERTEBRATES

In the hydrosphere, a large number of nontarget organisms cohabit with a small number of target pests and vector insects such as mosquitoes, midges, and blackflies. Nontarget fauna include useful predators of some pest insects, which are important in the dynamics of food chain relationships as well. Therefore, it is expedient to examine the effects of pyrethroids on nontarget aquatic animals.

Acute toxicity of pyrethroids - laboratory studies

Literature dealing with acute toxicities of pyrethroids to nontarget aquatic invertebrates has been compiled and presented in Table 2. Adequate data are unavailable for most nontarget aquatic invertebrates, however. For comparison purposes, toxicity data of some of the newer pyrethroids against target pests, such as mosquitoes and blackflies, are also listed (Table 2). A majority of the toxicity data has been available for the photostable pyrethroids such as cypermethrin, deltamethrin, fenvalerate, permethrin, etc. The most widely tested among these pyrethroids is permethrin. Based on Table 2, the photostable pyrethroids could be ranked in order of their decreasing toxicity to invertebrates as: permethrin and fenvalerate < cypermethrin < deltamethrin. In general, mollusks - both gastropods and bivalves, were the least sensitive of all invertebrates studied to permethrin, cypermethrin and fenvalerate. Among arthropods, however, crustaceans, phylogenetically closer to insects than mollusks, showed noticeable sensitivity to pyrethroids. The LC_{50} values for cladocerans, *Daphnia magna* and *D. pulex,* a copepod, *Nitocra spinites,* amphipods, *Gammarus pseudolimnaeus* and *G. pulex,* and decapods (lobsters, shrimps, etc.), fall near those (0.02 to 3.0 μg[A.I.]/liter) for mosquito and blackfly larvae. The isopod, *Asellus aquaticus,* and the mysid shrimp, *Mysidophis bahia,*have shown even higher sensitivies than other crustaceans to pyrethroids such as cypermethrin and permethrin. It should, however, be pointed out that most use pattems of pyrethroids do not coincide with biotopes supporting these taxa. Unlike the parent compounds, the degradation products of deltamethrin, cypermethrin, fenvalerate and permethrin have exhibited several thousand-fold decreased toxicity to *D. magna* under laboratory conditions (Table 3).

Of the nontarget aquatic hexapods which are even closer phylogenetically to target pest and vector insects, several predaceous and nontarget species show approximately the same order of sensitivity to pyrethroid chemicals as mosquito larvae. These include mayflies, *Baetis* spp., *Cloeon dipterum, Ephemerella* sp., and *Hexagenia* spp.; a stonefly, *Pteronarcys dorsata*; whirligig beetle, *Gyrinus natator;* caddisflies, *Brachycentrus americanus* and *Hydropsyche* spp.; and the snipefly, *Antherix* spp. The water boatman, *Corixa punctata,* and backswimmer, *Notonecta undulata*, have low sensitivity to some of the pyrethroids.

The accumulation of pyrethroids by the uptake of dissolved quantities in pore water above sediments can be another phenomenon in which benthic invertebrates such as chironomid midges could be exposed to pyrethroids. Muir et al. (1985) reported on the bioconcentration of four compounds namely, *cis*- and *trans*-cypermethrin, deltamethrin, fenvalerate and *cis*- and *trans*-permethrin by the larvae of *Chironomus tentans* Fab. in sand, silt and clay sediments and water (sediment/water ratio of 1:5). The test larvae were exposed for 24 h (in sediment) to 48 h (water above sediment) to 12-640 ng/g of ^{14}C-labelled cypermethrin and 5-10 ng/g of the other three pyrethroids. The data revealed that larvae in water above sand accumulated greater concentrations (5- to 15-fold) of each pyrethroid than larvae held in water above silt and clay sediments. The lower bioavailability of these compounds in the latter case was attributed to greater sorption of residue to suspended particulates. The data further revealed that the larvae had no adverse changes in their behavior when exposed to sediments containing 5 ng/g of each pyrethroid. At 10 ng/g, midge larvae were immobilized. However, a majority of them survived after they were transferred to pyrethroid-free water.

These data suggest a potential danger to the well-being of nontarget aquatic invertebrates. However, these laboratory tests were carried out either in static, flowing or intermittent flow systems. Depending on the physical and chemical properties of the pyrethroid, and the life stage, body size, and weight of exposed organisms, a test organism in a static water system is exposed to pesticide concentrations in water for a longer period of time than in intermittent flow and flow-through systems. Therefore, the impact of pyrethroids on nontarget aquatic organisms is best studied under field conditions.

Effects of pyrethroids - field studies

The toxicity of pyrethroids to nontarget aquatic invertebrates in the field may be different than shown in the laboratory. The effects of pyrethroids on nontarget aquatic invertebrates need to be appraised in three major sectors of pest control programs such as public health, agriculture and forestry.

Public health use of pyrethroids. Several pyrethroids have been evaluated against mosquitoes, blackflies and tsetse flies in simulated as well as actual field trials. However, studies on the impact of these compounds on nontarget aquatic invertebrates have been generally limited to aquatic arthropods, especially crustaceans and aquatic insects. Other nontarget invertebrates that inhabit wetland habitats have been less well studied.

