9 THE IMPACT OF PESTICIDES ON NONTARGET AQUATIC INVERTEBRATES IN WETLAND RICEFIELDS: A REVIEW

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9.1. Introduction

Aquatic invertebrates that inhabit the soil-floodwater ecosystem of wetland ricefields are considered important as nutrient recyclers, rice pests, biological control agents, food items, and vectors of human and animal diseases (Roger, Heong, and Teng, 1991). The functionality of this aquatic community depends on the relative and absolute population densities of the various groups and their activity rates. The widespread introduction of chemical pesticides to control rice pests (microbial pathogens, weeds, nematodes, snails, insects, and rodents) has significantly increased grain yields. However, because pesticides are often unspecific, they have the potential to profoundly modify the soil-floodwater communities of wetland ricefields. It is important to understand and predict how pesticide use affects the ecology of the ecosystem and to consider the implication of these changes for rice production and rice-producing environments.

9.1.1. Components of the Aquatic Macroinvertebrate Fauna

Invertebrates that inhabit the soil-floodwater ecosystem of ricefields are derived from contiguous water bodies and span the whole spectrum of freshwater fauna

(Fernando, Furtado, and Lim, 1980). The dominant groups are crustaceans (crabs, crayfish, shrimps), microcrustaceans (ostracods, copepods, cladocerans), aquatic insect larvae (mosquitoes, chironomids), aquatic insects (coleopterans, hemipterans), molluscs (gastropods, bivalves), annelids (oligochaetes, leeches), nematodes and rotifers (Kurasawa, 1956; Heckman, 1974, 1979; Kikuchi, Furusaka, and Kurihara, 1975; Clement, Grigarick, and Way, 1977; Yatsumatsu, Hashimoto, and Chang, 1979; Fernando, Furtado, and Lim, 1980; Lim, 1980; Ishibashi and Itoh, 1981; Grant, Tirol, Aziz, and Watanabe, 1983; Grant, Roger, and Watanabe, 1985, 1986; Watanabe and Roger, 1985; Roger and Kurihara, 1988; Roger, Heong, and Teng, 1991; Simpson, Roger, Oficial, and Grant, 1993a, 1993b, 1994a, 1994b, 1994c).

Extensive species lists have been compiled for a ricefield in northeastern Thailand (Heckman, 1979) and a deepwater ricefield in Bangladesh (ODA, 1984). Crop cycle population dynamics of floodwater biota have been reported in temperate (Kurasawa, 1956; Ishibashi and Itoh, 1981) and tropical ricefields (Heckman, 1974; Grant, Tirol, Aziz, and Watanabe, 1983; Grant, Roger, and Watanabe, 1985; Ali, 1990; Simpson, Roger, Oficial, and Grant, 1993a; 1993b, 1994a, 1994b, 1994c). Density estimates for field populations of aquatic invertebrate are scarce and vary considerably between location, management strategies, stages of crop development, and sampling methods (Table 9.1).

9.1.2. The Role of Aquatic Macroinvertebrates

Aquatic invertebrates in ricefields contribute to nutrient cycling in several ways. Grazers and detritivores (microcrustaceans, insect larvae, gastropods, oligochaetes) perform important roles in the decomposition of the photosynthetic aquatic biomass (PAB), which develops in ricefield floodwater. Aquatic oligochaetes have an important role in ensuring the translocation of organic matter that accumulates in the detritus layer at the soil-water interface. Aquatic invertebrates also contribute to nutrient cycling through their bioperturbations, which release native minerals from the soil (Grant, Roger, and Watanabe, 1986) and through the decomposition and mineralization of their body tissues. Therefore aquatic and soil invertebrates are considered fundamental components of ricefield fertility (Roger, Grant, Reddy, and Watanabe, 1987; Roger and Kurihara, 1988).

When nutrients enter the floodwater they are potentially available for PAB development. If primary productivity increases, it encourages the proliferation of grazer populations, which may inhibit further algal growth and reduce biological N_2 fixation (Wilson, Greene, and Alexander, 1980). PAB that is not ingested will ultimately join the detritus pool, which is recycled more slowly. Any factor that changes the relationship between primary production and grazers could have important consequences for nutrient availability.