In several studies, photostable pyrethroids such as cypermethrin, fenvalerate and permethrin were evaluated for their effects on nontarget organisms in a variety of habitats ranging from 5-liter tanks, to experimental and natural mesocosms (Mulla et al. 1975, Miura and Takahashi 1976, Mulla and Darwazeh 1976, Solomon et al. 1980, Tagatz and Ivey 1981, Crossland 1982, Hill 1985). Detailed information on these studies, including pyrethroid rate of application, habitat description and test periods, is given in Table 4. Cypermethrin at 1.4 and 100 g/ha in experimental and natural ponds, respectively, caused no adverse effects on various invertebrates belonging to the taxa Platyhelminthes, Rhynchocoela, Rotifera, Annelida, and Mollusca. This pyrethroid, however, caused > 95% reduction in the populations of arthropod fauna such as Crustacea (Cladocera, Ostracoda, Copepoda, Amphipoda and Isopoda), Insecta (Ephemeroptera, Odonata, Hemiptera, Coleoptera and Diptera), and Arachnida (Hydracarina or water mites). In the majority of these groups, recovery of populations occurred within 6 mo posttreatment. The effects of fenvalerate in 5-liter aquarium tanks were only visible in Polychaeta (Annelida) and Amphipoda, causing approximately 50% reduction in numbers by 6 d after application. In experimental ponds (Miura and Takahashi 1976) however, this compound at 84 g/ha, produced > 95% mortality in Cladocera, Ostracoda, and Copepoda soon after application; the populations of cladocerans and ostracods started to build up in the ponds 4 d after application. At a lower rate (28 g/ha), this pyrethroid caused slight mortality in corixids, notonectids, dytiscids and hydrophilid beetles as evidenced by dead organisms collected in the treated pond. However, there

Table 2. Acute toxicity of pyrethroids to invertebrates.

Taxon	Organism	Size/ stage	Test condition[a]	Pyrethroid	Toxicity parameter	Toxicity (ug/liter)[b]	Footnote references[c]
MOLLUSCA							
Gastropoda							
	Limnaea stagnalis L.	Eggs	S	Permethrin	48-h LC_{50}	>200[d,e]	4
		Adults	S	Permethrin	48-h LC_{50}	> 10[d,e]	4
Bivalvia							
	Crassostrea gigas Thunberg[f]	Larvae	F	Permethrin	48-h LC_{50}	>4.8[d]	4
			F	Cypermethrin	48-h LC_{50}	>2.3[d]	4
		Juveniles	F	Permethrin	48-h LC_{50}	>4.8[d]	4
	Crassostrea virginica Gmelin[f]	10 g	F	Cypermethrin	96-h EC_{50}	370[g]	4
		Larvae	S	Fenvalerate	24-h EC_{50}	>1[d,g]	21
ARTHROPODA: CRUSTACEA							
Cladocera							
	Daphnia magna Straux	First instar	S	Permethrin	48-h EC_{50}	0.6	4
						0.8 - 1.3[e]	4
					72-h EC_{50}	3.4	4
		Adult	S	Permethrin	24-h $EC_{60\text{-}80}$	0.5	20
			S	Cypermethrin	48-h $EC_{90\text{-}95}$	1.3[e]	4
						3.1 - 22.0[e]	4
					72-h EC_{50}	0.2 - 1.6	4
						0.3 - 0.8[e]	4
		Juvenile	S	Permethrin	48-h EC_{50}	0.4	4
		Adult			48-h EC_{50}	0.2 - 0.6	4
	Daphnia pulex Leydigia	Adults	S	Allethrin	— LC_{50}	0.021	4
Copepoda							
	Nitocra spinitis Boeck[f]	0.7 mm	S	Permethrin	96-h LC_{50}	0.15[e]	9
				Fenvalerate	96-h LC_{50}	0.38	9
Amphipoda							
	Gammarus pseudolimnaeus Bonsfield	Small juveniles	S	Fenvalerate	96-h LC_{50}	0.05	4
		Juvenile/adults	F	Fenvalerate	96-h LC_{50}	0.03	4

Table 2. Continued.