Table 9.1. Population Density Estimates of Aquatic Invertebrates in Wetland Ricefields

Crustacean zooplankton:		
200 to 800/L	Japan	Kikuchi, Furusaka, and Kurihara (1975)
Cladocerans:		
Daphnia 198/L	Japan	Kurasawa (1956)
Bosmina 15/L	Japan	Kurasawa (1956)
max. 300/L	Malaysia	Ali (1990)
0 to 1,100/L	Philippines	Simpson, Roger, Oficial, and Grant (1994b)
0 to 33,000/sq m	Philippines	Simpson, Roger, Oficial, and Grant (1994b)
Copepods:		
Cyclops 42/L	Japan	Kurasawa (1956)
max. 800/L	Malaysia	Ali (1990)
0 to 1,700/L	Philippines	Simpson, Roger, Oficial, and Grant (1994b)
0 to 40,000/sq m	Philippines	Simpson, Roger, Oficial, and Grant (1994b)
Ostracods:		
0 to 422/L	Philippines	Grant, Tirol, Aziz, and Watanabe (1983)
10 to 20,000/sq m	Philippines	Grant, Roger, and Watanabe (1986)[a]
300 to 37,000/sq m	Malaysia	Lim and Wong (1986)
0 to 4,300/L	Philippines	Simpson, Roger, Oficial, and Grant (1994b)
0 to 98,000/sq m	Philippines	Simpson, Roger, Oficial, and Grant (1994b)
Chironomid larvae:		
max. 18,000/sq m	California	Clement Grigarick, and Way (1977)
8,000/sq m	Philippines	Grant, Roger, and Watanabe (1986)[a]
0 to 700/L	Philippines	Simpson, Roger, Oficial, and Grant (1994b)
0 to 10,000/sq m	Philippines	Simpson, Roger, Oficial, and Grant (1994b)
Mosquito larvae:		
0 to 350/L	Philippines	Simpson, Roger, Oficial, and Grant (1994b)
0 to 7,000/sq m	Philippines	Simpson, Roger, Oficial, and Grant (1994b)
Molluscs:		
max. 1,000/sq m	Philippines	Grant, Roger, and Watanabe (1986)[a]
0 to 1,500/sq m	Philippines	Simpson, Roger, Oficial, and Grant (1994c)
Oligochaetes:		
max. 12,500/sq m	Philippines	IRRI (1984)
max. 18,500/sq m	Philippines	IRRI (1985)
max. 40,000/sq m	Japan	Kikuchi, Furusaka, and Kurihara (1975)
40 to 330/sq m	India	Senapati, Biswal, Sahu, and Pani (1991)
0 to 40,000 sq m	Philippines	Simpson, Roger, Oficial, and Grant (1993a, 1994b)

a. Quote in Grant, Roger, and Watanabe (1986) but previously unpublished

The role of aquatic oligochaetes in contributing to nutrient cycling and modifying biological activities in ricefields has received more attention than other invertebrate groups. Furthermore, research conducted on these organisms in other freshwater environments could be applicable to flooded ricefields. Potential roles and effects of aquatic oligochaetes in ricefields include: (1) stimulation of OM mineralization (Grant and Seegers, 1985a, 1985b); (2) biostratification of the soil (Davis, 1974; Kurihara and Kikuchi, 1980; McCall and Tevesz, 1982; Robbins, 1986; Kurihara, 1989); (3) reduction of weed abundance (Kikuchi, Furusaka, and Kurihara, 1975; Kurihara and Kikuchi, 1980; Kurihara, 1989); (4) destruction of the oxidized soil surface layer (Kurihara and Kikuchi, 1980); (5) enhancement of nutrient transfer across the soil-floodwater interface (Kurihara and Kikuchi, 1980; Kikuchi and Kurihara, 1982); (6) increased soil pH (Kikuchi, Furusaka, and Kurihara, 1977; Kurihara, 1989); (7) decreased soil Eh (Kikuchi, Furusaka, and Kurihara, 1977; Kurihara, 1989); (8) changes to soil microbial populations (Wavre and Brinkhurst, 1971; Kikuchi and Kurihara, 1977; Fukuhara, Kikuchi, and Kurihara, 1980; Kurihara and Kikuchi, 1980; Kurihara, 1989); (9) increased biotic and abiotic oxygen demand (Kikuchi, Furusaka, and Kurihara, 1977); (10) provision of a food source for aquaculture species (Aston, Sadler, and Milner, 1982; Marian and Pandian, 1984); and (11) enhancement of denitrification and nitrification in the soil (Chatarpaul, Robinson, and Kashik, 1980).

Flooded ricefields and irrigation schemes in tropical and subtropical regions create habitats favorable for the propagation of several invertebrates vectors and intermediate hosts of human and animal diseases (Roger and Bhuiyan, 1990). The most important groups are mosquito larvae and gastropod snails. Adult mosquitoes transmit malaria, encephalitis, filarial worms, dengue fever, yellow fever, and other diseases. Certain species of gastropod snails (*Oncomelania, Bilinus, Biomphalaria, Limnea* spp.) are intermediate hosts of parasitic trematode (Schistosomiasis) and nematode species that infect man.

Some invertebrate species that inhabit the floodwater are regarded as rice pests. Probably the most serious is the golden snail (*Pomacea canaliculata* Lamarck). It is a voracious herbivore that can devastate rice seedlings and cause yield losses of up to 40 percent (PDA and FAO, 1989). Chironomid larvae have been reported to inflict damage by feeding on germinating seeds and young seedlings (Clement, Grigarick, and Way, 1977). Barrion and Litsinger (1984) reported that chironomid larvae, ostracods, and corixids were observed to damage the roots of two-week-old rice seedlings.

The floodwater may contain a rich array of invertebrate predators, competitors, and parasites of pest and vector species. It is important to conserve these organisms as agents of biological control to suppress the development of deleterious organisms. For example, aquatic predators are reported to consume up to

90 percent of mosquito larvae that develop in the floodwater. If the natural predators are destroyed, the number of emerging mosquitoes could increase. Therefore, cultural practices favoring biological control agents should be encouraged (Mather and Trinh Ton That, 1984).

In traditional subsistence rice culture, farmers often depend on aquatic food items taken from their ricefields to supplement their diet. Invertebrates such as snails, crabs, and crayfish are consumed directly, others are important as prey items for harvested vertebrate species such as frogs, fish, and ducks.

9.1.3. Factors Affecting Pesticide Hazard in Ricefields

Results of studies on the impact of pesticides on nontarget organisms in wetland ricefields must be interpreted carefully to avoid erroneous conclusions. Factors to be considered include the chemicals, rate and frequency of applications, nature of the impact, agroenvironmental conditions, and methodology.

Pesticides applied in ricefields include: insecticides, herbicides, fungicides, molluscicides, rodenticides, and nematicides. Insecticides are potentially the most toxic to aquatic invertebrates. All categories of insecticides (organochlorines, organophosphates, carbamates, pyrethroids, and insect growth regulators) are currently in use in ricefields. Each pesticide category contains a multitude of different chemicals, and care should be taken to avoid generalizations about pesticide impacts without reference to the actual chemical involved. These chemicals are applied at different rates and frequencies, in various combinations, in different formulations, and by different methods. It is important to appreciate the possible implications of these differences to recognize potential pesticide impacts on nontarget organisms.

Pesticide impacts on aquatic invertebrates have often been reported where experimental concentrations are considerably higher than those resulting from field applications at recommended rates. Such information is useful in the context of pesticide misuse and accidental spillages, but where pesticides are used judiciously the findings are of limited value. However, it should also be appreciated that farmers' application rates and recommended rates are often different. Pesticides are sometimes applied at higher than recommended rates, in the belief that they will be more effective. Conversely, some farmers apply pesticides at lower than recommended rates to reduce costs.

Quantifying pesticide inputs for comparative purposes is difficult because one application of pesticide X at 2 kg ai/ha, two applications of X at 1 kg ai/ha, and one application of Y at 2 kg ai/ha will probably all have different effects. Consequently, quantification in terms of total amount or frequency of application is not fully satisfactory. The problem is compounded when different pesticides are applied in combination with each other; antagonistic or synergistic activities are largely undocumented.

It is important to know the formulation, method of application, and solubility of a pesticide. Solvents used with emulsifiable concentrates are often toxic themselves. Pesticides in ricefields can be sprayed, broadcast, incorporated in the soil, or used for dipping rice seedlings at transplanting. Carbamates and organophosphates are considered less toxic in ricefields if applied in granular form (Arce and Cagauan, 1988). Incorporation (Siddaramappa and Seiber, 1979) or deep-placement (Siddaramappa, Tirol, and Watanabe, 1979) of carbofuran reduced its concentrations in floodwater and increased its persistence in soil. When pesticides are sprayed late in the crop cycle, it has been suggested that a significant proportion is intercepted by the rice canopy and that little of it reaches the floodwater. When applied as granules, more of it enters the floodwater, although interception of carbofuran granules by floating macrophytes and rice plants has been reported (Lim, Abdullah, and Fernando, 1984; Ali, 1990). Once a pesticide has entered the floodwater, its toxicity is dependent on its solubility; carbaryl is less soluble than carbofuran and therefore less available to water-column invertebrates. As pesticides degrade, decomposition products form that are often toxic themselves, sometimes more toxic than the parent chemical.

The nature of pesticide impacts on nontarget organisms can be nominally divided into lethal, sublethal, or indirect effects. Lethal effects are observed when pesticide concentrations are sufficient to cause mortality directly. Sublethal effects include alteration of behavioral and physiological activities, interference with reproduction and maturation, and morphological changes. Sublethal impairment can reduce the chances of survival for the individual and the population. The most commonly perceived indirect pesticide effects in ricefields are reductions in species diversity, changes in community structure, and proliferation of selected species (Ishibashi and Itoh, 1981; Roger and Kurihara, 1988, Roger, Heong, and Teng, 1991). It can not be concluded that pesticides have no impact simply because no mortality was observed.