Taxon	Organism	Size/ stage	Test condition[a]	Pyrethroid	Toxicity parameter	Toxicity (µg/liter)[b]	Footnote references[c]
		Adults	F	Fenvalerate	24-h LC_{50}	0.13	4
					48-h LC_{50}	0.07	4
					96-h LC_{50}	0.03	4
	Gammarus pulex L.	5 mm	S	Cypermethrin	24-h LC_{50}	0.04	19
					24-h LC_{50}	0.10	19
				Permethrin	24-h LC_{90-95}	1.0	13
Decapoda							
	Crangon septemspinos (Say)[f]	1.3 g	S	Cypermethrin	96-h LC_{50}	0.01	10
				Fenvalerate	96-h LC_{50}	0.04	10
				Permethrin	96-h LC_{50}	0.13	10
	Penaeus aztecus Ives[f]	20 mm	S	Permethrin	96-h LC_{50}	0.34	10
	Penaeus duoarum Burkenroad[f]	—	F	Cypermethrin	96-h LC_{50}	0.04	18,22
				Deltamethrin	96-h LC_{50}	1.50	8,18
				Fenvalerate	96-h LC_{50}	0.84	18
				Permethrin	96-h LC_{50}	0.22	5,6,7,18
	Uca pugilator (Bose)[f]	—	S	Cypermethrin	96-h LC_{50}	0.20	10
				Deltamethrin	96-h LC_{50}	< 0.56	8
				Permethrin	96-h LC_{50}	2.20	5,6,10
	Homarus americanus Milne-Edwards[f]	450 g	S	Cypermethrin	96-h LC_{50}	0.04	10
				Fenvalerate	96-h LC_{50}	0.14	10
				Permethrin	96-h LC_{50}	0.73	10
				Deltamethrin	96-h LT[i]	0.40	4,8
	Procambarus blandingi Hobbs[f]	24 g	F	Permethrin	96-h LC_{50}	0.12	22
	Procambarus clarkii Girard	0.05-0.5 g	S	Permethrin	96-h LC_{50}	0.15 - 0.23[e]	10
	Orconectes sp.	2.3 g	F	Cypermethrin	96-h LC_{50}	0.07	19
Paracarida							
	Mysidopsis bahia (Molenock)		F	Cypermethrin	96-h LC_{50}	5.0[h]	3,4
				Fenvalerate	96-h LC_{50}	8.0[h]	3,4,18
				Permethrin	96-h LC_{50}	20.0[h]	3,4,18
ARTHROPODA-INSECTA							
Ephemeroptera						0.4	
	Baetis parvus Dodds	Larvae	F	Deltamethrin	24-h LC_{50}	1.1	12
				NRDC 160	24-h LC_{50}		12

Baetis rhodani Pictet	Larvae	F	Cypermethrin	96-h EC_{50}	6.0[h]	4,13
				96-h LC_{50}	12.0[h]	4,13
			Permethrin	24-h LC_{90-95} (1-h exposure)	1.0	13
Cloeon dipterum L.	5 mm	S	Cypermethrin	24-h EC_{50}	0.07	1,4
				24-h LC_{50}	0.60	1,4
	Early Instar	S	Permethrin	72-h EC_{50}	0.03	1,4
Ephemerella sp.		F	Fenvalerate	24-h EC_{50}[j]	0.31	1,4
				48-h EC_{50}[j]	0.07	1,4
				96-h LC_{50}	0.93	1,4
Hexagenia bilineata (Say)		F	Permethrin	96-h LC_{50}	0.10	13
Hexagenia rigida (McDunnough)	Nymphs	–	Permethrin	6-h LC_{50}	0.6 - 2.0	2
Plecoptera						
Pteronarcys dorsata (Say)		F	Fenvalerate	72-h EC_{50}	0.13	1
				72-h LC_{50}	>1.0	1
		F	Permethrin	72-h EC_{50}	0.15	1
				72-h LC_{50}	>0.40	1
				28-d LC_{30}	0.04	1,4
Hemiptera						
Corixa punctata (Illiger)	Adults	S	Permethrin	24-h EC_{50}	0.7	1,4
				24-h LC_{50}	>5.0	1,4
Notonecta undulata Say	Adults	S	Allethrin	48-h LC_{50}	29.0	11
			Dimethrin	48-h LC_{50}	0.1[ek]	11
			Tetramethrin	48-h LC_{50}	33.8[k]	11
			Resmethrin	48-h LC_{50}	1.9[k]	11
			Bioresmethrin	48-h LC_{50}	1.2[k]	11
Coleoptera						
Gyrinus natator (Portevin)	Adults	S	Cypermethrin	24-h EC_{50}	0.07	1,4
				24-h LC_{50}	0.60	1,4
Trichoptera						
Brachycentrus americanus Banks		F	Permethrin	96-h EC_{50}	0.40	1
				96-h LC_{50}	>0.5	1
Brachycentrus subnubilis Curtis		F	Permethrin	24-h EC_{90-95} (1-h exposure)	1.0	13
Hydropsyche californica Banks	Larvae	IF	Deltamethrin	24-h LC_{50}	0.4	12
			NRDC-160	24-h LC_{50}	0.7	12
Hydropsyche pellucidula Curtis		F	Permethrin	24-h LC_{90-95} (1-h exposure)	0.1	13

Table 2. Continued.

Taxon	Organism	Size/ stage	Test condition[a]	Pyrethroid	Toxicity parameter	Toxicity (µg/liter)[b]	Footnote references[c]
Diptera							
Antherix sp.		Larvae	F	Fenvalerate	3-d LC_{50}	0.60	1
					7-d LC_{50}	0.12	1
					14-d LC_{50}	0.07	1
					28-d LC_{50}	0.03	1
Culex/*Aedes* spp.[l]		Larvae	S	Cypermethrin	24-h LC_{50}	0.07 - 1.0	15,16,17
				Deltamethrin	24-h LC_{50}	0.02 - 0.4	15,16,17
				Fenvalerate	24-h LC_{50}	0.9 - 2.8	15,16,17
				Permethrin	24-h LC_{50}	0.5 - 3.0	15,16,17
		Pupae	S	Cypermethrin	24-h LC_{50}	0.40	15,16,17
				Deltamethrin	24-h LC_{50}	0.07 - 0.6	15,16,17
				Fenvalerate	24-h LC_{50}	1.2 - 5.3	15,16,17
				Permethrin	24-h LC_{50}	0.7 - 6.0	15,16,17
Simulium spp.[l]		Larvae	IF	Deltamethrin	24-h LC_{50}	0.02	12
			F	Deltamethrin	24-h LC_{50} (1-h exposure)	0.10	14
				Permethrin	24-h LC_{50} (1-h exposure)	1.0	13

[a] F- flow-through system, IF - intermittent flow system, S-static.