Information on pesticide impacts on aquatic invertebrates in farmers' ricefields or in fields managed according to farmers' usual practices is scarce. Literature that reports the results of laboratory studies can be extrapolated to ricefield conditions only with extreme caution. Pesticides behave differently under field conditions and the degree of exposure of an organism will be dependent on its behavior, habitat, and food preferences (Lim, Abdullah, and Fernando, 1984). Smith and Ison (1967) concluded that benthic organisms were exposed to higher concentrations of pesticide residues and for longer periods than those inhabiting the water-column. Consequently, sensitivity to a particular chemical in laboratory tests is not necessarily observed under field conditions.

The impact of pesticides in the floodwater ecosystem of ricefields is dependent on an array of agroenvironmental parameters, including temperature, radiation, pH, soil type, crop and water management, and crop development. Behavior and persistence of pesticides in rice-based ecosystems are discussed in detail in Chapter 5. However, it is important to draw attention to some aspects of particular relevance to their potential impact on aquatic invertebrates. Pesticide concentration in the floodwater is highly dependent on water depth; if depth is doubled the maximum potential concentration is halved. Fertilizer management should be considered carefully in field experiments. Direct interactions with pesticides are unlikely, but there is evidence that aquatic invertebrates are affected more by nitrogen-fertilizer than pesticides when applied at realistic doses (Simpson, Roger, Oficial, and Grant, 1994b, 1994c). The closure of the rice canopy has implications for many floodwater parameters and pesticide interception, therefore the timing of pesticide applications relative to crop development should be afforded due consideration.

Sampling methodology and the manner in which data are presented could significantly alter the results and conclusions drawn from field experiments. Literature values of floodwater invertebrate densities have been presented in volume (Kurasawa, 1956; Kikuchi, Furusaka, and Kurihara, 1975; Ali, 1990) and spatial terms (Grant, Tirol, Aziz, and Watanabe, 1983; Grant, Roger, and Watanabe, 1986; Lim, 1980; Lim and Wong, 1986; Simpson, Roger, Oficial and Grant, 1993a; 1993b, 1994a; 1994b; 1994c). Expression of densities in volumetric terms is intrinsically erroneous unless floodwater depth is constant; doubling the water depth by irrigation will halve population densities.

9.2. The Impact of Pesticides on Aquatic Invertebrates

9.2.1. Floodwater Invertebrates

The most commonly reported impact of insecticides on floodwater invertebrates in ricefields is a proliferation of primary consumers after a transient decrease (Lim, 1980; Ishibashi and ltoh, 1981; Roger and Kurihara, 1988; Roger, Heong, and Teng, 1991). Ostracod (*Stenocypris major*) densities in Malaysian ricefields averaged 10,000/sq m in control and 21,000/sq m in carbofuran (0.2 percent ai/ha) treated plots (Lim and Wong, 1986). Ostracods were reported to be abundant in insecticide-treated ricefields in the Philippines (IRRI, 1986). Explanations for the proliferation of ostracods after insecticide applications include insecticide resistance, reduced competition and predation, high tolerance of juveniles relative to adults, parthenogenetic reproduction, and increased fecundity (Khudairi and Ruber, 1974; Wong, 1979; Lim, 1980; Grant, Tirol, Aziz, and Watanabe, 1983; Lim and Wong, 1986).

Application of the herbicide benthiocarb to experimental ricefields in Japan drastically reduced populations of snails, cladocerans, odonatans, midges, and mosquito larvae. Resurgence of midges, cladocerans, and mosquito larvae occurred rapidly to densities exceeding those of the controls (Ishibashi and Itoh, 1981). Lim (1980) found that nematodes, hemipterans, and dipterans dominated in nontreated fields whereas ostracods, dipterans, and conchostracans dominated in fields when pesticides were applied at the recommended dose. Total zooplankton decreased from 1,500 per li to 400 per li after the application of carbofuran but recovered within two weeks, largely due to the resurgence of ostracods and chironomid larvae. Subsequent applications of endosulfan and carbaryl produced inconclusive results and no apparent impact, respectively. It was considered that the carbaryl had no impact because it was applied as a spray, which was intercepted by the rice plants and prevented from entering the floodwater. The resurgence of chironomid larvae and ostracods was also reported in Japanese ricefields when predatory invertebrates such as Odonata larvae were decreased following the application of a mixture of propoxur, thiobencarb, and simetryne (Takamura and Yasuno, 1986). Grigarick et al. (1990) reported that the fungicide triphenyltin hydroxide (TPTH) adversely affected a wider range of microcrustaceans than a chitin synthesis inhibitor Benzoylphenyl urea (BPU) and that mosquito larvae (*Culex tarsalis*) resurged due to reduced predation.