[b] Toxicity in µg active ingredient technical material/liter, unless stated otherwise. Exposure time the same as toxicity data recording time unless indicated otherwise.

[c] 1. Anderson (1982), 2. Friesen et al. (1983), 3. Garnas and Schimmel (1981), 4. Hill (1985), 5. Jolly and Avault (1978), 6. Jolly et al. (1978), 7. Kenaga (1979), 8. Lhoste and L'Hotellier (1982), 9. Linden et al. (1979), 10. McLeese et al. (1980), 11. Mills et al. (1969), 12. Mohsen and Mulla (1981), 13. Muirhead-Thompson (1978), 14. Muirhead-Thompson (1981a), 15. Mulla et al. (1978), 16. Mulla et al. (1980), 17. Mulla et al. (1982), 18. Schimmel et al. (1983), 19. Stephenson (1982), 20. Stratton and Corke (1981), 21. Tagatz and Ivey (1981), 22. Zitko et al. (1979).

[d] Expressed in mg (A.I.)/liter.

[e] EC material (emulsifiable concentrate).

[f] Marine or estuarine organisms tested in salt water.

[g] Measure of reduction in shell growth; it is not a toxicity value.

[h] ng (A.I.)/liter.

[i] LT - lethal threshold in µg (A.I.)/liter.

[j] Measure of reduction in swimming activity; it is not a toxicity value.

[k] LC_{50} calculated from dosage/mortality data.

[l] Target pest species.

Table 3. Acute toxicity of major metabolites of photostable pyrethroids to *Daphnia magna*.[a]

		EC$_{50}$ (μg[A.I.]/liter) at	
Parent compound[b]	Metabolite[c]	24 h	48 h
C	–	–	1.3
P	–	–	0.6
C,D,E,F,P	3-Phenoxybenzyl acid	17,000	10,000
C,D,E,F,P	3-Phenoxybenzyl alcohol	147,000	85,000
C,P	3-(2,2-Dichlorvinyl)-2, 2-dimethyl cyclopropane carboxylic acid [*cis:trans*, 40:60]	199,000	128,000

[a] Hill (1985).
[b] C, D, F, and P stand for cypermethrin, deltamethrin, fenvalerate and permethrin, respectively.
[c] Ester hydrolysis product(s).

were no significant differences between numbers of nontarget insects trapped in treated and control ponds during the 4 d period following treatment.

Like cypermethrin and fenvalerate, permethrin had no apparent adverse effects on invertebrates such as Coelenterata, Platyhelminthes (Turbellaria), Rhynchocoela, Rotifera, Annelida (Oligochaeta, Hirudinea and Polychaeta), and Mollusca (Gastropoda and Bivalvia). Most affected were the aquatic arthropods, *e.g.*, Cladocera, Ostracoda, Copepoda, Amphipoda, Isopoda, Hydracarina, Ephemeroptera, Plecoptera, Odonata, Hemiptera, Coleoptera, Trichoptera and Diptera. These animals sustained from 50 to > 95% loss in population densities as a result of permethrin applications. Nevertheless, population recovery in most cases occurred within 6 mo.

In actual mosquito larvicidal evaluations, some pyrethroids were studied by Mulla et al. (1969, 1972, 1980, 1982) for their impact on nontarget arthropods in experimental field ponds. Ephemeroptera (mayflies) was the most sensitive group to most of the pyrethroids except tetramethrin (Table 5). Affected populations decreased 50 to 100%. However, recovery to pretreatment or control levels took place within 2 - 4 wk after treatment. Other arthropods that showed some sensitivity to these compounds were ostracods to cypermethrin, and Odonata to all the photostable pyrethroids such as cypermethrin, deltamethrin, fenpropathrin, fenvalerate, permethrin and phenothrin. However, populations of these organisms recovered from this transient loss within 2 wk after treatment, indicating lack of persistence of these compounds in aquatic mesocosms at the applied practical rates.

Apart from the use of pyrethroids as larvicides in mosquito and blackfly control, some of the new photostable pyrethroids have been evaluated in tsetse fly (*Glossina* spp.) control in Africa. In these control programs, pyrethroids were applied by helicopter to narrow bands of forest plantations along river banks. Aerial applications of these chemicals, including ULV formulations, resulted in contamination of rivers or tributaries directly and/or through spray drift.

Table 4. Application of pyrethroids to simulated, experimental and natural field ponds in nontarget assessment studies.[a]

Pyrethroid	Rate (g [A.I.]/ha)	Habitat description	Test period posttreatment (d)	Footnote references[b]
Cypermethrin	1.4[c]	Experimental ponds $5 \times 5 \times 1$ m deep	350	2
	100	Natural ponds (2) 20×5 m	14, 112	1
Fenvalerate	0.01, 0.1,1.0, 10 μg/liter	5- to 6-liter tanks	56	7
	28, 84	Experimental ponds	6	3
Permethrin	210	Natural pond (3) 0.02-0.4 ha	350	2
	56, 112	Experimental ponds $4 \times 7 \times 0.3$ m deep	7-16	4,5
	5,50 μg/liter	Limnocorrals 25 m^2 by 4 m deep	100	6

[a] Modified after Hill (1985).

[b] 1. Crossland (1982), 2. Hill (1985), 3. Miura and Takahashi (1976), 4. Mulla and Darwazeh (1976), 5. Mulla et al. (1975), 6. Solomon et al. (1980), 7. Tagatz and Ivey (1981).

[c] Multiple applications were made to pond water (eight applications to one pond and two applications each to two other ponds) and two applications to pond soil at 5- to 7-d intervals.

Experimental details of these studies are summarized in Table 6. Contamination of habitat water by cypermethrin, deltamethrin and permethrin and their impacts on nontarget aquatic fauna were evaluated in several studies (Molyneux et al. 1978, Takken et al. 1978, Spielberger et al. 1979, Smies et al. 1980, Baldry et al. 1981, Everts et al. 1983).

The aforementioned studies showed that cypermethrin at 100 g (A.I.)/ha caused 50% mortality in mayflies with some toxicity to aquatic coleopterans and hemipterans; it had no adverse effects on gastropods, odonates, trichopterans and dipterans. Deltamethrin at 20 and 40 g (A.I.)/ha in the Karami River habitat caused a significant loss in the populations of both Oligochaeta and Hirudinea (leeches); it also severely affected decapod populations in all the habitats. Of the two prawns, *Caridina africana* Kingsley and *Macrobrachium raridens* (Hilgendorf), which were markedly affected by deltamethrin, only the former species was found reestablished one year after treatment. Deltamethrin in all habitats caused a significant reduction (≥ 50%) in the populations of Ephemeroptera, Plecoptera, Odonata, Hemiptera, Coleoptera, Trichoptera and Diptera. The impact of permethrin on decapods and aquatic insect groups was similar to that of deltamethrin. However, recovery of most populations in deltamethrin-contaminated water of River Marahoue was noticed within 6 mo after pesticide applications.

In summary, the above discussion clearly indicates that nontarget arthropods such as crustaceans and aquatic insects will be affected during applications of photostable pyrethroids in vector control programs. However, the effect

Table 5. Effects of some pyrethroids on nontarget aquatic arthropods in experimental ponds.[a]

Pyrethroid (formulation)	Application rate (g [A.I.]/ha)	Effects on nontarget taxa[b]					
		Ostracoda	Ephemeroptera	Odonata	Hemiptera	Coleoptera	Footnote references[c]
Allethrin	110 - 220	–	XX/R	0	–	–	2
Cypermethrin (EC2.5)	1.1 - 11	X/R	XX/R	XX/R (dragonfly)	–	0	5
Deltamethrin (EC0.21)	0.28 - 1.1	–	XX/R	X/R (damselfly)	–	–	3
Dimethrin	110 - 220	–	XX/R	0	–	–	2
Fenpropathrin (EC)	11 - 55	–	XX/R	XX/R (dragonfly)	–	0 (Dytiscidae)	5
Fenvalerate (EC2.4)	11 - 55	–	XX/r	X/R (damselfly)	–	–	3
Permethrin (EC0.8)	5.5 - 27.5	–	XX/R	X/R (damselfly)	–	–	3
Phenothrin (EC2)	27.5- 55	–	XX/R	X/R (dragon- & damselflies)	–	0	4
Resmethrin (EC2)	55 - 220	–	XX/R	0	–	–	2
Tetramethrin (EC20)	55 - 550	–	0	0 (damselfly)	0	–	1

[a] Ponds measured 6 by 6 m with 30 cm water depth. Ponds provided an alkaline habitat with average water pH of 9.5, situated near the upper end of Salton Sea, southern California.

[b] Effects are abbreviated as: no data taken, 0, no effects; X, some effect ~25% loss in number; XX, major effect > 50 - 100% loss in number; R, complete recovery within 2-4 weeks posttreatment; r, partial recovery within 2-4 wk posttreatment.

[c] References 1, 2, 3, 4, and 5 as Mulla et al. 1969, 1972, 1978, 1980, and 1982, respectively.

Table 6. Experimental details of pyrethroid applications to riverine forests in tsetse fly control.

Pyrethroid (formulation)	Application: Rate (g [A.I.]/ha)	Application: Method	Habitat treated	Study period (d)[a]	Footnote references[b]
Cypermethrin (ULV)	100	Helicopter application 4- to 6- km runs	0.4- to 2-ha blocks along tributaries of River Karami, Nigeria	6	4,5
Deltamethrin (ULV)	20,40	"	"	6	4,5
Deltamethrin[c]	12.5 5 applications	Helicopter 15-km runs	River Marahoue, Ivory Coast	30	2
Deltamethrin[d]	12.5	"	River Komoe Valley, Upper Volta	10	1,3,6
Deltamethrin (ULV)	0.36, 12.25 2 applications	"	"	10	1,3,6
Permethrin (ULV)	1.9,4.3	"	"	10	1,3,6
Permethrin (ULV)	200,300	Helicopter 4-6 spray runs	0.4- to 2-ha blocks along tributaries of River Karami, Nigeria	6	4,5

[a] Study period refers to number of days posttreatment.