Sato and Yasuno (1979) found that the concentrations of several insecticides in the floodwater of Japanese ricefields were higher than acutely toxic concentrations determined in the laboratory for five species of chironomid larvae. Gorbach, Haaring, Knauf, and Werner (1971) observed mortality of Coleoptera and Tipulidae larvae after an application of endosulfan (0.5 kg ai/ha) in a ricefield in Indonesia. Hydrocorisidae and Cyclopidae showed no sign of mortality. Applications of fenitrothion temporarily reduced the population of the zooplankton *Moina* sp. in a Japanese ricefield (Takaku, Takahashi, and Otsuki, 1979). Rotifers, cladocerans, and copepod populations were reported to be adversely affected when carbofuran was applied at 5.6 kg ai/ha in a Malaysian ricefield (Ali, 1990). Carbofuran applied at manufacturers' recommended rates was not acutely toxic to cladocerans in a Malaysian ricefield, but populations were indirectly suppressed later in the growing season (Lim, Abdullah, and Fernando, 1984).

Total biomass of aquatic invertebrates was significantly reduced by application of carbofuran (1 kg ai/ha) to a ricefield in Senegal (Mullie et al., 1991). Nontarget invertebrate taxa in Californian ricefields were reduced by 57 percent and abundance by 67 percent when TPTH was applied. With the exception of some benthic and crustacean species, the community had recovered after fifty days.

Simpson, Roger, Oficial, and Grant (1994b) studied the impact of realistic carbofuran and butachlor application regimes on the population dynamics of floodwater invertebrates in Philippine ricefields. Significant pesticide effects were observed on ostracod, copepod, cladoceran, and chironomid, and mosquito larvae populations. However, the impacts were relatively small, transient, and inconsistent. It was concluded that at realistic application rates carbofuran and butachlor did not effect crop cycle population dynamics of floodwater invertebrates.

Snails are not usually affected directly by conventional rice insecticides and herbicides, but their populations may increase because of reduced competition. Gastropod populations showed no signs of mortality after endosulfan application in Indonesian ricefields (Gorbach, Haaring, Knauf and Werner, 1971). Molluscs were reported to be abundant in insecticide-treated ricefields in the Philippines (IRRI, 1986). In India, Roger, Grant, and Reddy (1985) observed that molluscs (*Limnea* and *Vivipara*) were abundant in BHC-treated plots. After harvest, Ishibashi and Itoh (1981) observed larger snail populations in fields previously treated with the herbicide benthiocarb than in the control. Simpson, Roger, Oficial, and Grant (1994c) found little evidence that indigenous snail populations were affected by carbofuran or butachlor applications. The incidence of pesticide impacts on nontarget indigenous molluscs is likely to increase with the increasing use of molluscicides to combat the golden snail problem.

Aquatic invertebrate groups found in the floodwater of ricefields are common to many shallow freshwater ecosystems. Given the relative dearth of information available on *in situ* toxicity of pesticides in the floodwater of ricefields, useful insight into potential pesticide impacts can be obtained from field and laboratory experiments pertaining to these habitats. Crosby and Mabury (1992) reviewed the potential impacts of pesticides commonly used in Californian ricefields (molinate, thiobencarb, MCPA, londax, carbofuran, and methyl parathion) in this manner.

Pesticide impacts reported on aquatic invertebrates in other shallow freshwater ecosystems include no effect, differential mortality and recovery patterns between species and life stages, feeding effects, changes in population density and community structure (Hurlbert et al., 1970; Hurlbert, Mulla, and Wilson, 1972; Gliwicz and Sieniawska, 1986; Day and Kaushik, 1987; Helegen, Larson, and Anderson, 1988; Mani and Konar, 1988; Day, 1989; Hatakeyama and Sugaya, 1989; Wijngaarden and Leeuwangh, 1989; Neugebauer, Zieris, and Huber, 1990; Hanazato and Yasuno, 1990a, 1990b, 1990c; Hanazato, 1991).