[b] 1. Baldry et al. (1981), 2. Everts et al. (1983), 3. Molyneux et al. (1978), 4. Smies et al. (1980), 5. Spielberger et al. (1979), 6. Takken et al. (1978).

[c] Two weeks prior to these applications, habitat received one treatment of permethrin at 40 g(A.I.)/ha.

[d] Application made after other nonpyrethroid insecticide, endosulfan.

of this change in faunal composition on the overall ecosystem dynamics has not been elucidated in the literature.

Agricultural use of pyrethroids. Pyrethroids have been used to control insect pests in a variety of agricultural crops such as cotton, vegetables, fruit orchards, corn, soybean, vines, coffee, and other crops.

The contamination of aquatic habitats by agricultural use of pyrethroids and its impact on nontarget aquatic organisms has been addressed in a limited number of field trials. Six case studies have been elucidated in the literature, including three on cypermethrin by Crossland et al. (1982) and one more on this compound and two on permethrin (Hill 1985). Information on application rate, method, and site along with posttreatment duration of each study is summarized in Table 7. In trials by Crossland et al. (1982), two applications of cypermethrin were applied by tractor-mounted equipment to potato and sugarbeet fields adjacent to a 0.02- to 0.1-ha pond. Cypermethrin was also applied by mist blower to vineyards next to two streams and a drainage ditch. In other studies (Hill 1985), multiple (15 to 17) aerial applications of cypermethrin and permethrin

Table 7. Information on pyrethroids applied to agricultural crops adjacent to aquatic study sites.

Pyrethroid	Application: Rate	Application: Method	Application: Source crop	Study site(s)	Post-treatment period (days)	Footnote references[a]
1. Cypermethrin (EC)	70 g (A.I.) (in 300 liter/ha)	Two ground applications, 28 d apart	Sugar beet and potato	3 ponds (0.02-0.01 ha, 1-2 m deep) (next to source crops)	7	1
2. Cypermethrin (EC)	30 g (A.I.)/ha	Mist blower	Vineyards	2 streams	1-2	1
3. Cypermethrin (EC)	45 g (A. I.)/ha (in 400 liter/ha)	Mist blower	Vineyards	Ditch	1-2	1
4. Cypermethrin (EC)	150 g (A.I.)/ha (in 27 liter/ha)	Fixed wing aircraft; 16 applications 5 d apart	Cotton (17 ha)	Pond (3 ha, 2.5-m deep)	300	2
5. Permethrin	224 g (A. I.)/ha (in 20 liter/ha)	Fixed wing aircraft; 15 applications, 5 d apart	Cotton (17 ha)	Pond (3 ha, 2.5-m deep)	36	2
6. Permethrin	224 g (A.I.)/ha	17 ground applications, 5 d apart	Cotton (2 ha)	Pond (1.2 ha)	50	2

[a] 1. Crossland et al. (1982), 2. Hill (1985).

were made from a fixed-wing aircraft at 5-d intervals to cotton fields; adjacent ponds were exposed to pesticide drift from these applications.

The effects of these treatments on various invertebrates were studied in aquatic habitats contaminated by the two pyrethroids. Rotifers, annelids (Oligochaeta and Hirudinea) and mollusks (Gastropoda and Bivalvia), were not adversely affected by cypermethrin and permethrin. Among arthropods, nontarget insects were affected more by both pyrethroids than were the crustaceans. Most crustaceans, such as Cladocera, Ostracoda, Copepoda, Isopoda, and Decapoda (both caged and natural populations of crayfish, *Procambarus clarkii*), did not significantly decrease in number after habitat contamination by the two compounds. Amphipods were the only crustaceans that showed reduction in number within 2 d posttreatment of cypermethrin; however, complete recovery of these populations occurred within a short time. The most sensitive organisms to permethrin treatments in case study #5 and to cypermethrin in case studies #2 and #3 were aquatic insects such as Ephemeroptera, Odonata, Hemiptera (gerrids and notonectids), and Coleoptera (whirligig beetles) (Table 7). As expected from their acute toxicities to insects, permethrin was more toxic than cypermethrin. Permethrin caused 100% mortality of populations of the affected organisms with some recovery occurring within 6 mo; cypermethrin caused less reduction of insect populations, with complete recovery taking place within 6 mo or less following treatment.

The foregoing discussion shows that in a variety of study sites, only the aquatic stages of nontarget insects were adversely affected by permethrin and cypermethrin. However, the population recovery of insects with aerial or terrestrial stages (mayfly, dragonfly, etc.) was not affected even by multiple applications over short (*e.g.*, 5-d) intervals. Moreover, the amount of low level residues (see below) falling onto water surfaces and residue loss through adsorption and microbial action in aquatic habitats during posttreatment period, may further reduce the risks of pyrethroid toxicity to nontarget invertebrates.