Many laboratory studies have been performed to investigate pesticide toxicity to aquatic invertebrates found in ricefields. Barrion and Litsinger (1982) found that carbofuran was acutely toxic to ostracods, chironomid larvae, corixids, and some predatory insects at 0.75 kg ai/ha. Grant, Roger, and Watanabe (1983) determined the toxicity of carbofuran and endosulfan to two species of ostracods recorded in ricefields; 48-hour LC_{50} values ranged between 0.34 to 4.0 mg/L and 3.0 to >56.0 mg/L, respectively. These values are relatively high, indicating that ostracods are resistant to some conventional pesticides (Grant, Roger, and Watanabe, 1986). Filtration and assimilation rates of algae by cladocerans and copepods are affected, not always negatively, by low concentrations of the pyrethroid fenvalerate (Day, Kaushik, and Solomon, 1987). Pyrethroids were acutely toxic to species of cladocerans and copepods between 0.12 and 5.0 ug/L and reduced reproductive and filtering rates at < 0.01 ug/L (Day, 1989). Carbaryl and endosulfan inhibited growth and egg production of a cladoceran species (Krishnan and Chockalingam, 1989). Crayfish did not suffer mortality when exposed to carbofuran (0.2–0.8 mg/L) in field and tap water static bioassay tests (Andreu-Moliner, Almar, Legarra, and Nuñez, 1986).

9.2.2. Soil Invertebrates

The soil fauna in wetland ricefields is dominated by aquatic oligochaetes and nematodes. Nontarget effects of pesticides on nematodes in ricefields has received very little attention. Ishibashi and Itoh (1981) found no effect of the herbicide benthiocarb on average population densities of saprophitic and parasitic nematodes in a Japanese ricefield. Among a plethora of biocidal chemicals applied to irrigated ricefields in the Philippines only monocrotophos and ethofenprox provided limited evidence of impacts on nematode population densities (Prot and Matias, 1990).

Information about pesticide impacts on populations of aquatic oligochaetes in ricefields is also scarce. Application of endosulfan to a ricefield in Indonesia did not cause Tubificidae mortality (Gorbach, Haaring, Knauf, and Werner, 1971). The recent disappearance of aquatic oligochaetes from some Japanese ricefields is thought to be associated with the use of some pesticides. This conclusion was arrived at when oligochaetes reappeared soon after a change in the type of herbicide applied and was supported by laboratory tests (Kurihara and Kikuchi, 1988).

In Philippine ricefields, a pesticide regime consisting of carbofuran, butachlor, and triphenyl tin hydroxide, applied at recommended rates, reduced aquatic oligochaetes population density over the cropping season from 1,800/sq m to less than 200/sq m (Roger et al., 1992). In a two-year study of the combined impacts of pesticide and nitrogen fertilizer management, aquatic oligochaete populations were adversely affected by carbofuran applications (0.6 to 2.5 kg ai/ha) during the first crop, but possibly stimulated during the second year (Simpson, Roger, Oficial, and Grant, 1993a). The adverse effects observed were manifest as interference with population development not reductions in population densities. A survey of aquatic oligochaetes in farmers' fields in the Philippines did not identify differences between populations attributable to pesticide use (Simpson, Roger, Oficial, and Grant, 1993b).

Earthworm mortality was reported in Texan ricefields after a carbofuran application of 0.56 kg ai/ha (Flickinger, King, Start, and Mohn, 1980). In Indian ricefields, 6 and 34 percent reductions in population densities of *Darwida willsi* Michaelsen were reported after malathion applications of 0.75 and 3.0 kg ai/ha, respectively (Senapati, Biswal, Sahu, and Pani, 1991).

To gain further understanding of the likely impacts of pesticides on aquatic oligochaetes in ricefields one must refer to literature from similar ecosystems and laboratory tests. Pesticide stimulation and depression of burrowing activity has been reported in contaminated lake sediments (Keilty, White, and Landrum, 1988a, 1988b, 1988c; Keilty and Landrum, 1990). Whitley (1968) observed that the respiration rates of lumbricid and tubificid worms were increased in the presence of aqueous pollutants. Exposure to sublethal concentrations of some pesticides has been shown to increase reproductive activity, suggesting a response to compensate for chemical stress (Senapati, Biswal, Sahu, and Pani, 1991). Pesticide tolerance of some oligochaetes has been shown to increase with long-term exposure to low concentrations (Keilty and Landrum, 1990). Some oligochaetes are more tolerant of toxicants in polycultures than in monocultures (Chapman and Brinkhurst, 1984; Keilty, White, and Landrum, 1988a).

Pesticide impacts on aquatic oligochaetes reported from laboratory toxicity tests across a range of chemicals and concentrations include: death, hyperactivity, muscular spasms and convulsions, and reversible and nonreversible morphological changes (Whitten and Goodnight, 1966; Whitley, 1968; Naqvi, 1973; Magallona, 1989). Several authors have suggested that aquatic oligochaetes possess a greater tolerance of pesticides than other aquatic invertebrates (Naqvi, 1973; Bailey and Lui, 1980).

9.2.3. Biodiversity

It is generally accepted that crop intensification and agrochemical use decrease biodiversity and provoke "blooms" of individual species. However, quantitative data on aquatic invertebrate diversity in ricefields are rare. Furthermore, the limited amount of data available were obtained by different methods of sampling, over different time frames and from different locations.

The only reference on the diversity of aquatic invertebrates in traditional ricefields is a 1975 study by Heckman (1979) in Thailand where 183 species (protozoans excluded) were recorded in one field within one year. In a two-year study of the aquatic invertebrate community in ricefields in Selangor, Malaysia, Lim (1980) found that species heterogeneity decreased after a granular application of carbofuran, but that total invertebrate populations increased because of a rapid recruitment of ostracods. The total number of aquatic invertebrate taxa recorded was thirty-nine. Single sampling by Takahashi, Miura, and Wilder (1982) in four Californian ricefields recorded 10–21 taxa. In surveys of 18 sites in the Philippines (IRRI, 1986) and India (Roger, Grant, and Reddy, 1985;

Roger, Grant, Reddy, and Watanabe, 1987), it was found that population dominance was inversely proportional to diversity and that ostracods, chironomids, and molluscs dominated the invertebrate community at most sites, with a few species attaining exceptionally high densities at some sites. The highest number of taxa recorded at a site was twenty-six, the lowest, two.

The marked decrease in values recorded since 1975 might be taken as a rough indication of a decrease in species richness. This agrees with but does not demonstrate the generally accepted concept that crop intensification has reduced biodiversity in ricefields (Roger, Heong, and Teng, 1991). Decrease of biodiversity in ricefields may also be attributed to the disappearance of permanent reservoirs of organisms in the vicinity of the fields (Fernando, Furtado, and Lim, 1979).

9.2.4. Bioconcentration

Pesticide uptake by aquatic animals is primarily through ingestion and absorption through respiratory organs. Once within an organism they can accumulate in body tissues, particularly fat. Bioconcentration of pesticides in food chains has been demonstrated in many ecosystems but has received little attention in ricefields. Available data refer to pesticide accumulation *in vitro* by BGA common in ricefields (Das and Singh, 1977; Kar and Singh, 1979). The ability of microalgae to accumulate pesticides has also been demonstrated in freshwater environments (Wright, 1978). Invertebrate grazers feeding on contaminated algae may ingest significant quantities of pesticide. Predatory invertebrates that consume herbivores are similarly at risk. Chen, Hsu, and Chen (1982) observed thiobencarb bioconcentrations thirty times above ambient in dragonfly naiads in a model ricefield ecosystem.

Bioconcentration of pesticides is important when considering the ricefield ecosystem as a possible environment for aquaculture (rice-fish, rice-shrimp). Sastrodihardjo, Adianto, and Yusoh (1978) found that the application of endrin and phosphamidon affected fish directly and indirectly through feeding on contaminated *Tubifex* sp.. Pesticide bioaccumulation in the worms' body tissues may account for this observation.

9.3. The Implications of Pesticide Impacts on Aquatic Invertebrates in Ricefields

9.3.1. Soil Fertility

At current application rates of inorganic fertilizer, most nitrogen absorbed by the rice crop originates from the soil. Available soil nitrogen is released by the turnover of a microbial biomass that represents only a few percent of total soil nitrogen (Watanabe, De Datta, and Roger, 1988). The microbial biomass is replenished by the recycling of (1) crop residues, (2) nutrients from the PAB, and (3) rhizosphere exudates. Therefore invertebrates play an important role in maintaining soil fertility when involved (1) in the recycling of nutrients from the PAB and detritus by grazing and (2) in the translocation of nutrients to the deeper soil layer where they contribute to the replenishment of the microbial biomass. Pesticide effects on grazer populations might affect algal primary production and nutrient recycling in floodwater. Pesticide effects on benthic feeding detritivores could have implications for the quantity of nutrients immobilized in the detritus layer and for the translocation of material across the soil-water interface. These effects probably have implications for soil fertility, especially nitrogen availability, but little data is available.

Most available information refers to the impacts of insecticides on algal grazers and the consequent effects on microalgae and N_2-fixing cyanobacteria. A commonly reported phenomenon is the development of algal blooms due to reduced grazing (Raghu and MacRae, 1967; Grant, Roger, and Watanabe, 1983; Grant, Roger, and Watanabe, 1986). Increased nitrogenase activity in the water of a ricefield treated with carbofuran (6 kg ai/ha) was attributed to inhibition of micro-crustaceans and consequent buildup of nitrogen-fixing blue-green algae (Tirol, Santiago, and Watanabe, 1981). This effect was, however, reported only after the first application of HCH or carbofuran. After repetitive applications, grazers, especially ostracods, resurged and algal growth was suppressed (Roger and Kurihara, 1988). This may have implications for the quantity of N_2 fixed by cyanobacteria. Because of the relative higher resistance to grazing of cyanobacteria forming mucilaginous colonies, the resurgence of grazers has a selective effect on cyanobacteria flora and leads to the dominance of mucilaginous forms, which are usually less active in biological N_2 fixation (Antarikanonda and Lorenzen, 1982; Grant, Roger, and Watanabe, 1985). The structure of the algal community may also be changed when pesticide impacts only occurs on specific grazer species. Changes in floral populations will eventually feedback on invertebrate grazers, ultimately returning the system to a new equilibrium.