In the foregoing studies, residue levels of cypermethrin were determined in both water and mud samples of aquatic habitats. Mud samples showed no pyrethroid residue at detectable levels; water samples, however, revealed the presence of detectable residues. The initial surface water residue levels of cypermethrin in the pond in study 1 (Crossland et al. 1982), were 6 to 23 μg/liter, which declined to < 5 μg/liter in 24 h. Water samples from 20- to 30-cm depth, showing an initial residue of 0.07 μg/liter, fell to < 0.02 μg/liter in 24 h. The initial surface residue titer in the flowing water of streams and drainage ditches was higher (0.14 to 1.01 mg/liter) than in the pond water described above; these higher residues decreased to < 20 μg/liter in 3 h. The maximum residue of 0.4-1.7 μg/liter in subsurface water soon after application, fell to 0.1 μg/liter or less in 4 h posttreatment. In study 4 (Hill 1985), the residues of cypermethrin in subsurface water were mostly below the detection limit of 0.02-0.05 μg/liter. No data on the residue of permethrin in habitat water are available.

The residue profile of cypermethrin in water immediately after application, coupled with a rapid decay (4-24 h), explains the limited effect of pyrethroids on populations of nontarget aquatic invertebrates in some case studies. Moreover, the application rates of both cypermethrin and permethrin used in case studies were equivalent to actual field rates being practiced in agricultural insect control programs. It is thus evident that contamination of aquatic habitats through spray drift from agricultural applications of both cypermethrin and permethrin posed no serious risks to most nontarget organisms, except some aquatic insects which recovered within the same season of treatment. The intensity of impact, if any, is deemed to be far less if one or two treatments are used per season. On the other hand, invertebrates in habitats subjected to more frequent treatments are likely to be affected more, and especially those species which show greater sensitivity to these insecticides.

Forestry use of pyrethroids. The new photostable pyrethroids offer great potential as effective tools to protect vast expanses of forestlands from pest insects such as spruce budworm, *Choristoneura fumiferana* (Clemens), and many other species. Owing to their high toxicity to aquatic organisms in laboratory studies, however, the employment of these insecticides in large scale forest pest management programs raises questions of greater economic and environmental concern, including the impact of these compounds on nontarget invertebrates in streams, ponds and lakes in or adjacent to forestlands under pyrethroid treatment programs. Except for one 5-yr (1976-81) study on permethrin, there have been little or no data available on pyrethroids so far. In this case study, permethrin applied in the field at 17.5 g(A.I.)/ha or higher against *C. fumiferana* in Canadian forests, was evaluated for its impact on lake, pond and stream fauna in several trials (Kingsbury 1976, 1983, Kingsbury and McLeod 1979, Kingsbury and Kreutzweiser 1980a,b, 1987a,b, Kreutzweiser 1982, Kreutzweiser and Kingsbury 1982) and later reviewed for possible effects on nontarget species (Hill 1985). In this study, an oil-based formulation of permethrin was applied aerially at rates ranging from 8.8 to 140 g (A.I.)/ha. Applications were made to aquatic habitats in forested lands in the same manner in which these habitats would receive pesticide residues during actual pest control operations. Application rates, test site description and site locations are given in Table 8. The study sites included lakes, ponds and streams. The effects on nontarget fauna were ranked as no effect, partial absence immediately after treatment, or complete disappearance after treatment. Posttreatment recovery of populations within 6 and 12 mo posttreatment was also monitored. Nematoda, Platyhelminthes (Turbellaria), Rotifera, Annelida (Oligochaeta, Hirudinea), and Mollusca (Gastropoda and Bivalvia), were not affected by permethrin applications in any study habitats. As expected, the most affected organisms were aquatic arthropods, especially crustaceans and insects.

Of the crustacean fauna, Cladocera and Copepoda were absent in sites 1 and 2 (lake) and site 11 (pond) after application of permethrin. Their populations recovered almost completely within 6 mo of the treatments. Ostracoda at site 11, Amphipoda at 1, 3 (stream) and 11, and Isopoda at 1 and 11, sustained a similar impact, as did Cladocera and Copepoda. However, neither amphipods nor isopods recovered within 12 mo after treatment. A small number of Decapoda at site 3 were not affected by this pyrethroid.

Among insects, Ephemeroptera and Trichoptera were affected most by permethrin treatments in a majority (15) of the study sites. Complete recovery of populations was noticed within 6 mo posttreatment. Plecoptera (all sites except

Table 8. Permethrin application sites in Canadian forestry studies during 1976-1980.[a]

Year	Application rate (g [A.I]/ha)	Study site	Application area	Location	Footnote references[b]
1976	140	1. Lake (10 ha × < 3 m)	Lake and surroundings	Quebec	1
	35	2. Lake (30 ha × < 14 m)	Lake and surroundings	Ontario	1
	70	3. Stream (sandy bed)	5 km of stream valley	Ontario	1,8
1977	70	4. Stream (rocky bed)	5-8 km of stream valley	Quebec	4,8
	35	5. Stream (rocky bed)	5-8 km of stream valley	Quebec	4,8
1978	17.5	6. Stream (mixed bed)	5-8 km of stream valley	Quebec	4
	8.8	7. Stream (gravel bed)	3-5 km of stream valley	Quebec	4
	2 times 17.5	8. Stream (gravel bed)	3-5 km of stream valley	Quebec	3
	2 times 17.5	9. Stream (mixed bed)	3-5 km of stream valley	Quebec	3
	2 times 17.5	10. Stream (mixed bed)	3-5 km of stream valley	Quebec	3
	2 times 17.5	11. Pond (0.25- to 1-m deep)	930 ha block	Ontario	3,6
1979	17.5	12. Stream (mixed bed)	930 ha block	Ontario	5
	17.5	13. Pond (1- to 2-m deep)	630 ha block	Ontario	5
1980	17.5	14. Stream (gravel bed)	630 ha block	Quebec	7
	17.5	15. Stream (rocky bed)	400 ha block	Quebec	7
	2 times 17.5	16. Stream (rocky bed)	400 ha block	Quebec	7
	17.5	17. Stream (gravel bed)	600 ha block	New Brunswick	2
	2 times 17.5	18. Stream (rocky bed)	600 ha block	New Brunswick	2

[a] Modified from Hill (1985).

[b] 1. Kingsbury (1976), 2. Kingsbury (1983), 3. Kingsbury and Kreutzweiser (1983), 4. Kingsbury and Kreutsweiser (1980a), 5. Kingsbury and Kreutzweiser (1980b), 6. Kingsbury and McLeod (1979), 7. Kreutzweiser (1982), and 8. Kreutzweiser and Kingsbury (1982).

1, 2, 11 and 12), Odonata (1, 4, and 13), Hemiptera (6, 8, 9, 10-stream), and Coleoptera (all sites except 1, 2, 4, 5, and 12) were only partially affected during the treatments and complete recovery of populations occurred within a few weeks to a few months (6) posttreatment. Moreover, like their insect relatives, Hydracarina (water mites) were also partially affected by permethrin applications to all sites except 1, 2, 11, and 12. Kingsbury and Kreutzweiser (1987a,b) noticed that the recovery of populations of affected invertebrates in forest stream habitats was relatively slower after the second or multiple application(s) than after the first or single treatment of permethrin applied at the same rate. The direct toxicity of permethrin applications to aquatic invertebrates resulted in some secondary effects on other aquatic animals in the food chain, especially some carnivorous fish species depending on aquatic invertebrates for food. For example, caged native trout and salmon showed reductions in growth rate and the uncaged natural populations showed declining density in forest stream habitats due to depletion of their food supply, aquatic invertebrates, which were directly affected by permethrin application. Direct exposure of these fish to permethrin treatments in the streams did not affect them. The reductions in growth rate and density of these fish were not permanent, and a recovery was noticed 4 mo after treatments.

The foregoing discussion clearly indicates that some aquatic arthropods were affected by permethrin applied to lake, pond and stream habitats in the forest ecosystem. The recovery of these animals was noticeable within a few weeks to a few month (ca. 6 mo) after treatments. Of these arthropods, however, ephemeropterans and trichopterans were most sensitive to permethrin at as low as 8.8 g [A.I.]/ha, a rate similar to field application rates. Apart from direct mortality of aquatic arthropods, the downstream movement of permethrin up to 2 km away from treated area was indicated by reductions in the abundance of downstream organisms. In some instances such as in sites 3 and 4, the density and diversity of stream benthic organisms were suppressed for up to 16 mo after permethrin application at 709 g (A.I.)/ha; in lake situations, benthic fauna recovered to normal preapplication levels within 12 mo of treatment with permethrin (35 g [A.I.]/ha).

In almost all studies in the three use sectors of public health, agriculture, and forestry, detrimental effects of pyrethroids on the populations of both nontarget insects and crustaceans have been demonstrated. It is understandable that these two groups would be more sensitive to pyrethroid applications since they are closely related phylogenetically to target insects. The recovery of most populations was noticed within a short time after application. The effects of this short-term disruption or absence of some of these organisms, especially those critical to aquatic food chain, can regulate the density and growth pattern of dependent fish populations cohabiting the same ecosystem.

SUMMARY

The impacts of pyrethroids on nontarget aquatic invertebrates have been analyzed and discussed in this review. Various pyrethroids, both photolabile and photostable, along with toxicological data as to their mammalian and insect toxicity have been described. The mode of entry of these compounds into wetland habitats has been examined, and direct and indirect sources of habitat contamination by pyrethroids have been discussed. Direct sources include purposeful applications of pyrethroids in vector control as well as agricultural and silvicultural pest control programs. Indirect avenues through which water bodies could be contaminated with pyrethroid residues include spray drift, runoff and/or erosion processes.

A major portion of this review is devoted to the impact of pyrethroids on nontarget aquatic species. Based on laboratory data on acute toxicity of pyrethroids against nontargets, the relatively newer photostable and more effective pyrethroids have been ranked, in order of decreasing toxicity, as: permethrin = fenvalerate < cypermethrin < deltamethrin. In general, pyrethroids were more toxic to nontarget aquatic insects and crustaceans than to other phylogenetically distant invertebrates. In field studies, depending on their use pattern, the effects of pyrethroids on nontarget aquatic fauna have been discussed under three categories, i.e., public health, agriculture, and forestry. In almost all field studies, nontarget aquatic insects such as Ephemeroptera, Odonata, Plecoptera, Hemiptera, Coleoptera and Trichoptera, and crustacean groups such as Cladocera, Ostracoda, Copepoda, Amphipoda, Isopoda and Decapoda, were more severely affected by photostable pyrethroids than other invertebrate groups. However, populations of affected organisms generally recovered to pretreatment levels within weeks to months after application. The impact of these transient effects of pyrethroids on nontarget species will have a short-term bearing on the densities of dependent carnivorous fish species in aquatic ecosystems.

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