9.3.2. Disease Vectors and Intermediate Hosts

The possible nontarget effects of pesticides on disease vectors and intermediate hosts in ricefields include transient population decrease, proliferation if natural predators and competitors are adversely affected, and resurgence of resistant strains.

Mosquito larvae populations, suppressed by natural enemies in traditional ricefields, can develop large populations in intensive irrigated systems (Heckman, 1979; Lim, 1980; Grant, Roger, and Watanabe, 1983; Takamura and Yasuno, 1986; Roger and Kurihara, 1988). Broadcast application of nitrogen fertilizer leads to the proliferation of mosquito larvae (Simpson, Roger, Oficial, and Grant, 1994b). Disease problems associated with the proliferation of mosquito larvae in intensive irrigated rice systems are especially acute where urbanization has occurred in rice-growing regions, bringing humans and pests closer together.

Mulla and Lian (1981) observed that agricultural insecticide applications were directly toxic to mosquito larvae and adults and their predators. Whether or not the application of pesticides in ricefields for agricultural purposes is beneficial to vector control depends on their relative impact on vectors and predators. Reductions in the incidence of malaria and Japanese encephalitis have been reported in Japan since 1945. This could be attributed to the reduction of mosquito vector populations by agricultural insecticides (Self, 1987; Mogi, 1987). In Korea, agricultural pesticide application reduced the density of the Japanese encephalitis vector *Culex tritaeniorhyncus* in rice-growing areas but had no effect on the main malaria vector *Anopheles sinensis* (Self, 1987). The decrease of *C. tritaeniorhynchus* after 1970 in Japan could be attributed to the switch from organochlorine to carbamate pesticides that have less adverse affects on vector predators (Wada, 1974; Mogi, 1987).

Mosquitoes are particularly adept at producing strains resistant to conventional insecticides. In the rice-growing areas in the United States, the elimination of malaria by suppressing the vector with DDT in the post–World War II era led the way to extensive insecticide use against mosquitoes and agricultural pests. Organochlorine, organophosphate, carbamate, and synthetic pyrethroid insecticides have been used extensively enough in the United States to produce resistance in some riceland mosquitoes (Bown, 1987).

There is no available literature on the nontarget impacts of pesticides on gastropod intermediate host species. However, evidence from other species suggests that pesticides, with the exception of molluscicides, may have little effect or induce population increases (Gorbach, Haaring, Knauf, and Werner, 1971; Ishibashi and Itoh, 1981; IRRI, 1986; Roger, Grant, and Reddy, 1985; Simpson, Roger, Oficial, and Grant, 1994c). Increasing use of molluscicides to combat golden snails may increase the incidence of negative nontarget effects of pesticides on intermediate host species.

9.4. Conclusions and Proposed Research Strategy

Despite the recognized importance of aquatic invertebrate populations in wetland ricefields, current knowledge on pesticide impacts is too fragmentary to draw definitive conclusions. Furthermore, available information deals almost exclusively with insecticide in transplanted irrigated rice, whereas foreseeable changes in rice technology and pesticide use indicate a shift toward direct seeded rice with an increased use of herbicides and, possibly, molluscicides. Simultaneously, insecticide use is expected to decrease, with increased adoption of integrated pest management (IPM) and biological control. Therefore, it is difficult to recommend pesticide practices in the context of the management of nontarget aquatic invertebrate fauna.

It is also important to emphasize that impacts on nontarget organisms in wetland ricefields can be beneficial, detrimental, or both. If disease vectors or pest species are adversely affected, the impacts will be beneficial. However, should there be damaging effects on the nutrient recyclers, agents of biological control, and food species, the consequences will be detrimental. When beneficial and deleterious biota are affected simultaneously the desirability of the impact becomes a value judgment. If impacts are better understood, pesticide management could be developed to favor beneficial organisms without promoting deleterious organisms.

Laboratory research has studied the roles of aquatic invertebrates in ricefields and the tolerance of individual species to selected pesticides. It is important that more research be conducted *in situ* to quantify the impacts of pesticides on the various roles of aquatic invertebrates under realistic field conditions and cultural practices. Particular attention should be given to the long-term effects of pesticide applications on nutrient cycling and disease vectors.

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